ESTIMATING AQUIFER RESPONSE FOLLOWING FOREST RESTORATION AND CLIMATE CHANGE ALONG THE MOGOLLON RIM, NORTHERN ARIZONA

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ABSTRACT

ESTIMATING AQUIFER RESPONSE FOLLOWING FOREST RESTORATION AND CLIMATE CHANGE ALONG THE MOGOLLON RIM, NORTHERN ARIZONA

Clinton J. W. Wyatt

Landscape-scale forest restoration treatments are planned for four national forests in Northern Arizona: the Coconino, Kaibab, Tonto, and Apache-Sitgreaves National Forests. The first analysis area comprises 900,000 acres on the Coconino and Kaibab National Forests where the U.S. Forest Service is proposing restoration activities on approximately 600,000 acres over a ten year period pending acceptance of an Environmental Impact Statement. These forest restoration treatments are intended to accomplish a number of objectives including reducing the threat of catastrophic wild fire and subsequent flooding and to restore forest health, function, and resiliency. Previous studies suggest that in semi-arid, ponderosa pine watersheds there was a possibility to increase surface water yields 15-40% when basal area was reduced by 30-100%. Because of these results, there is considerable interest in the amount of increased water yield that may recharge from these activities.

The objectives of this study were to 1) examine the state of knowledge of forest restoration thinning and its hydrological responses and to evaluate the quality and type of related references that exist within the literature and 2) simulate possible changes in recharge and aquifer response following forest restoration treatments and climate change. A systematic review process following the guidelines suggested by the Collaboration for

Environmental Evidence was conducted to examine literature relevant to this topic. The Northern Arizona Regional Groundwater-Flow Model was used to simulate the changes expected from forest restoration treatments and climate change.

The systematic review returned 37 references that were used to answer questions regarding tree removal and the associated hydrological responses. Data from individual studies suggest that forest treatments that reduce tree density tend to increase surface water yield and groundwater recharge while reducing evapotranspiration. On average, there was a 0-50% increase in surface water yield when 5-100% of a watershed was treated. Groundwater results were less conclusive and there was no overall correlation for all studies between percent area treated and groundwater recharge. A majority of studies (33 of 37) reported statistically significant results, either as increases in water yield, decreases in evapotranspiration, or increases in groundwater table elevation. Results are highly variable, and diminish within five to ten years for water yield increases and even quicker (< 4 years) for groundwater table heights.

Using a groundwater-flow model, it was estimated that over the ten-year period of forest restoration treatment there was a 2.8% increase in annual recharge to aquifers in the Verde Valley compared to conditions that existed in 2000-2005. However, these increases were assumed to quickly decline after treatment due to regrowth of vegetation and forest underbrush. Furthermore, estimated increases in groundwater recharge were masked by decreases in water levels, stream baseflow, and groundwater storage resulting from surface water diversions and groundwater pumping. These results should be used in conjunction with other data such as those recovered from paired-watershed studies to

help guide decision-making with respect to groundwater supply and demand issues, operations, and balancing the needs of both natural and human communities.

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PREFACE

Chapter 2 and 3 of this thesis were written as separate manuscripts and contain some material that is repeated from each other and Chapter 1. Chapters 2 and 3 were written for submission to academic journals and units reflect this. Chapter 4 summarizes conclusions from Chapters 2 and 3.

CHAPTER 1 – INTRODUCTION

1.1 STATEMENT OF SIGNIFICANCE

Few studies that have attempted to quantify the relationship between forest thinning and groundwater recharge; even fewer have looked at this relationship in arid and semi-arid climates. Many studies have analyzed the effect that removing trees, often by clear-cutting, will have on surface water runoff (Bosch and Hewlett, 1982, Brown et al., 2005). Other studies have looked at the effect that tree removal has on evapotranspiration, soil moisture storage, and snowpack accumulation (Kolb et al., 2009, Bazan et al., 2012, Stegman, 1996). Because of the dearth of groundwater studies in these areas, there is significant uncertainty with regards to how regional aquifers, streams, and springs in Northern Arizona will be affected by landscape-scale forest restoration treatments that are planned on four national forests beginning in 2014. There is a need to fill this knowledge gap so that appropriate management practices can incorporate any change in aquifer response following restoration.

Based on previous research, it is anticipated that forest restoration thinning treatments planned for the Four Forest Restoration Initiative (Draft EIS Chapter 1, 2012) will increase groundwater recharge by a modest yet significant amount. The reasoning for this increase is that removing trees will cause a decrease in ET (sublimation is included in this variable) and an increase in snowpack accumulation. With more snow and less ET, more water will be available to infiltrate into the soils, increasing soil moisture storage and enhancing percolation down to regional aquifers. This may result in an increase in groundwater recharge and water available for storage to regional aquifers in Northern Arizona.

A numerical groundwater-flow model recently developed by the U. S. Geological Survey (USGS) (Pool et al., 2011) called the Northern Arizona Regional Groundwater-Flow Model (NARGFM) will be used to simulate how these forest restoration treatments will impact groundwater recharge to the Coconino, Redwall-Muav, and basin-fill aquifers in Northern Arizona. Downscaled climate data available through the U. S. Bureau of Reclamation (Reclamation) will also be used to determine future climatic impact on the water budget for the area of interest. Four scenarios, including one baseline scenario and three scenarios derived from IPCC climate emission scenarios will be simulated with the NARGFM.

1.2 BACKGROUND

This research is part of a larger, collaborative effort between the Salt River Project (SRP) and Northern Arizona University's Ecological Restoration Institute (ERI) and School of Earth Sciences and Environmental Sustainability. The goal of this collaborative project is to determine the effects of alternative forest restoration treatments and wildfire on hydrologic and natural resource responses. The research presented here fulfilled two objectives of the larger planned effort. The results of this work will be important for landscape-scale ecosystem restorations, long-term forecasting and planning for water availability, and adaptive management practices being implemented for the 4FRI. Other objectives include the design and implementation of a paired watershed study, development of a data server where data, results, and findings will be made accessible to cooperators and managers, and the development of a monitoring program following forest restoration.

1.2.1 THE FOUR FOREST RESTORATION INITIATIVE

The Four Forest Restoration Initiative (4FRI) is a proposal by the United States Department of Agriculture's (USDA) Forest Service to conduct restoration thinning and burning treatments in four national forests located along the Mogollon Rim in Northern Arizona (Figure 1). These forests are ponderosa pine (*Pinus ponderosa*) dominated

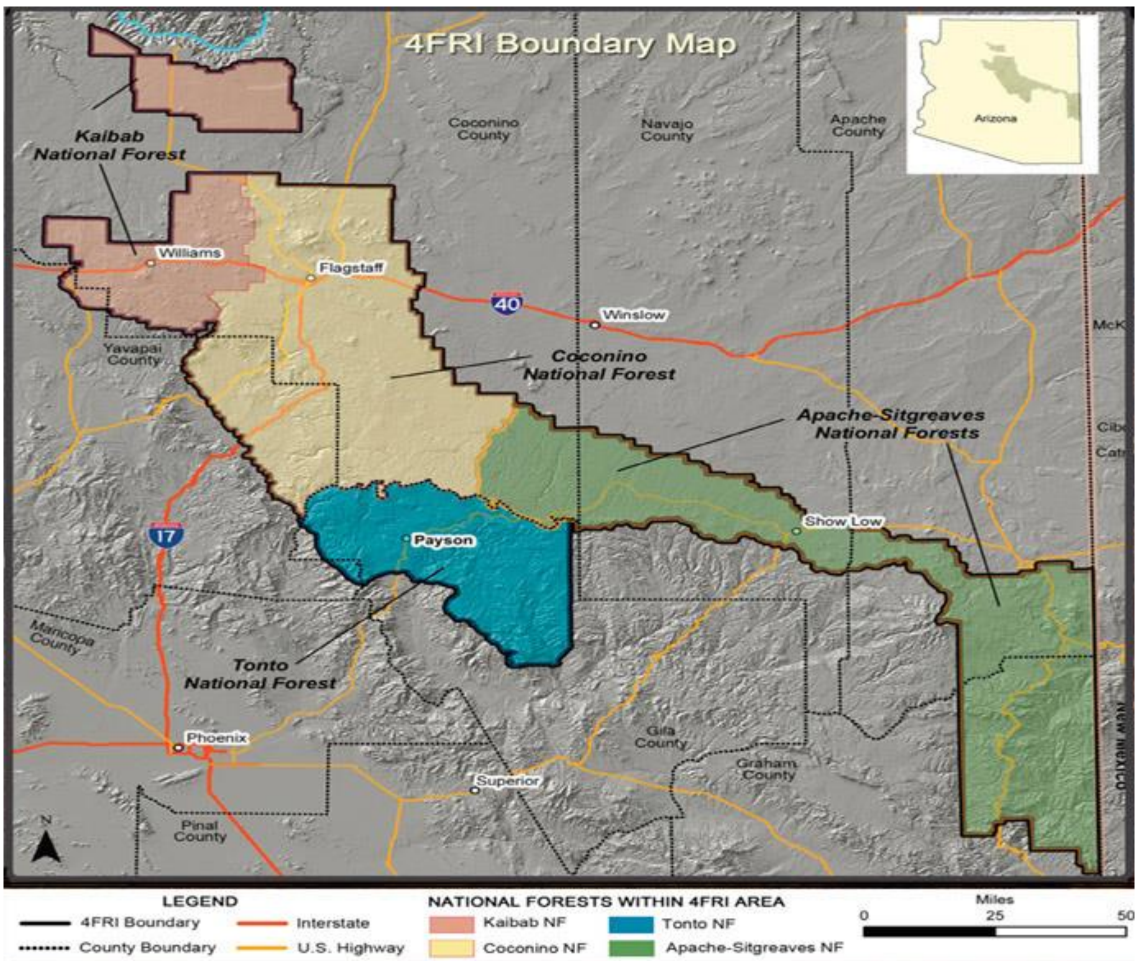

Figure 1. Four Forest Restoration Initiative (4FRI) map detailing national forests, major roads, and boundaries (from 4FRI.org).

ecosystems located at elevations between 6,000-8,000 feet and receive between 20-30 inches of precipitation annually. The Apache-Sitgreaves, Coconino, Kaibab, and Tonto National Forests comprise 2.4 million acres of federal forest land.

The purpose of these treatments is to reduce the threat of catastrophic wild fire and subsequent flooding and to restore forest health, function, and resiliency. Because historical practices such as old-growth logging and fire suppression have increased the density of young trees and forest underbrush, these forests are considered high risk for crown fires. Crown fires are fires that burn extremely hot – too hot for naturally, fire-adapted ecosystems like ponderosa pine forests – and burn all the way up the tree to the crown. These types of fires are considered unnatural and cause significant damage to the forest ecosystem, water resources, and structures in the immediate vicinity of the fire, including businesses, schools, and homes. The 4FRI treatments will remove this excess fuel and significantly reduce the risk of crown fires.

Healthy forested watersheds are life-support systems that are critical to the survival of flora and fauna living within and around a watershed. They also provide numerous ecosystem services that benefit humans and are important to the well-being and livelihood of nearby communities. For example, healthy forests provide provisioning (food and water), regulating (climate and carbon storage), supporting (soil formation and nutrient cycling), and cultural (education and aesthetic) services (Deal, 2008). Overuse of healthy ecosystems can diminish their capacity to provide these services. Of critical importance in the southwestern U. S. and other semi-arid regions is the preservation and restoration of forested watersheds to ensure and restore their ability to provide clean and abundant water. The goal of the 4FRI is to support forested ecosystems healthy enough to provide these benefits to natural and human communities.

The first analysis area slated for treatment includes approximately 900,000 acres, or ~38% of the total 4FRI area, on the Coconino and Kaibab National Forests (Draft EIS Chapter 1, 2012). Approximately 600,000 acres of this area is expected to receive some sort of treatment. The treatments are expected to take ten years to fully implement, and to begin sometime in 2014. Not included in 4FRI are forest areas, called shelf-stock, which will be treated in a similar manner along a similar timeline. These shelf-stock areas were included in the model simulations. A second round of restoration treatments is anticipated for additional parts of the Coconino and Kaibab National Forests, as well as areas within the Apache-Sitgreaves and Tonto National Forests. However, the exact details of these treatments for the second analysis area are uncertain. Because of the uncertainty regarding these treatments, only the first analysis area was included in the model simulations. Currently, an EIS is being prepared to analyze the environmental, social, and economic impacts that forest restoration treatments will have.

The forest restoration treatments are intended to accomplish a number of objectives. The treatments will reduce stand density within selected areas up to 50% (Draft EIS Chapter 1, 2012). They will restore a balance of age and class sizes to the forest (currently, 50% of the forest is of even-aged structure). Uneven-aged thinning (UEA) will be the most heavily used tree-removal treatment in the 4FRI area. This method will establish interspaces between adjacent groups of 50 to 70 square feet of basal area, establish tree groups of 0.1 to 1 acre in size with 4 to 20 dominant and co-dominant trees per 1/10 acre, produce interlocking crowns between mid-age and older trees to produce >40% canopy cover.

Additional thinning treatments include intermediate thinning and stand improvement thinning, which will increase vegetation diversity and composition by reestablishing aspen, grasslands, pine-sage, and a variety of oak size classes and forms that are important to many wildlife species. Treatments will restore natural fire regimes and reduce the estimated 41% of the project area able to support crown fires to 5-10%. The treatments will also restore the function of a number of springs and ephemeral streams throughout the forests, both of which are important to wildlife habitat, forest health, and water users in Arizona.

1.2.2 DOWNSCALED CLIMATE DATA

Bias corrected and downscaled climate data from the World Climate Research Programme's [sic] (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model ensemble were used to simulate future changes in precipitation in the study area (Maurer et al., 2007). This model output includes monthly climate projections from 1950-2099 over the contiguous United States as well as monthly hydrologic projections over the western United States. The goal of the WCRP was to coordinate the activities of climate modeling groups that have produced hundreds of simulations of past and future climates for the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4). These simulations are available through the U.S. Department of the Interior's Bureau of Reclamation's Research and Development office. Over 100 projections of monthly temperature and precipitation from 16 models are available at 1/8°

by 1/8° (12 km x 12 km) spatial resolution over the lower 48 states (Reclamation, 2012).

1.2.3 THE NOTHERN ARIZONA REGIONAL GROUNDWATER-FLOW MODEL

A numerical groundwater-flow model (MODFLOW), called the Northern Arizona Regional Groundwater-Flow Model, or NARGFM, was developed by the USGS to simulate the interactions between regional aquifers, streams, and springs in Northern

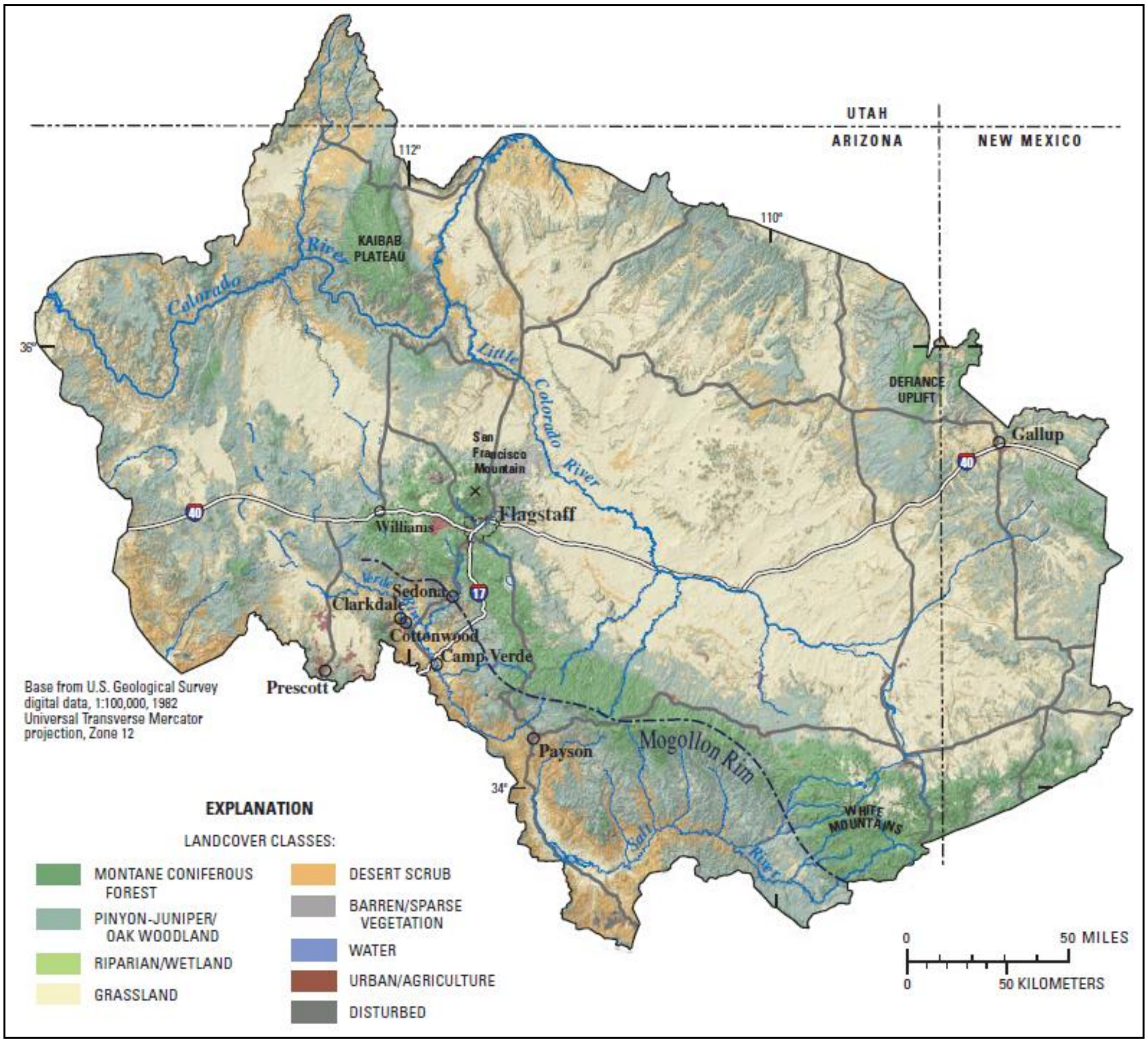

Figure 2. Northern Arizona regional groundwater-flow model boundaries and vegetative cover map. (From Pool et al. 2011.)

Arizona and to assess the adequacy of groundwater resources and the effect that increased pumping, especially in the Verde River basin, would have on these resources (Pool et al., 2011) (Figure 2). For this project, the NARGFM was used as a tool to estimate how the 4FRI forest restoration treatments and future climatic conditions will impact recharge to aquifers, discharge to streams and wells, and groundwater storage.

The NARGFM originated from the Arizona Department of Water Resources' Rural Watershed Initiative (RWI), a program with a goal to understand the adequacy of water supplies in rural areas with growing populations, a characteristic of the southwestern United States. RWI reports for three areas were studied by the USGS, including the Mogollon Highlands (Parker et al., 2005), the upper and middle Verde River watersheds (Blasch et al., 2006), and the Coconino Plateau (Bills et al., 2007). These areas comprise over 50,000 sq. mi. of federal, state, private, and tribal lands and are among the fastest growing locations in the United States. Due to of this growth and the relative scarcity of water in the dry, southwestern United States a numerical flow model was deemed necessary so that future managers like cities, land managers, and tribal authorities could investigate the effect that anticipated increases in pumping may have on groundwater resources.

The model was developed using hydrologic data and information acquired from the three RWI studies. Rather than developing groundwater-flow models for each distinct region and/or administratively defined basin or sub-basin, a regional framework was used to simulate the interconnectedness and dependency of groundwater basins and sub-basins – and their respective communities – on each other. This allowed and will continue to allow resource managers to examine the hydrologic consequences of groundwater development not only on their own resources, but on the resources of surrounding communities. This increases the scope of projects undertaken by and the awareness of water users.

Though the NARGFM was developed to assess the adequacy of groundwater supplies in the study area, with an emphasis on the effects of groundwater withdrawals on regional water tables and flow systems, for this project it is used to explore how land use and climate change will affect groundwater resources. Rather than adjusting pumping scenarios based on anticipated population growth and groundwater withdrawal, recharge rates were modified to simulate how forest restoration treatments will impact the regional water budget and groundwater system. A systematic review was conducted following the Collaboration for Environmental Evidence's systematic review guidelines to resolve the state of knowledge with respect to tree removal and its impact on hydrological responses, as well as to evaluate the quality and type of information that exist within the literature (CEE, 2010). The results from the systematic review were used to determine appropriate factors of change in recharge. I then applied these factors to the NARGFM to simulate changes in groundwater recharge following forest treatments. Similar recharge-change factors were used to simulate changes in precipitation from regional climate change.

1.3 PURPOSE AND OBJECTIVES

The purpose of this study was to estimate how the 4FRI treatments, additional shelf-stock treatments, and future climate scenarios will impact the water budget in Northern Arizona.

The following were the main objectives of this research:

1) Determine, through a systematic review process, the potential effect of removing trees on surface water runoff, groundwater recharge, soil moisture storage, transpiration, evaporation, and sublimation.
2) Simulate changes in groundwater recharge from landscape change and changing climatic conditions.
3) Assess the impacts that these changes may have on the groundwater budget of Northern Arizona, with a focus on the Verde Valley groundwater catchment area and associated tributaries.
4) Deliver the results to regional water use stakeholders so that they may be used to inform water management strategies in the study area.

1.4 STUDY AREA

The study area encompasses over 50,000 square miles of Northern Arizona and adjacent parts of western New Mexico and southern Utah (Figure 2). This area has an arid to semi-arid climate and temperature and precipitation vary considerably, both spatially and temporally. Lower altitudes have extremely hot summers but mild winters, while higher altitudes have moderate summers and severe winters. Basins receive 10 to 15 inches per year, surrounding mountain slopes receive 15 to 30 inches per year, and the mountains and Coconino Plateau receive 20 to 40 inches per year (Blasch et al., 2006). However, only about 10% of the annual precipitation in the area is recovered and used by people; the other 90% is lost to evapotranspiration (Ffolliott et al., 2000). Winter snowfall accounts for approximately 60% of annual precipitation but is responsible for 80-95% of streamflow (Baker, 2003) and almost all groundwater recharge (Blasch et al., 2006).

Elevation ranges from approximately 750 to 800 feet in the lowest reaches of the Colorado River, to 12,633 feet at Humphreys Peak, the highest natural point in Arizona.

Included in the study area are parts of four national forests: the Apache-Sitgreaves, Coconino, Kaibab, and Tonto National Forests, which comprise approximately 2.4 million acres of federal forest land. These forests are largely constrained to elevations of 6,000-8,000 feet and receive an annual average of 20 to 30 inches of precipitation per year as roughly equal proportions of summer monsoon rains and winter snowfall. Vegetation is predominately ponderosa pine trees but also includes alligator juniper, quaking aspen, and other mixed conifer species. The remainder of the model domain includes a wide variety of ecosystems including pinyon/juniper forests, riparian/wetland vegetation, grassland, and desert scrub (Figure 2).

Major rivers in the study area include the Colorado, Little Colorado, Verde, and Salt Rivers, and their associated tributaries. These major rivers are supported by a number of perennial streams and springs, as well as intermittent, or ephemeral, streams and springs that contribute flow on either a regular (seasonal) or irregular (event-based) basis. Major springs included in the study area include Blue, Del Rio, and Havasu springs, as well as Verde headwater springs and springs adjacent to Verde tributaries, and springs that discharge to the Colorado River. There are a number of other surface water bodies included in the study area, such as springs and lakes that are not modeled in the NARGFM, either due to lack of data or the inability of the model to simulate at those resolutions.

1.4.1 GEOLOGIC SETTING

The study area is predominately located in the Colorado Plateau Structural Province and Transition Zone, with smaller parts located in the Basin and Range Structural Province. These provinces contain a number of similar geologic units that have a different structural history (Figure 3). The Colorado Plateau is an area of uplifted sedimentary rock, underlain by basement rock and overlain by relatively young volcanic deposits and unconsolidated sediments. Proterozoic basement rocks include granite, metamorphic rocks, and Grand Canyon Super Group rocks. Basement rocks underlay younger units and are exposed in the Grand Canyon, Big and Little Chino Valleys, Verde Valley, Mazatzal Mountains, Bradshaw Mountains, and Sierra Ancha Mountains.

The sedimentary rocks include Phanerozoic sandstone, conglomerate, siltstone, mudstone, shale, limestone and dolomite units. Paleozoic rocks include Cambrian (Tapeats Sandstone) to Permian (Kaibab Limestone) sedimentary rocks. These units dip approximately 2 degrees southwest, thicken westward, and are characterized by east-to-west facies changes. These rocks underlie most of the study area and are exposed along the Mogollon Rim and in canyons of the Colorado River. The Redwall Limestone, Martin Formation, and Muav Limestone are all units of the Redwall-Muav Aquifer, an important source of groundwater for much of the northern part of the state. Additionally, the Middle Supai through Kaibab Formations are important units that make up the Coconino Aquifer.

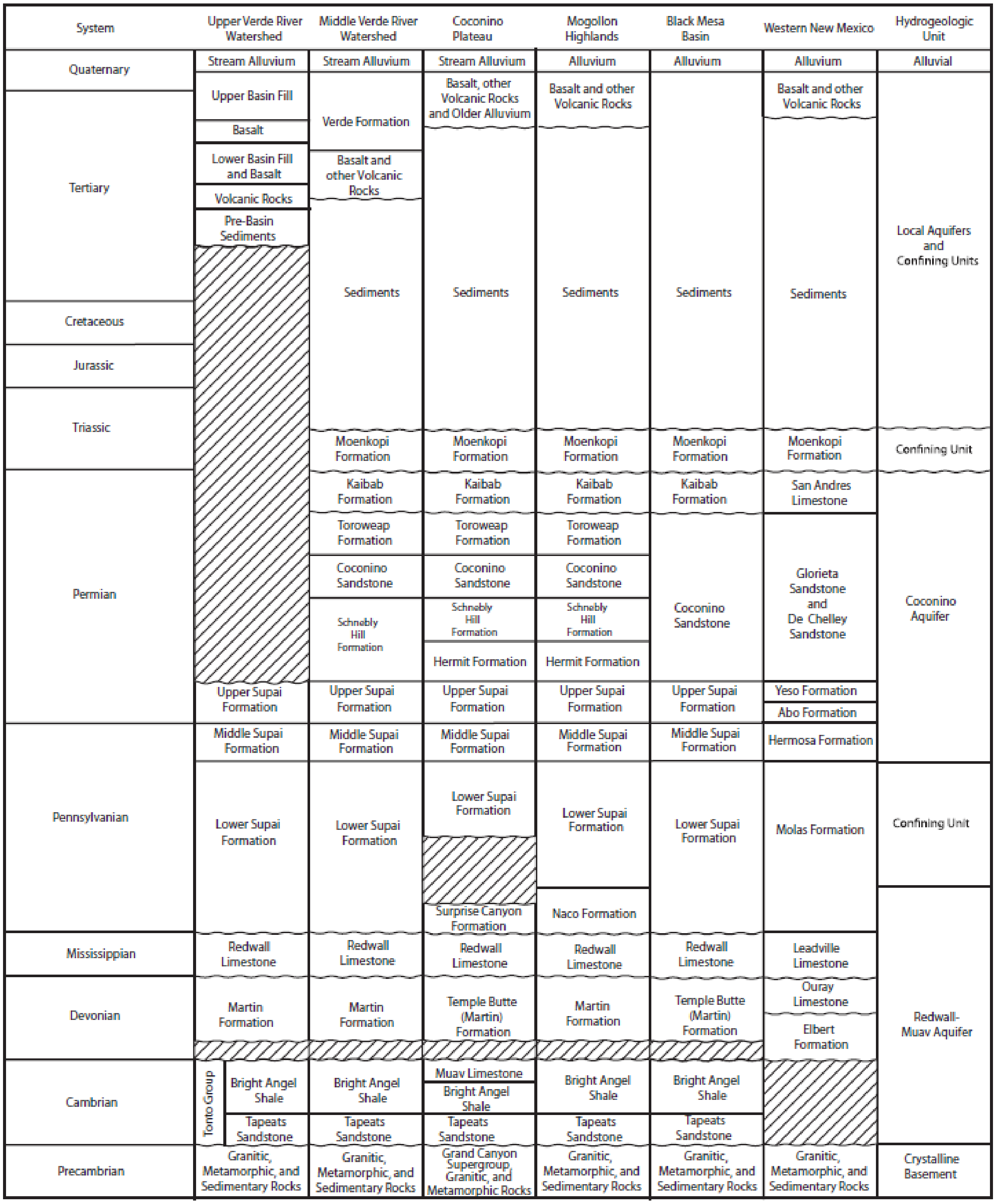

Figure 3. Generalized stratigraphic cross section of rock units located within physiographic provinces of the Northern Arizona Regional Groundwater-Flow Model study area (from Pool et al., 2011, modified from Hart et al., 2002).

Mesozoic Rocks include mostly the Triassic Moenkopi formation and younger unconsolidated sediments. The Moenkopi formation has a low permeability and serves as the confining unit for the Coconino Aquifer below, as well as some of the alluvial basin-fill aquifers above. Overlying sediments have good permeability and form disconnected aquifers throughout the study area. However, these aquifers were not included in the model domain and are therefore not important for this study. These units have undergone considerable structural disturbance and are therefore highly deformed and regionally discontinuous at the present time. Many of the sediments produced from this disturbance were later deposited in the basins located in the study area. These sediments include sand and gravels deposits at basin boundaries and silt, clay, and evaporates deposited in the basin center. These latter sediments often act as a confining unit to the basin-fill aquifers made up of the sand and gravel units. Some basins may have volcanic deposits interbedded with the basin-fill deposits. These volcanic units may form locally important zones of high permeability.

The structural history of the study area is complex. Major structural events include the Grand Canyon Orogeny, the Laramide Orogeny, and the basin and range structural disturbance. The Grand Canyon Orogeny was an event that was initiated approximately 830 Ma (Elston, 1979). This orogeny significantly tilted, folded, and faulted members of the Grand Canyon Supergroup and marked the end of deposition of what would become the pre-Cambrian rocks of the region. After these events, there was a relatively long period of erosion until the deposition of the Tapeats Sandstone and associated units over the now tilted Grand Canyon Supergroup and exposed basement rocks 300 million years later (about 530 Ma). These events created the iconic angular unconformity found two-thirds of the way down the Grand Canyon.

The Laramide Orogeny was a compressional event that occurred between 75 and 35 Ma that was largely responsible for the uplift of both the Rocky Mountains and the Colorado Plateau. This event lifted a large block of relatively horizontal sedimentary strata in the study area and surrounding area approximately 10,000 feet. The Laramide Orogeny was also responsible for a period of increased erosion that stripped most of the Colorado Plateau of its Mesozoic units (Pool et al., 2011). This event produced the regional 1 to 2 degree dip characteristic of the Colorado Plateau and resulted in the formation major features such as the Kaibab Uplift, Mesa Butte Fault, and Black Mesa Basin. The Mogollon Rim, where a majority of the 4FRI treatments are planned, is the erosional edge of the Colorado Plateau and marks the onset of the Transition Zone from plateau to basin and range.

The basin and range structural disturbance was an event that occurred during the middle Tertiary, roughly 17 to 10 Ma (Eaton, 1982). This marked a change from compressional stresses of the Laramide Orogeny to extensional stresses associated with basin and range formation. This event was characterized by normal faulting that created alternating series of horsts and grabens – basins and ranges – all the way from southern Oregon to northwestern Mexico, including major extension in southern Arizona, Utah, Nevada, and eastern California (Eaton, 1982). This established a number of north-northwest trending valleys in the study area including Big Chino Valley, Williamson Valley, Little Chino Valley, Verde Valley, and Tonto Creek Basin, all of which were created by extensional faulting (Pool et al., 2011). Basin-fill sediments associated with this disturbance constitute the primary water bearing units of the basin-fill aquifers.

A final major event – the establishment of the Colorado River in the Grand Canyon by 9 to 6 Ma – created the heavily dissected landscape of Northern Arizona including the Grand Canyon, where over a mile of down cutting has occurred (Pool et al., 2011). This rapid erosion has dewatered regional aquifers in the area, significantly altering the associated groundwater-flow systems. This has led to the establishment of several major springs in the area, the most prominent of which is Havasu Spring in western Grand Canyon. These springs are important to communities in the region, especially the Havasupai tribe living at the bottom of the Grand Canyon at Havasu Creek, northwest of Grand Canyon Village.

1.4.2 GENERAL HYDROGEOLOGY

The major aquifers in the study area include the Redwall-Muav (R-aquifer), Coconino (C-aquifer), and basin-fill aquifers (Pool et al., 2011). The R- and C-aquifers have groundwater divides that are largely coincident with the Mogollon Rim and trend northwest-southeast. This divides the regional flow systems into two parts: one part flows northward into the Colorado and Little Colorado Rivers and one part flows south to the Verde and Salt Rivers. The focus of this work is on the flow system in and around the Verde River groundwater catchment basin as simulated by the NARGFM. There are a number of smaller aquifers that are not as important regionally but are used extensively to meet local demands. Some of these local aquifers include Quaternary alluvial aquifers and the Payson Granite, which are connected to the regional aquifers, and smaller disconnected aquifers in the alluvium, volcanic rocks, Kaibab Formation, Coconino Sandstone, Supai Group, and Proterozoic rocks. These minor aquifers were included in the model because of their ability to transmit water to the regional aquifers via percolation after discharging. Regional recharge in the study area is estimated to be approximately 4% of annual precipitation and as high as 8% along the Mogollon Rim (Parker, 2005).

The R-aquifer is the deepest aquifer in the study and comprises the Tapeats Sandstone, Bright Angel Shale, Muav Limestone, Temple Butte Limestone, and Redwall Limestone (Pool et al., 2011). Some portions of this aquifer also include lower parts of the Supai Formation, Naco Formation, or Surprise Canyon Formation, all of which form an upper confining unit. Minor stratigraphic variations can be found throughout the study area. The Redwall and Muav Limestones are the main water-bearing units of the R-aquifer (Bills et al., 2007). The aquifer is underlain and confined by Proterozoic basement rock. The units of the R-aquifer are exposed in the northern, southern, and western portions of the study area in steep canyons and escarpments (Pool et al., 2011). Most of the R-aquifer is overlain by younger units and is usually found at considerable depth, often exceeding 3000 feet (Bills et al., 2000). The units of the R-aquifer underlie most of the study area, with the exception of Little Chino sub-basin, and therefore make up most of model layer 3 of the NARGFM. Recharge to the aquifer occurs mainly through downward leakage from overlying, fractured units of the C-aquifer and from direct infiltration where the units of the R-aquifer are exposed, mostly south of the Mogollon Rim (Pool et al., 2011). Recharge can also occur by percolation through unconsolidated alluvium and porous volcanic rocks that are associated with faulting and fracturing. Underflow may also contribute groundwater flow to the aquifer, mostly from the Little Colorado River Plateau, but higher elevations and faulting through the R-aquifer prohibit underflow from surrounding areas. The R-aquifer discharges mainly as spring flow to the Colorado, Little Colorado, and Verde River and their tributaries, as underflow to basin-fill aquifers in Little Chino Valley and Big Chino Valley, as discharge from wells, and as ET where the water table is at our near land surface.

The C-aquifer lies above the R-aquifer and comprises the Kaibab Formation, Coconino Sandstone, Schnebly Hill Formation, and Upper Supai Formation (Pool et al., 2011). Minor stratigraphic variations can be found throughout the study area. The top of the aquifer, the Kaibab Limestone, is typically unsaturated but provides a conduit for infiltration into the units below. The Coconino Sandstone is the main water-bearing unit of the C-aquifer (Hart et al., 2002). The aquifer is confined below by the Lower Supai Formation. The units of the C-aquifer crop out in the western, southwestern, and northeastern parts of the study area. In other areas, the aquifer is overlain by younger units and can be found at considerable depth, often exceeding 1000 feet (Bills et al., 2000). The C-aquifer extends throughout approximately half of the study area, making up half of model layer 1 of the NARGFM. Recharge to the aquifer occurs mainly by direct infiltration from runoff through the Kaibab Limestone and by percolation from fractured volcanic rocks and overlying perched zones (Hart, 2002). This occurs predominately in the southern and western edges of the study area, and in the northeastern edge of the study area on the Defiance Uplift. Groundwater discharges from the C-aquifer as spring discharge to the Little Colorado and Verde River drainage systems, downward leakage to the R-aquifer and ET where the water table is at or near land surface.

The alluvial basin-fill aquifers found throughout the study area include Big Chino Valley and Williamson Valley, Little Chino Valley and Lonesome Valley, Upper Agua

Fria Basin, Verde Valley, and Tonto Creek Basin (Pool et al., 2011). These aquifers are associated with the basin and range physiography characteristic of the Transition Zone and comprise upper and lower layers, a coarse- and fine-grained facies, and interbedded basalt flows. As described earlier, these valleys trend north-northwest. The coarse-grained facies are found at the basin boundaries and the fine-grained facies are found in the basin center. Generally, the basin boundaries are unconfined while the centers are confined. Furthermore, the upper basin-fill facies are usually more permeable than the lower basin-fill facies. Interbedded basalt flows are generally poor aquifers but are associated with zones of high permeability in the upper basin-fill in the Paulden area of the Big Chino Basin and the lower basin-fill in the Little Chino Basin. Local perched aquifers are associated with Quaternary flood-plain alluvium that overlies low permeability rocks or fine-grained facies at basin centers. These basin-fill aquifers are generally a few hundred feet thick but thicknesses exceed a thousand feet in some locations such as the Big Chino Valley, where the maximum recorded thickness of the basin is 1800 feet (Blasch et al., 2006). The basin-fill aquifers, their upper and lower layers, and the associated volcanic deposits cover approximately half of model layers 1 and 2 and are important mainly in the southern and western parts of the study area. Recharge to these aquifers occurs mainly through percolation through fractured Paleozoic rocks associated with areas of high elevation, through ephemeral stream channel alluvium, and from underflow from the R-aquifer. Groundwater discharges in different places depending on the aquifer but, generally, groundwater discharges as underflow to other basin-fill aquifers, underflow to the R- and C-aquifers, discharge to wells, discharge to streams and springs, and as ET where the water table is at or near land surface and phreatophytes have access to the shallow water table (Pool et al., 2011).

CHAPTER 2 – SYSTEMATIC REVIEW OF FOREST TREATMENT EFFECTS ON WATERSHED BUDGETS – IMPLICATIONS FOR SURFACE WATER AND GROUNDWATER

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2.1 ABSTRACT

A systematic review was conducted to examine the state of knowledge of forest restoration thinning and its hydrological responses and to evaluate the quality and type of information that exist within the literature. Two questions guided the systematic review: 1) how do forest treatments conducted on conifer-dominated watersheds affect the water budget? And, 2) how do forest treatments impact groundwater systems? A total of 37 references met the systematic review criteria and were considered appropriate for answering these two questions. Data from individual studies suggested that forest treatments that reduce tree density tend to increase water yield and groundwater recharge while reducing evapotranspiration. Specifically, when 5-100% of a conifer-dominated watershed is treated, the literature suggests a corresponding 0-50% increase in water yield, though higher values are possible. Although most studies showed an increase in groundwater table height following tree removal, the correlation between percent area treated and the percent increase in groundwater recharge could not be established. Thus the change in water yield associated with forest thinning is highly variable, and tends to diminish within five to ten years of treatment. The benefits diminished even quicker (≤ 4 years) for groundwater table heights.

2.2 BACKGROUND

The purpose of this systematic review was to examine forest treatments on conifer-dominated forested catchments and the effect that treatments have on watershed hydrology, as well as the broader issue of the impacts of changing forest cover on groundwater recharge. Forest structures in the southwestern United States (Arizona, New Mexico, and adjacent parts of Utah and Colorado) have been significantly altered from their Pre-European settlement conditions by old-growth logging, fire suppression, cattle grazing, and road building (Covington, 2003). This has increased the density of younger trees and forest underbrush providing fuel to alter regular, low-intensity fire regimes and produce devastating crown fires (Harrington and Sackett, 1990).

To minimize the likelihood of large-scale crown fires in Northern Arizona, the U.S. Forest Service (USFS), with assistance from collaborators, is planning to restore these four national forests in Northern Arizona to increase forest resiliency and function and reduce the threat of catastrophic wildfires. This project, called the Four Forest Restoration Initiative (4FRI), is planned to begin as early as 2014, pending approval of the Environmental Impact Statement (EIS) (Draft EIS Chapter 1, 2012). The initial treatments will include mechanical thinning and burning and will be applied on about 240,000 ha (600,000 acres) of Kaibab and Coconino National Forest land. Subsequent treatments will mostly target at-risk areas on the Tonto and Apache-Sitgreaves National Forests.

An important issue the 4FRI addresses is how changing forest cover affects watershed hydrology. A number of studies have attempted to answer this question (Hibbert, 1967; Bosch and Hewlett 1982; Stednick, 1996; Brown et al., 2005; Zou et al., 2010). Based on these previous studies, the expected outcome of the 4FRI treatments is an overall increase in surface water runoff and groundwater recharge on the treated watersheds. Baker (2003) reported a 15-40% increase in water yield with a 30-100% reduction in basal area on ponderosa pine watersheds. The goal of this review was to examine the relationship between changes in water yield, evapotranspiration, soil moisture storage, groundwater, and tree removal. The findings from this work will be used to inform water management decisions in Arizona, see if there is a consensus within the literature, and to provide a baseline for future work.

2.3 OBJECTIVES

The objectives of this systematic review are to:

1) design and conduct a systematic review of all relevant literature relating to the removal of trees and the effects this has on the water budget;
2) determine the quality of evidence contained within the collected literature;
3) quantify the relationship between tree removal and components of the water budget and how significant these relationships are;
4) determine how applicable these results are to proposed 4FRI treatments.

2.4 METHODOLOGY

We hypothesized that a significant number of references examining the effects of tree removal on watershed hydrology existed to undertake a systematic review following the guidelines of the Collaboration for Environmental Evidence (CEE, 2010). Because this systematic review is targeted at providing reliable data for the 4FRI, we tailored our questions to target the most relevant studies. We formulated the following questions: 1) how do forest treatments conducted on conifer-dominated watersheds affect the water budget? and 2) how do forest treatments impact the groundwater system? We assumed these questions were specific enough to give us results that are reliable and useful, and that the question was broad enough that it would capture any references that may have been marginalized with more specific interventions (e.g. “treatment” instead of “restoration” or “harvest”) and forest type (e.g. “conifer” instead of “ponderosa pine” or “Douglas-Fir").

Two reference search strategies were developed based on the above questions and following the systematic review procedures as defined by Collaboration for Environmental Evidence (CEE, 2010). These included relevant search terms and combinations of these terms. A number of publication types and research databases were used for this search including peer reviewed articles, dissertations and theses, and books. We used search engines that were considered appropriate for finding these references, including Web of Knowledge, Proquest Dissertations and Theses, and World Cat, respectively. Gray literature was also used as a source of data and found with various popular search engines.

Study inclusion criteria included the most relevant information for answering each of the two questions. If the title appeared to include relevant criteria the reference was kept for further review. Abstracts were then reviewed to further constrain the studies that met the inclusion criteria and filter out those that did not. Criteria included variables like forest type, climate, type of intervention, water budget variables measured, and quality of study. A kappa analysis, a statistical technique used to test inter-rater agreement for qualitative items, was used to test reviewer agreement when conducting the abstract review stage (Carletta, 1996) (see Appendix B). The studies that passed the abstract review stage were kept for full text review.

A modified version of Pullin and Knight’s (2003) hierarchy of evidence quality (HEQ) was used to determine which studies reported reliable and strong evidence, which studies were considered with caution, and which studies’ data were excluded due to lack of strong evidence (Table 1). Each study that passed the title and abstract review stage and underwent a full text review was assigned to one of these categories. These categories were designed to rate the studies with respect to their relevance in answering the two questions.

Table 1. Hierarchy of Evidence Quality (modified from Pullin and Knight, 2003).

Category	Quality of Evidence
I	Strong evidence obtained on multiple water budget variables from multi-year, randomized, controlled trials of appropriate size.
II-1	Evidence from well-designed, multi-year controlled trial(s) with randomization.
II-2	Evidence or a comparison of differences between sites with and without controls.
II-3	Evidence obtained from multi-year study or from dramatic results in uncontrolled experiments or from a controlled, single-year study.
III	Opinions of respected authorities based on qualitative field evidence, descriptive studies or reports of expert committees.

Relevant data were extracted and recorded on master spreadsheets during full text review (see Appendices C and D). Relevant data included author, year, location, climate, forest type, soil, mean annual precipitation, treatment type, percent of area treated, and observed effects. This information was then used to determine the quality of evidence and apply a category to each reference. This category reflects the relative usefulness and reliability of each study in answering the systematic review questions. Additional information and tables relating to methodology are provided as supporting material.

2.5 RESULTS

Over 2,000 references were reviewed to find relevant studies that would help to answer the systematic review questions (Table 2).

Table 2. Details of the systematic review elimination process.

Elimination steps	Number of references
Studies captured from electronic databases	~2000
Studies remaining after title elimination	102
Studies remaining after abstract elimination	84
Studies remaining after full text elimination	82
Studies remaining after Quality of Evidence review and assignment	80
Reviews	43
Original Research	37

Description of Studies

After quality of evidence elimination, there were 80 studies remaining. 37 of these were original research papers and were used in this review (Figure 4). The types of studies included peer reviewed journal articles as well as technical reports, dissertations, and popular literature articles. Two papers that passed the abstract review were rejected during the full-text review. Two more papers were rejected during the quality of evidence review. As mentioned, 37 studies were original research. The remaining 43 studies were summary articles.

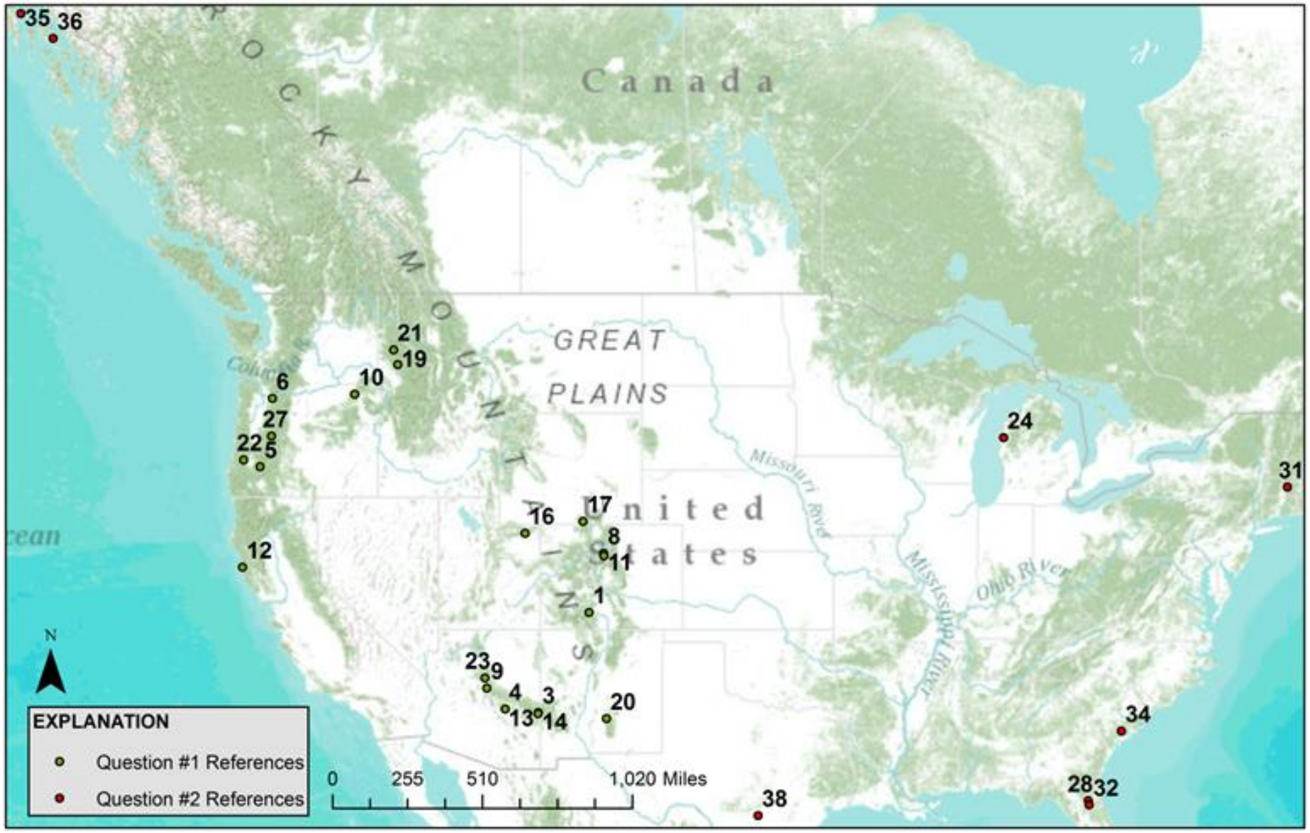

Figure 4. Map showing the distribution of experimental studies located in Northern America that were included in this review. Numbers correspond to identification numbers (see Appendices C and D). Studies not shown include those located in China, Japan, and Australia.

Experimental studies comprised 37 of the references that were reviewed. Results from 23 studies were used to answer question #1: how do forest treatments conducted on conifer-dominated watersheds affect the water budget? Results from fifteen studies were used to answer question #2: how do forest treatments impact the groundwater system? One study (Rockefeller, 2004) was included in both. Of these 37 studies, 31 were peer reviewed journal articles, five were project or technical reports from an academic or public institution, and one was a dissertation. Thirty five were assigned to quality of evidence category II-1 and the other two were assigned to quality of evidence category II-3 because of their short post-treatment observation period (less than 1 year) (see Appendix C and D). The results from these studies were plotted to visualize potential relationships between mean annual precipitation (MAP), percent area treated, water yield increase, and groundwater levels (Figures 5-8).

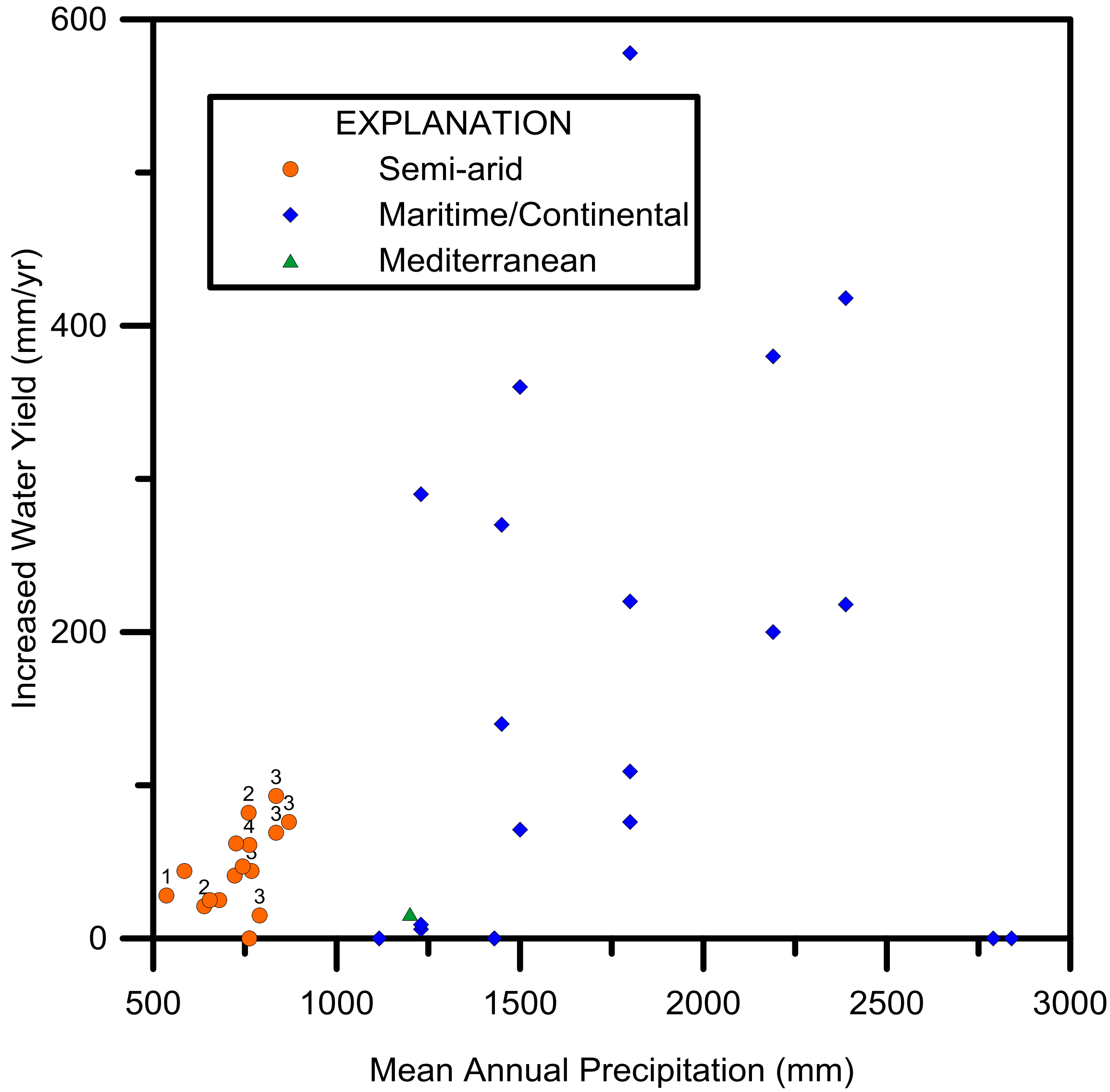

Figure 5. The distribution of increased water yield as a function of mean annual precipitation.

Numbers indicate studies located in Arizona that report water yields following forest treatment.
[1] Castle Creek, AZ (Rich, 1972)
[2] Workman Creek, AZ (Rich and Gottfried, 1976)
[3] Beaver Creek, AZ (Baker 1986)
[4] White Mountains, AZ (Gottfried, 1991)

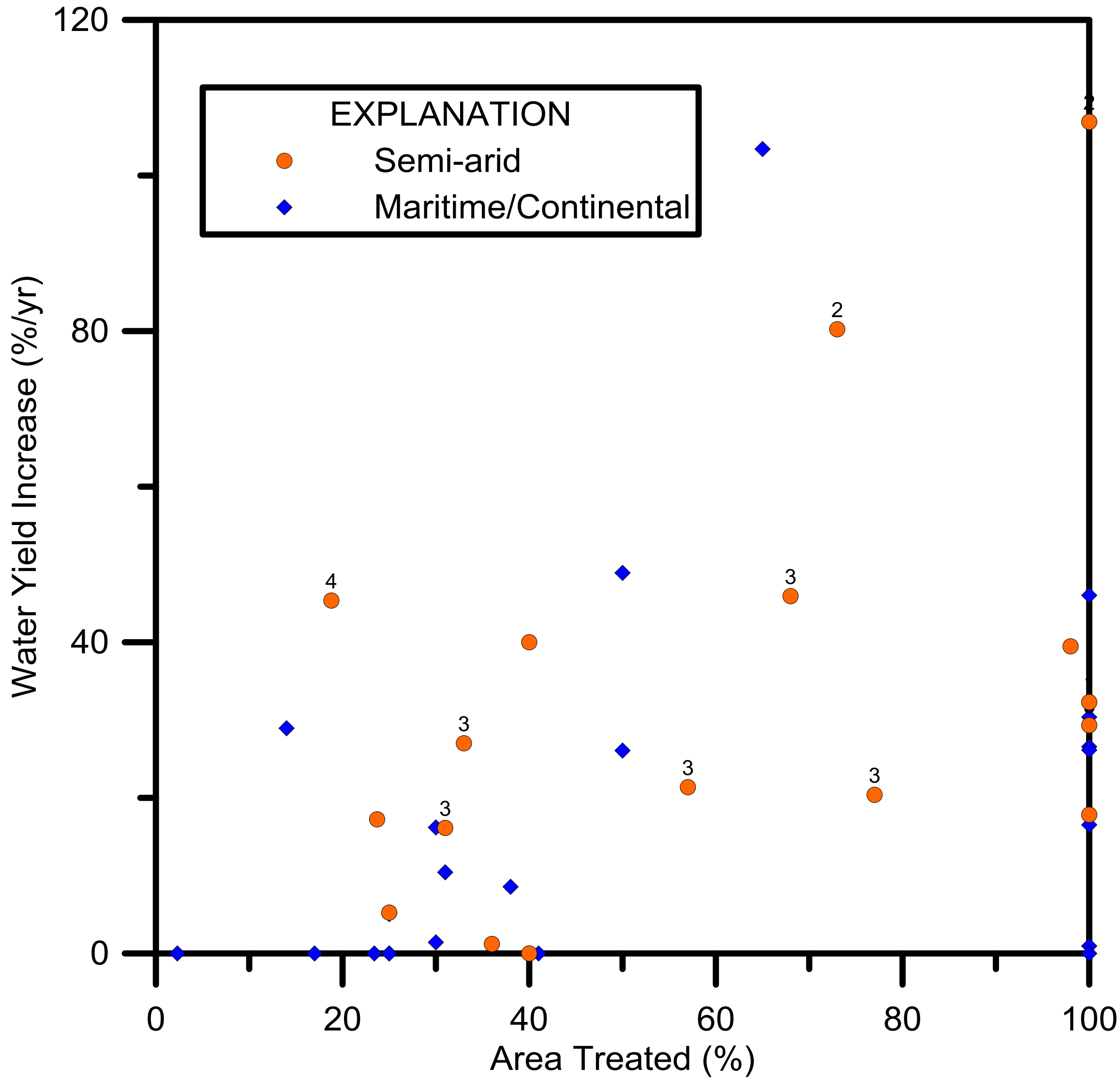

Figure 6. The distribution of mean water yield percent increase as a function of mean percent area treated. Water yield increase was determined by taking water yield increase divided by mean annual streamflow to arrive at percent increase. Therefore, only those studies that reported mean annual streamflow are included in figure.

Numbers indicate studies located in Arizona that report water yields following forest treatment.
[1] Castle Creek, AZ (Rich, 1972)
[2] Workman Creek, AZ (Rich and Gottfried, 1976)
[3] Beaver Creek, AZ (Baker 1986)
[4] White Mountains, AZ (Gottfried, 1991)

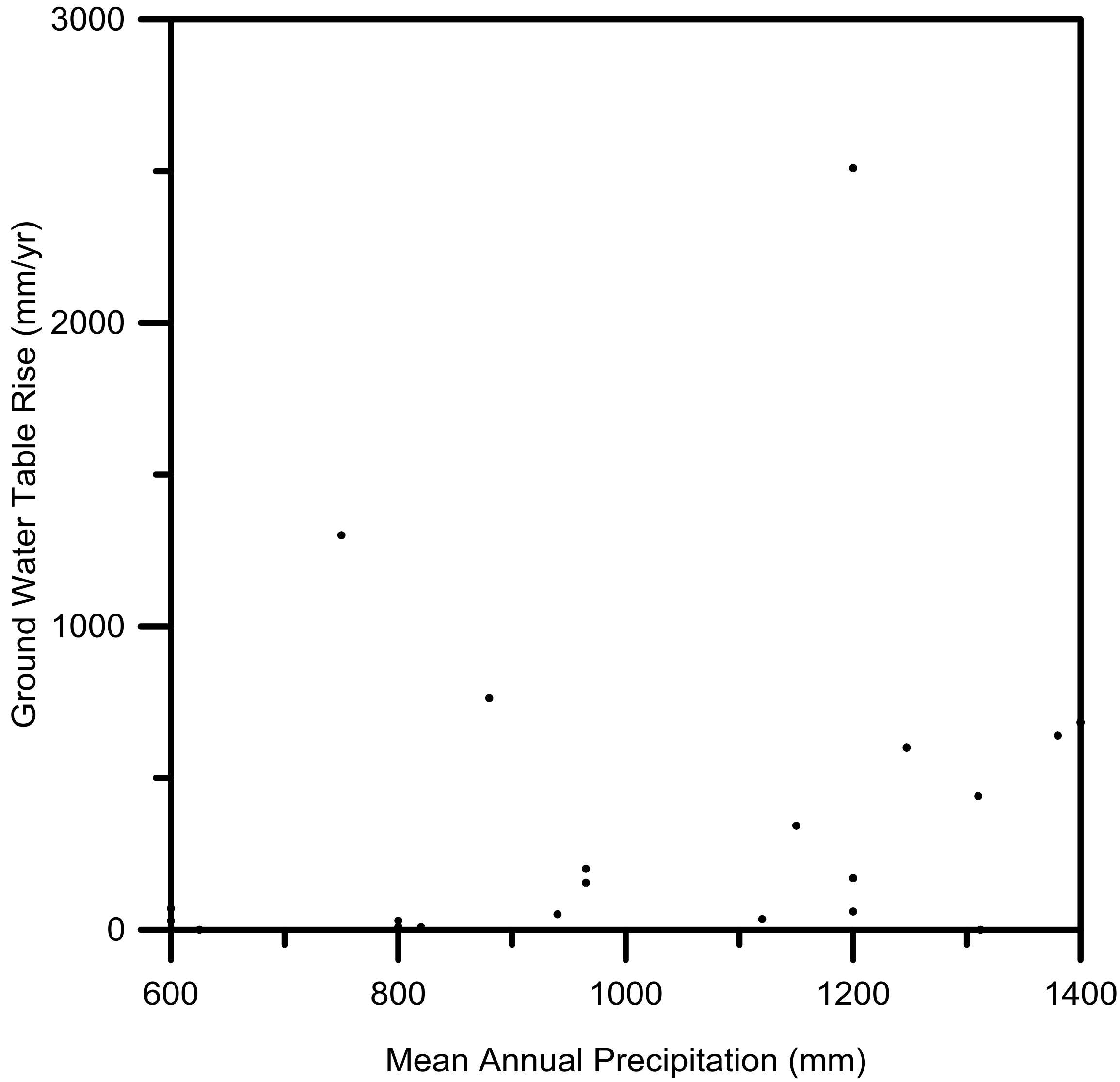

Figure 7. The distribution of groundwater table rise as a function of mean annual precipitation.

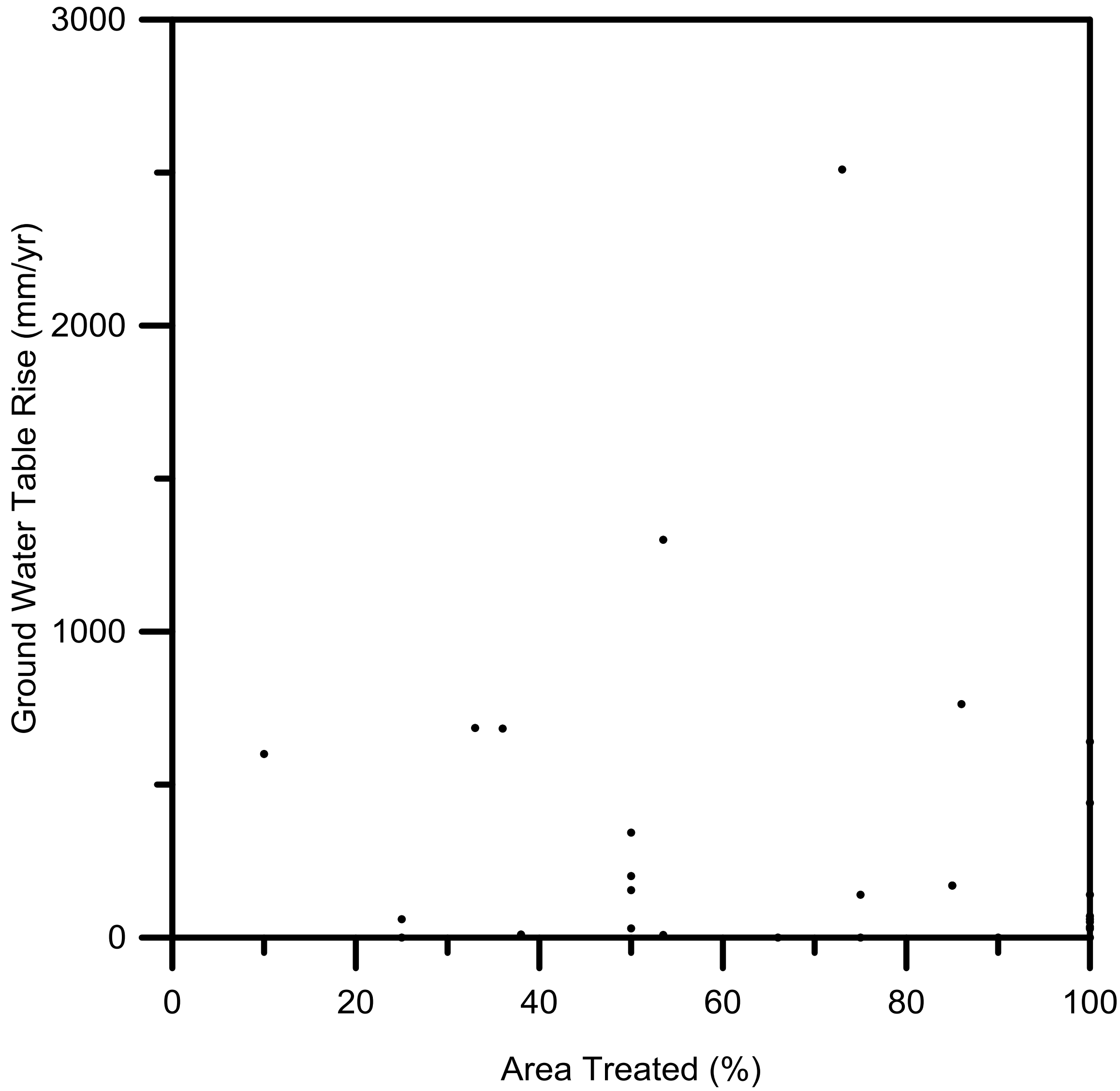

Figure 8. The distribution of groundwater table rise as a function of percent area of the forest treated.

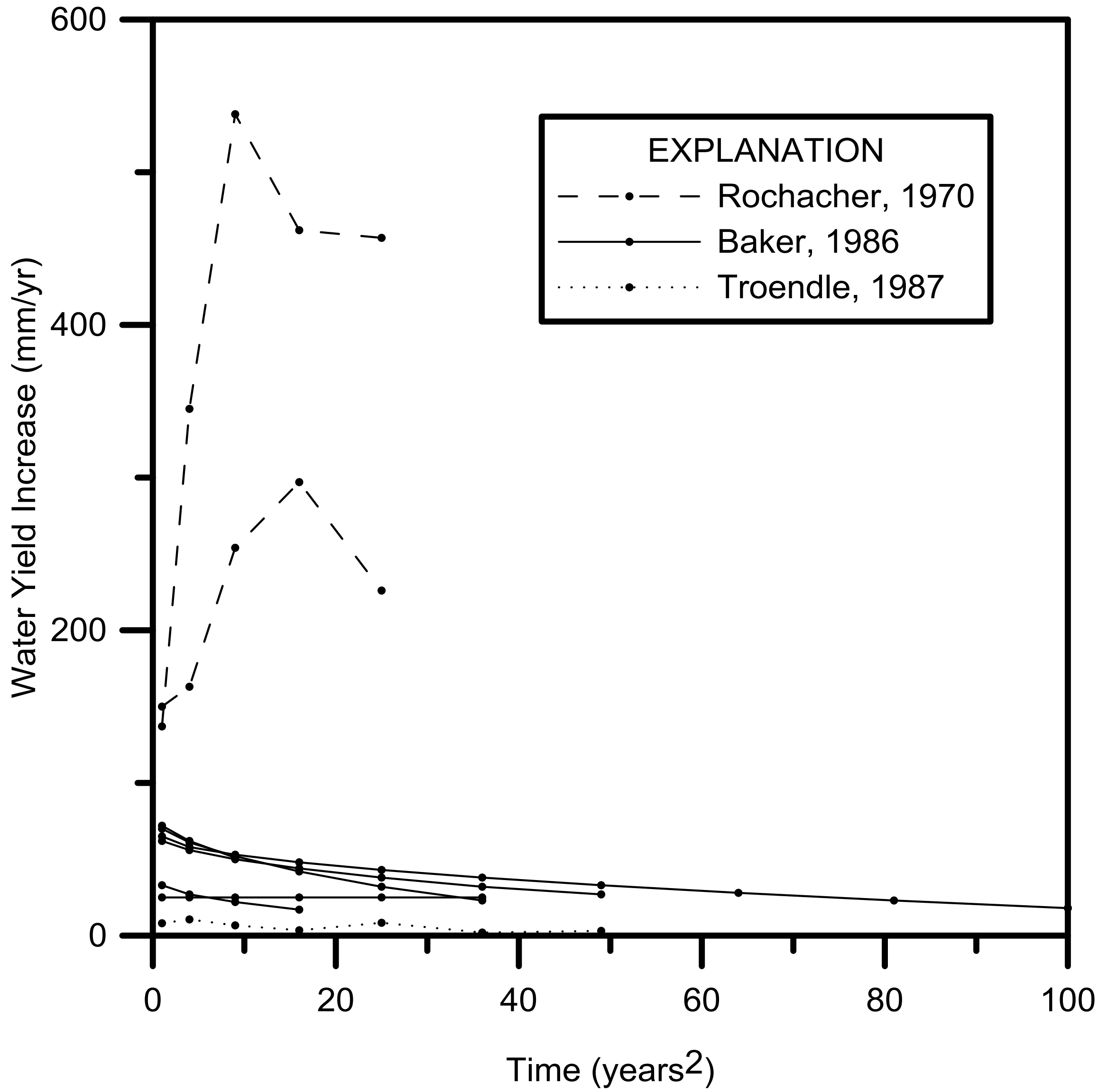

Figure 9. Length of response for water yield studies that reported on multiple annual values.

The results from the semi-arid watershed studies reported increased surface water yields ranging from 14.7 mm to 98 mm following treatments. This is close to the 25 mm to 75 mm range cited in earlier reviews (Bosch and Hewlett, 1982 and Stednick, 1996). Only one semi-arid study reported results that were not significant (p = 0.37) (Troendle and King, 1987).

Common reasons given for an increase in water yield were an overall reduction in evapotranspiration (ET) and interception and increase in snowpack accumulation. Kolb (2009) reported a reduction in ET following treatment at a site-level study that measured ET using the tower-based eddy covariance approach. Though data were collected for only two years, they observed a 17% reduction in ET for the first year and a 15% reduction in ET in the second year. Stegman (1996) examined reduced interception and a redistribution of snow following forest restoration treatments and reported an increase in snowpack accumulation following forest treatments. Groundwater recharge was not measured or analyzed by any of the studies in locations with semi-arid climates.

The maritime-continental studies reported water yield increases ranging from 6 mm to 578 mm with an average response of 210 mm for all eleven studies. The main reason given for increases in water yield in maritime-continental sites was similar to that given for the semi-arid sites: a reduction in ET and interception, as well as an increase in snowpack accumulation or rain availability. Water yield results from three studies (Harr, 1980, Fowler et al., 1987, and Caissie et al., 2002) were not significant, as they fell outside the 95% confidence interval. The reason given for their non-significance was the natural variability in precipitation and runoff. However, Harr (1980) would have significant results if a 90% confidence interval had been used and Fowler et al. (1987) did report increases in soil water content (up to 20 cm) and snow water content (up to 11 cm). Caissie et al. (2002) reported increases in the magnitude of summer peak flows, but not for annual flows. Hubbart et al. (2007) reported calculated ET reduction using the water budget method. The authors reported a 35% reduction in ET on one watershed and a 14%

reduction on another. Rockefeller (2004) reported a 6% to 107% increase in water table elevations following treatments. All results were highly dependent on precipitation.

The groundwater studies that were reviewed came from low-elevation locations around the world. Because of the variety of climates, elevations, and precipitation regimes, the forest and soil type was variable. Most treatments were clear-cuts with only two instances of selective cutting. Study area size ranged from 0.052 ha to 350 ha (0.13 to 865 acres) and an average water table depth from 0.3 meters to 25 meters. Three of the fifteen studies collected reported no observable effect on water tables in their watersheds (Bubb and Croton, 2002, Johnson et al., 2007, and Bazan, 2012). Bubb and Croton (2002) showed no change in water table elevation but reported streamflow increases that lasted for three years. Johnson et al. (2007) reported no effects on three controlled watersheds, but observed effects on three others. Bazan (2012) concluded that secondary recharge via fracture flow was not affected by treatment, though surface flow did increase from 3% of the pre-removal water budget up to 10% of the post-removal water budget. Overall, it was difficult to draw conclusions about how removing trees affects groundwater recharge. Because a majority of studies looked at changes in the water table, rather than recharge, it was not possible to establish a percent change in recharge following treatment. Studies that observed changes in groundwater table elevation reported increases in the water table ranging from 22 mm to 2150 mm. Peck and Williamson (1987) was the only study that measured changes in recharge, where increases of 10 to 60 mm/year, or 6-10% per year, were observed. Data extracted from all references are included in Appendices C and D.

Generally, when comprehensive annual data was available, we used the calculated annual mean water yield increases to generate a response time-graph (Figure 9). Figure 9 shows a diminishment of treatment effects over time, with changes in water yield becoming negligible between 4-10 years post-treatment. Groundwater studies reported observed increases in the groundwater table for 4 months to 4 years post-treatment.

2.6 DISCUSSION

The studies examined in this review included a variety of forest treatments with clear-cutting being by far the most common, being used exclusively or with other treatment types in 26 of the 37 studies. Other treatments included single-cuts, patch-cuts, group-cuts, thinning methods, conversion to grassland, shelterwood-cuts, alternative-cuts, overstory removal, partial-cuts, strip-cuts, selective-cuts, and other techniques like specific tree type removal (Cypress-cuts and hand-removing Alligator Juniper) and various forms of light and heavy disturbances. This wide application of different forest treatments within and across studies made it difficult to draw conclusions that would be applicable to the 4FRI treatments.

2.6.1 Question #1

How do forest treatments conducted on conifer-dominated watersheds affect the water budget?

Analyses of results from the 23 collected studies demonstrated several important lessons. First, there were relatively few studies that examined the impact of forest treatments on the entire water budget. Furthermore, only three of the 23 studies found in this systematic review used thinning methods to treat their watersheds. Most of the study sites were clear-cut or some variation of clear-cut (e.g. strip-cuts, group-cuts, patch-cuts). In addition, regardless of treatment type or the percent of the watershed treated, there was usually an increase in water yield reported following treatment. Only rarely were non-significant or non-responsive results reported. Water yield increased between 0-50% percent when 5-100% of a conifer-dominated watershed was treated, with slightly higher yields for semi-arid regions (Figure 6). Only a few studies lie outside this range. This is comparable to the results reported by Baker (2003) where water yield increased 15-40% when basal area was reduced by 30-100% in a ponderosa pine watershed. While area treated and basal area reductions are not exactly correlated, the literature indicates a trend of increasing water yield with increased frequency of tree removal.

The most common reasons given for increased water yield were a decreases in evapotranspiration (Kolb, 2009) and increases in snowpack accumulation (Stegman, 1996). The literature therefore indicates that forest treatments on conifer-dominated watersheds can alter water yield. Treatments that remove trees have the potential to increase annual water yields depending on the intensity and type of treatment. The effect of increase water yields diminish rapidly, however, usually between 4-10 years after forest restoration treatments have been applied. This reduction in water yield is attributed to the regrowth of underbrush and new forest stands that occurs when there are no measures taken to maintain post-treatment conditions.

2.6.2 Question #2

How do forest treatments impact the groundwater system?

Because 13 of 15 studies reported an increase in groundwater level following tree removal, it was considered probable that when forested watersheds have trees removed, an increase in the groundwater table level, and thus groundwater recharge, is possible. No other significant hydrologic response was deemed supported by the available data. For responsive study sites, groundwater table elevation increased by as much as 2150 mm/yr. For the one study that measured recharge (Peck and Williamson, 1987), recharge increased 6-10% per year. There was no linear relationship between percent of a watershed that receives treatment and change in the groundwater table elevation.

Groundwater response is largely attributed to a reduction in evapotranspiration and canopy interception. Tree removal allowed more of the precipitation to reach the soil surface, infiltrate, and increase soil moisture storage. Once precipitation falls on the thinned forest, fewer trees means that less water is used from soil water storage by the plants and more is available for recharge (Bazan et al., 2012). Most hydrological responses reported diminished rapidly. Bliss and Comerford (2002) found increasing groundwater levels immediately returning to normal after four months while Borg et al. (1987) reported observable increases in groundwater table elevation for up to four years after treatment. This indicates that responses can be both immediate and intense but short-lived and unsustainable if watersheds are allowed to naturally regenerate or are re-vegetated. These findings are similar to those reported by Sun et al. (2001) in a review summarizing treatment effects on the hydrologic system in the wetland forests of the southern United States.

2.6.3 Implications for 4FRI

The restoration thinning treatments that will be used in 4FRI are different from those used in the studies collected in this systematic review. Few studies reported on the effect that thinning – and more importantly, restoration thinning – treatments have on the water budget. This may reflect a bias in the search strategy developed for this review, or a lack of restoration forest thinning studies in the landscape change-water budget response literature. Nevertheless, it is likely that an increase in water yield will accompany the proposed thinning treatments conducted on the 4FRI area. However, the impacts on water yield and groundwater recharge are expected to be variable.

Furthermore, it is unclear how applicable the groundwater results are to the 4FRI. Many of the studies examined were located in low elevations and wet climates with shallow (≤ 25 m or 82 feet) water tables and forest types comprising either eucalyptus or conifer species. In contrast, the 4FRI treated will be on ponderosa pine-dominated watersheds in a semi-arid climate with basalt-derived soils at elevations of 1,828-2,438 m (6,000-8,000 feet) that provide recharge to deep aquifers (91-1,100 m or 300-3600 feet). Only one study reported using thinning as a treatment while the rest used various types of cuts, including mostly clear-cuts. In contrast, none of the 4FRI treatments will use clear-cutting.

Intuitively, one would expect that removing trees has the potential to increase groundwater recharge. However, any recharge to the local aquifers would take considerable time, possibly decades, to recognize because of the significant seasonal and annual variations in precipitation in this semi-arid climate. In addition, other factors may mask the effects of restoration thinning treatments, including variations in climate and groundwater pumping.

2.6.4 Uncertainty and Error

Sources of error in this analysis include but are not limited to publication bias, study errors, and poor systematic review methodology. There is a potential that publication bias could have contributed to the types of studies collected in this review. Only seven of the 37 studies reported non-significant (at a 95% confidence interval) or non-observable results. Furthermore, two of these seven studies reported observable results on other experimental watersheds within the same study. There may have been other non-significant studies or studies that reported decreasing water yields following tree removal that were not published.

Study errors may have affected the information collected as part of this systematic review. It was outside the scope of this paper to analyze every method used within each study. Based on a methodological value judgment, control-watershed experiments were assumed to be the most reliable method. This assumption may have biased the types of experiments collected in this review. It is assumed that these errors were excluded during the peer review process.

A final source of error considered was poor systematic review methodology. The purpose of this systematic review was to collect references in a systematic, standardized way to minimize publication and author bias and make the review process as rigorous, transparent, and well-defined as possible. While the objectives of this review were relatively constrained, it was not possible to eliminate all bias, error, or uncertainty when conducting the stages of this systematic review. A few examples included a search strategy and study inclusion criteria that may have placed emphasis on journal publications over gray literature or an emphasis on studies reporting increased water yield over studies reporting non-significant results or decreased water yields. This may have led to the extraction of data that were not useful and/or the reporting of results that that may have been inappropriate for the data collected.

These sources of uncertainty were not considered limiting. However, uncertainty in the analysis may have contributed to obscuring actual relationships or magnifying perceived ones. Nevertheless, the results obtained from this systematic review are considered by the authors as reliable.

2.6.5 Recommendations for Future Research

It is unclear if additional research will significantly eliminate the uncertainties found within water yield and groundwater studies or if there is an inherent limitation to how fine and conclusive the results drawn from them can be. The authors recommend several areas of future research that may better determine any possible relationships and minimize uncertainty.

Most of the studies collected in this systematic review use a paired-watershed method to evaluate the impact that removing trees had on streamflow or groundwater. The development of a more systematized and structured approach to developing a controlled-watershed experiment, developing water and energy balances for the watershed, and reporting these variables will lead to more structured data sets that will be useful to compare across studies. This approach would facilitate data accumulation and manipulation as well as the ability to recognize relationships between studies, especially those with similar climates and forest types. The methods used in measuring variables and collecting data appear to be appropriate, but a more rigorous application of testing against the null hypothesis as well as the transparency of results and description of methods would help future researchers and decision-makers draw useful conclusions. Full disclosure of data and methods, while beyond the scope of most references collected, would have facilitated the recognition of any actual relationships and the drawing of conclusions from these data.

To make reviews like this one more useful, future studies could focus on measuring all water budget variables rather than just one or two. This comprehensive approach would help reduce uncertainty and ambiguity in these types of studies and make useful contributions to accumulated data within and across studies. A focus on restoration thinning treatments rather than harvesting would provide important information for the 4FRI and similar forest restoration efforts. Any information on how restoration thinning treatments affect the water budget, as well as any other contributing factors, would be useful in the planning and adaptive management processes of these projects.

2.7 CONCLUSIONS

Numerous studies throughout the world have attempted to quantify the hydrologic effects of removing trees from forested watersheds. The reasons for these disturbances have been many, including timber harvest, tree stand improvement, deforestation, and ecological restoration. There is an impetus for the restoration of catastrophic fire-prone forested watersheds, especially in the semi-arid southwestern United States. For example, the 4FRI restoration treatments will help minimize the threat of catastrophic wildfires while returning forests to a healthy condition. It is believed that improved forest health coincides with improved hydrologic conditions on these watersheds. This review summarized the state of knowledge with respect to forest harvest and treatments and their hydrologic effects. Generally, when 5-100% of conifer-dominated watersheds were treated, there was a water yield increase of, on average, 0-50%. Overall, observed increases in groundwater table elevation increases 22-2150 mm/yr and, where measured, recharge increased 6-10%.

There have been very few forest treatment experiments on conifer-dominated watersheds that focused on the effects to groundwater levels. For this reason, the authors include all studies that looked at the impact of tree removal on groundwater. Most effects on the groundwater system are variable and site-specific. A treatment that removes trees will, generally, result in increased groundwater recharge and groundwater levels. These effects are short lived and unsustainable unless it is the express intent of the agency to produce a sustainable increase. Otherwise, natural vegetation or replacing forest stands with agriculture causes diminishing returns that become negligible within just a few years.

One of the knowledge gaps found in this review was the impact that restoration thinning treatments have on conifer-dominated watersheds in semi-arid climates. For instance, only one of the references studied groundwater and semi-arid conifer-dominated watersheds. Understanding water balance changes due to semi-arid forest management is vital to planned landscape-scale treatments on about 240,000 ha (600,000 acres) of ponderosa pine watersheds throughout four national forests in Arizona. The implications from such studies would help to define expected hydrologic response to such treatments and could be used for different purposes, such as the development of adaptive management practices, projects to increase watershed function, or a payment for ecosystem services system to support forest restoration.

2.8 ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of Liz Kailles and Dave Huffman of the Ecological Restoration Institute for helping design and review the manuscript. Support was provided by the Salt River Project and the National Science Foundation. The statistics consulting center at Northern Arizona University provided statistical analysis support.

CHAPTER 3 – INTERPRETIVE MODEL OF REGIONAL SEMI-ARID AQUIFER RESPONSES TO LARGE-SCALE FOREST RESTORATION TREATMENTS AND CLIMATE CHANGE

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3.1 ABSTRACT

The purpose of this study was to develop an interpretive model to assess the impacts that proposed forest restoration treatments and climate change will have on large regional, deep, semi-arid aquifers. We simulated how tree basal area reductions impact groundwater recharge from historic conditions to 2099. Spatial analyses of proposed landscape-scale forest restoration treatments were conducted to determine areas and rates of potential increases in groundwater recharge. Changes in recharge were applied to the model by identifying zones of basal area reduction from forest restoration treatments and applying recharge-change factors to these zones. Over a ten-year period of forest restoration treatment, a 2.8% increase in recharge to one adjacent groundwater basin (the Verde Valley sub-basin) was estimated compared to conditions that existed from 2000-2005. However, this increase in recharge was assumed to quickly decline after treatment due to regrowth of vegetation and forest underbrush and their associated increased evapotranspiration. Furthermore, estimated increases in groundwater recharge were masked by decreases in water levels, stream baseflow, and groundwater storage resulting from surface water diversions and groundwater pumping. These results showed that there is an imbalance between water supply and demand in this regional, semi-arid aquifer, that current practices may not be sustainable into the far future, and that comprehensive action should be taken to minimize this water budget imbalance.

3.2 INTRODUCTION

Landscape-scale forest restoration thinning and burning treatments are planned for approximately 600,000 acres of over-dense ponderosa pine forest within the Coconino and Kaibab National Forests along the Mogollon Rim in Northern Arizona. This area has a semi-arid climate and receives 20-30 in of precipitation per year as summer monsoon rain and winter snow. This area also has two deep (>1000 ft) regional aquifers: the Redwall-Muav (R-) and Coconino (C-) aquifers. Basin-fill aquifers also exist in the adjacent transition zone and basin and range provinces found in south-central Arizona.

Forest restoration treatments are planned to begin within the next decade and are expected to take approximately ten years to complete (Draft EIS Chapter 1, 2012). The purpose of this endeavor, called the Four Forest Restoration Initiative (4FRI), is to reduce the threat of catastrophic wildfire, restore forest health and resiliency, and restore streams, springs, and biologic functions of forested watersheds. Based on previous regional and international studies that show surface water yield increasing after similar reductions in tree basal area in forested lands (Bosch and Hewlett, 1982), we hypothesized that groundwater recharge would increase to the deep, regional Redwall-Muav and Coconino aquifers and basin-fell aquifers following forest restoration treatments. Through groundwater modeling and estimations of recharge effects as a result of changing forest cover and climate change, we assessed how this landscape-scale forest restoration may affect groundwater recharge to these regional aquifers.

3.3 PREVIOUS STUDIES

Many previous studies have looked at the relationship between land use/land cover change and the hydrologic system. Specifically, researchers have attempted to quantify the effect that removing trees would have on the water budget. Most of this previous work (e.g. Bosch and Hewlett, 1982) focused on the relationship between tree cover and surface water yield. Some studies (e.g. Gottfried, 1991) have investigated arid and semi-arid conifer-dominated watersheds and have attempted to quantify the treatment/yield relationship. Baker (2003) reported that water yield increased by 15-40% when basal area was reduced by 30-100% in ponderosa pine watersheds in north-central

Arizona. A systematic review of the literature from coniferous forests worldwide found an average of 0-50% increase in water yield when basal area is reduced by 5-100% (Chapter 2).

Fewer studies have attempted to quantify variables in the water budget other than surface water yield, such as evapotranspiration (ET), soil water storage, and groundwater recharge. A study by Kolb et al. (2009) reported a 17% and 15% reduction in ET in the first two years, respectively, following a 35% reduction in basal area in the semi-arid ponderosa pine forest of the Centennial Forest near Flagstaff, AZ. Other studies reported increases in snow pack accumulation following tree removal (e.g. Troendle and King, 1987 and Stegman, 1996). There have been even fewer studies that investigated the effect that removing trees has on groundwater recharge and soil moisture storage in arid and semi-arid forested watersheds (e.g. Bazan et al., 2012 and Scanlon et al., 2005). Because of the lack of published literature on the effects of tree removal on groundwater recharge, we used an interpretive groundwater-flow model to understand how landscape-scale forest restoration treatments might impact groundwater recharge and regional aquifers.

3.4 THE NORTHERN ARIZONA REGIONAL GROUNDWATER-FLOW MODEL

The Northern Arizona Regional Groundwater-Flow Model (Pool et al. 2011), hereafter referred to as the NARGFM, was used to simulate changes in recharge to aquifers of the Mogollon Rim in Northern Arizona following planned forest restoration treatments. The NARGFM was developed using the three-dimensional finite-difference modular groundwater-flow model code MODFLOW-2005 (Harbaugh, 2005). The NARGFM was originally developed to simulate the interactions between deep regional aquifers, streams, and springs in Northern Arizona and to assess the adequacy of groundwater resources and the effect that increased pumping, especially in the Verde River basin, would have on these resources.

The boundary conditions that were used include surface watershed boundaries, groundwater basin divides, and low-permeability crystalline rocks along the southern boundary of the Verde River basin and adjacent sub-basins. By simulating a large region and defining known physical boundaries, major groundwater-flow divides within the model area were simulated rather than set at arbitrary locations. The entire boundary of the model was represented as a no-flow boundary except where groundwater outflow was simulated at discrete locations along streams. There was assumed to be no groundwater inflow anywhere along the model boundary.

The NARGFM model grid comprises 600 rows, 400 columns, and three layers totaling 720,000 1 km by 1 km (0.62 by 0.62 mi) grid cells. The model grid is rotated counterclockwise 60 degrees West of North to better align with regional structural trends that are assumed to influence groundwater flow. The NARGFM has three model layers that were used to represent hydrostratigraphic units within Northern Arizona (Figure 10). Layer 3, the lowest layer, extends across the entire model area and represents the Redwall-Muav aquifer, except in the southern and eastern parts of the model domain where the Redwall-Muav aquifer is absent and crystalline rocks are present. Layer 2 is less extensive and represents the Supai Formation, a confining unit, which extends over most of the Colorado Plateau, as well as sands and gravels in the Verde and Big Chino Valley extensional basins and the lower volcanic unit in Little Chino Valley and Upper Agua Fria sub-basins. Layer 1 is the least extensive layer within the model and represents the Coconino aquifer, the alluvial basin-fill aquifers located in Big Chino Valley, Little Chino Valley, and Agua Fria sub-basins, and the Verde Formation in the Verde Valley.

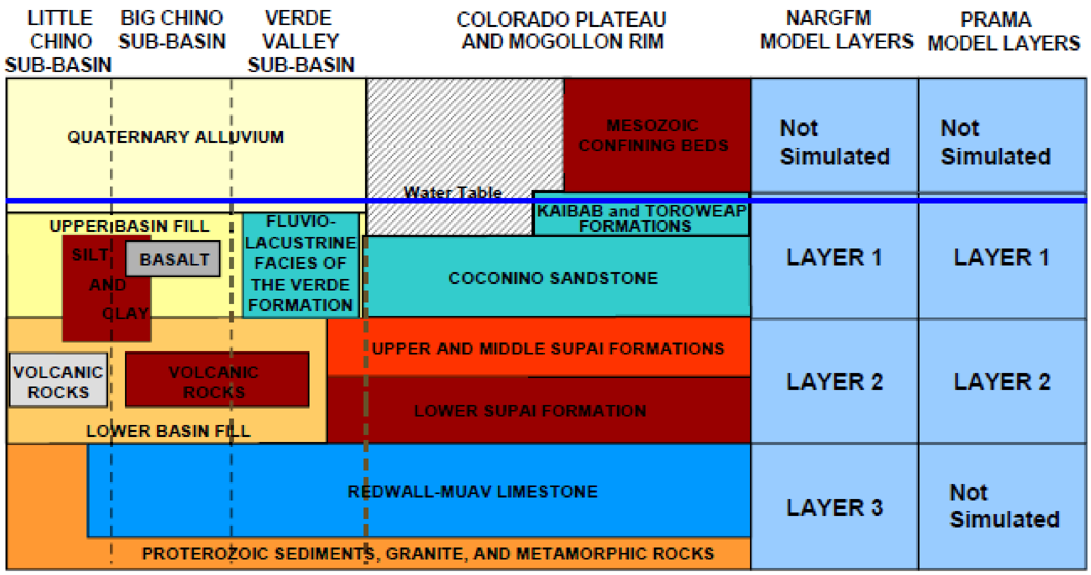


Figure 10. Conceptual model of the NARGFM detailing the relationships between geographic locations, hydrogeologic units, and model layers. Confining beds are shaded red-brown (Pool et al., 2011).

Inflows and outflows were simulated at locations of natural and artificial recharge, evapotranspiration, streams, springs, and groundwater withdrawals. Hydrostratigraphic properties were distributed across the model domain, based on literature, and calibration values were applied where appropriate. These include variables such as hydraulic conductivity, transmissivity, anisotropy (vertical and horizontal), specific storage, and specific yield.

The NARGFM was calibrated to steady-state conditions for groundwater flow that were assumed to exist in 1910 and for transient conditions between 1910 and 2005 (Pool et al., 2011). Nine multi-year, transient stress periods were used during the simulation period. The initial period of transient simulation covers 1910-1938 (10,227 days). The second transient period simulated initial groundwater development in the Little Chino sub-basin for the years 1938-1939. Thereafter, each stress period was approximately decadal in length (3652 to 3653 days), except for the last stress period which simulated the years 2000-2005 (2192 days). Each stress period was simulated using five time-steps with each successive time-step length 1.2 times longer than the previous time-step.

3.5 THE FOUR FOREST RESTORATION INITIATIVE

The 4FRI, proposed by the U.S. Forest Service, is a collaborative effort to reduce the threat of catastrophic wildfires and restore forest ecosystem health throughout four national forests along the Mogollon Rim, Arizona – the Kaibab, Coconino, Tonto, and Apache-Sitgreaves National Forests (Draft EIS Chapter 1, 2012). The initial treatments will include mechanical thinning and burning that will be applied to approximately 600,000 acres of Kaibab and Coconino National Forest land as early as 2014, pending approval of the EIS. Treatments will target at-risk wildfire areas.

The 4FRI first analysis area Environmental Impact Statement (EIS) has four treatment alternatives. Alternative C proposes the conservation of large trees and would thin 175,634 ha (434,001 acres) and burn 240,064 ha (593,211 acres). (Draft EIS Chapter 1, 2012). Alternative C was selected for the interpretive groundwater model simulations because it was one of two (B and C) that the NFS considered likely to be implemented. Non-4FRI forest restoration treatments, called shelf-stock, within these forests were

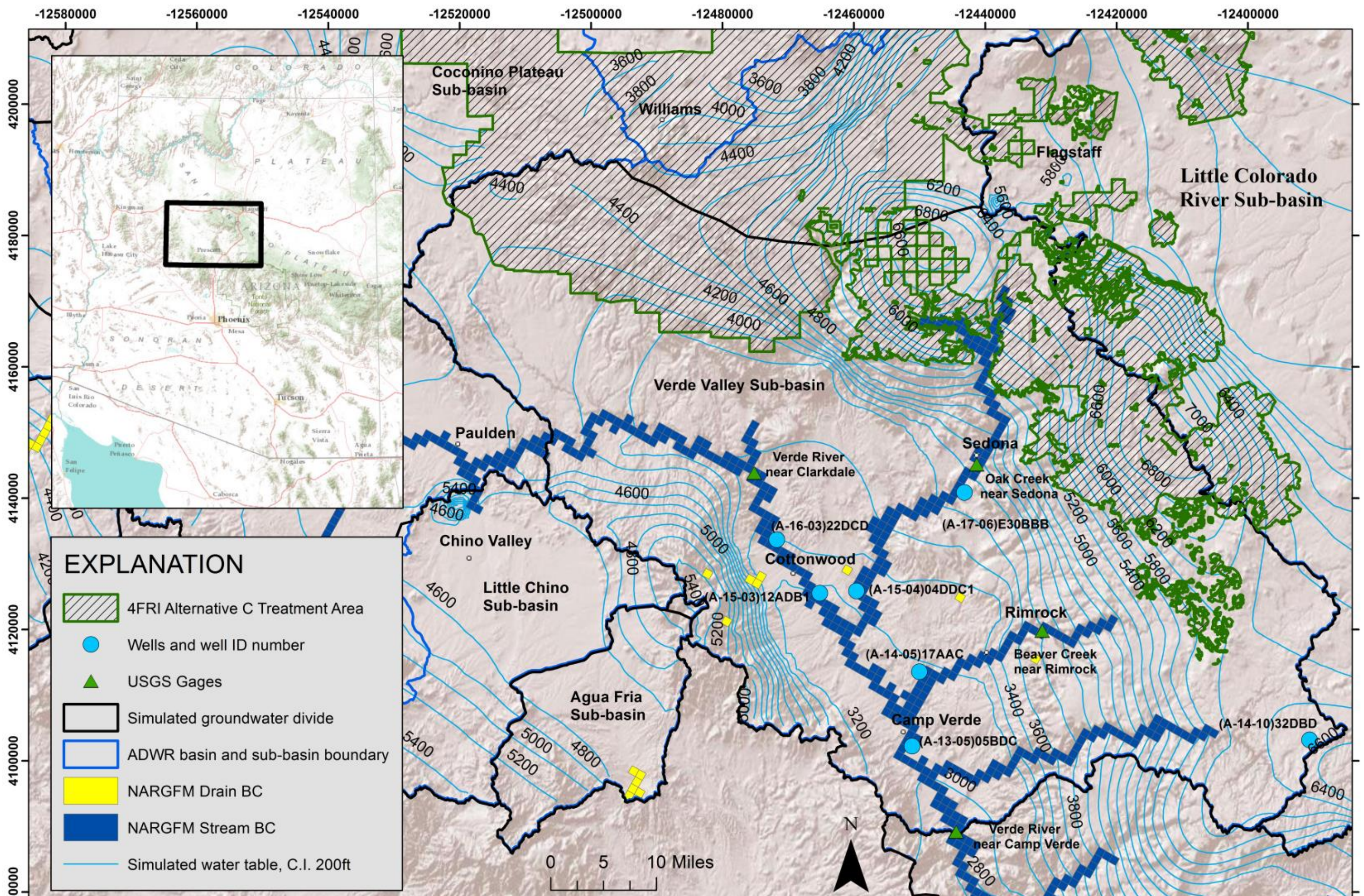


Figure 11. Simulated pre-development groundwater-flow system in the Verde Valley area. Included are the 4FRI analysis area, stream boundary conditions, drain boundaries conditions, wells, and gages of analysis shown.

previously analyzed under separate National Environmental Policy Act (NEPA) processes and were included in the simulations (Coconino and Kaibab National Forests, 2012). Shelf-stock data were compiled from multiple sources on the Coconino and Kaibab National Forests and represent planned or anticipated 4FRI shelf-stock at the time. There is considerable interest in how the proposed treatments will impact areas of high water use, such as the Verde Valley (Figure 11).

3.6 INCORPORATING CLIMATE CHANGE INTO MODEL SIMULATIONS

This study used bias corrected and downscaled climate projections derived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model ensemble (Maurer et al., 2007) to provide estimates of future precipitation for the study area. The WCRP CMIP3 climate projections include a multi-model ensemble of results produced from 16 climate models that simulated three of the potential emission scenarios identified by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007). The emission scenarios include the A1, A2, and B1 scenario families. These scenarios are based on demographic development, socio-economic development, and technological changes that may occur in the future and their impacts on greenhouse gas emissions.

Three emission scenarios from these scenario families, the A1B, A2, and B1 scenarios, were used to simulate future changes in precipitation for the interpretive period (2006-2099). In general, all emission scenarios result in warmer, drier conditions in the southwest, however there is considerable variability among model estimates as to the magnitude of precipitation changes (Maurer, 2007).

3.7 OBJECTIVES

To determine the response of the regional Redwall-Muav and Coconino aquifers to the 4FRI treatments and changing climatic conditions, the following objectives were designed for this study:

1. simulate changes in groundwater recharge from landscape change and changing climatic conditions; and
2. assess the impacts that these changes may have on the groundwater budget of Northern Arizona, with a focus on the Verde Valley groundwater catchment area and associated tributaries.

3.8 METHODS

A set of relatively novel methods were used for estimating changes in recharge from forest restoration treatments. Because the NARGFM is a groundwater model, and therefore does not model surface vegetation or precipitation, the only hydrologic parameter in the model that was manipulated to simulate these changes was the specified flux recharge property. For the interpretive simulation period 2006-2099, all other parameters, including pumping and ET of riparian areas were kept at the same values used for the last stress-period (2000-2005) of the calibrated groundwater-flow model. Other regional water supply studies have simulated changes in pumping that may result from an increased population in the future (ADWR, 2011, Reclamation, 2012, and Garner and Bills). However, we did not change these variables in this study because the objective was to isolate the impact of forest treatments and climate change on groundwater recharge.

A baseline scenario based off the period of instrument record was created to simulate future precipitation and recharge values similar to values for the period of instrumented record for the study area. The baseline scenario represents recharge conditions absent forest restoration and climate change. To project historical recharge conditions in the interpretive simulations, a synthetic annual precipitation record was created from 2006 (the end of the calibrated NARGFM was 2005) to 2099 by randomly sampling from annual precipitation values in the 1971-2000 precipitation normal (PRISM Climate Group, 2012). The precipitation normal was used by the USGS to estimate annual average recharge rates in the calibrated NARGFM. A longer normal from 1940-2005 became available during the USGS study and was used to create scaled decadal variations in recharge for the period of record for the calibrated NARGFM. Recharge values for each new future stress period (Table 4) were estimated from the synthetic precipitation values.

Because of the relatively few studies that have quantified groundwater recharge following tree removal in semi-arid, conifer-dominated watersheds, it was assumed that groundwater recharge responded in a similar way as literature documents runoff and streamflow responding after tree removal in these ecosystems. Specifically, when ponderosa pine tree basal area is reduced by 30-100%, surface water yield may increase 15-40% (Baker, 2003). Therefore, the assumption was made that as ponderosa pine basal area is reduced, groundwater recharge may increase by 15-40%.

There were multiple, converging lines of evidence which aided in this assumption. First, Baker (2003) reported on ponderosa pine watersheds in semi-arid climates, a scenario that matches the conditions of the 4FRI treatment area. Second, there are a number of studies that report evapotranspiration (Kolb, 2009) decreases and snowpack accumulation (Stegman, 1996) increases following the removal of trees. This allows for an increase in the availability of water to infiltrate into the subsurface and percolate down to recharge the aquifers. Third, there was good evidence to support the notion that afforestation, or adding trees, decreases groundwater recharge (Allan and Chapman, 2000), and therefore removing trees would have the opposite effect. Furthermore, a systematic review conducted in conjunction with this work (Chapter 2) showed that in 13 of 15 studies, when trees were removed from a watershed, there was an increase in groundwater table elevation. All of these sources supported the assumptions of increased recharge from reduction in basal area we made in this study.

Information on 4FRI scenario C pre-treatment and post-treatment basal area projections for stands within 4FRI treatments were obtained from the 4FRI GIS specialist for 4FRI (Mark Nigrelli, personal communication, 2012). These projections were simulated using Forest Vegetation Simulator (FVS) modeling of tree stand data (Dixon, 2002). The change in tree basal area (x) was calculated by finding the percent difference between pre- and post-treatment basal area projections. Based on the work by Baker (2003) the percent change in water yield (y) was described as:

$$y = 0.36x + 4.3 \qquad (\textit{equation 1})$$

This percent change in water yield (y) from equation 1 was applied to the groundwater model as a factor to adjust recharge based on average percent change in basal area per forest stand.

As an example of how the basal area change relationship was applied, areas that corresponded to a basal area reduction of approximately 30-39% (an average change of ~35%) were given a 16% increase in recharge (y=1.16) (Table 3). Any treatments that reduced basal area by less than 30% were assumed to produce no discernible hydrologic effect. This is supported by evidence found in Baker (2003) where little to no discernible increase in water yield was observed when basal area reduction in ponderosa pine forests was reduced by less than 30%. We assumed this relationship held for groundwater. The shelf-stock treatments were also accounted for in the simulations. However, estimates on changes in basal area are not consistently available for shelf-stock areas. Therefore, it was assumed that the shelf-stock areas would have similar proportions of treatment intensities (e.g. basal area changes) as 4FRI and would produce a similar hydrologic effect.

Table 3. Forest restoration treatment recharge-change factors for 4FRI scenario C and shelf-stock.

Zone	% BA Red.*	% Increase	Recharge Change Factor
1	> 0	N/A	N/A
2	0	N/A	N/A
3	1-29	N/A	N/A
4	30-39	16.275	1.16
5	40-49	19.775	1.19
6	50-59	23.275	1.23
7	60-69	26.775	1.26
8	70-79	30.275	1.3
11	31.87	15.3545	1.15

*Zones were delineated based on each 10% reduction in basal area (BA), then averaged before calculating percent increase in groundwater recharge. Zone 11 corresponds to shelf-stock treatment areas where basal area reduction was assumed to be equal to the 4FRI average. Factors were only applied to areas where 4FRI treatments are planned to occur. These factors were applied to stress period 12, or the years 2014-2023, when 4FRI treatments are planning to be conducted.

Recharge-change factors within the future NARGFM interpretations were applied to simulate likely changes in precipitation resulting from changes in climatic conditions. Downscaled climate model projections of precipitation were obtained from the WCRP and contain precipitation estimates resulting from several IPCC emission scenarios and over 30 models participating in the coupled-carbon-climate model intercomparison project (CMIP3) (Meehl et al., 2007). Multi-model ensemble precipitation estimates based on three emissions scenarios (A1B, A2, B1) were used. These scenarios are based on demographic development, socio-economic development, and technological changes that may occur in the future and their impacts on greenhouse gas emissions.

To capture the range of likely precipitation for the region under changing climatic conditions, the multi-model mean (the mean across all IPCC scenario simulations for emission scenarios A1B, A2, and B1) and the spread (+/- one standard deviation) was calculated across all models and all three emission scenarios. Thus, three climate change scenarios are considered that represent precipitation conditions associated with: (1) the mean of climate model projections; (2) conditions slightly wetter than the mean climate model projections (+1 standard deviation); and (3) conditions slightly drier than the mean climate model projections (- 1 standard deviation). To simulate these changes in precipitation, the residual between the baseline synthetic precipitation and the mean, mean +1 s.d., and mean -1 s.d. was calculated, converted into a factor of change (Table

4), and applied to the NARGFM (Figure 12). It was assumed that increases or decreases in precipitation result in a similar increases or decreases in recharge.

All spatial information was manipulated with ArcGIS 10.1 (ESRI, 2011). The NARGFM was simulated with MODFLOW 2005 (Harbaugh, 2005) using the Groundwater Vistas 6.17 user interface (Rumbaugh and Rumbaugh, 2011). All groundwater basins for this research are delineated by model simulation and may not coincide with Arizona Department of Water Resources designations (see Figure 11).

Table 4. Average climate change scenario recharge-change factors by stress period.*

Stress Period	Years	Scenario A	Scenario B	Scenario C
11	2006-2013	0.954	1.19	0.716
12	2014-2023	0.954	1.20	0.709
13	2024-2029	0.961	1.20	0.724
14	2030-2039	0.953	1.21	0.699
15	2040-2049	0.950	1.21	0.694
16	2050-2059	0.924	1.17	0.678
17	2060-2069	0.918	1.17	0.667
18	2070-2079	0.921	1.17	0.670
19	2080-2089	0.922	1.18	0.667
20	2090-2089	0.914	1.17	0.656

* All stress periods are transient and all factors were applied across the entire model domain.

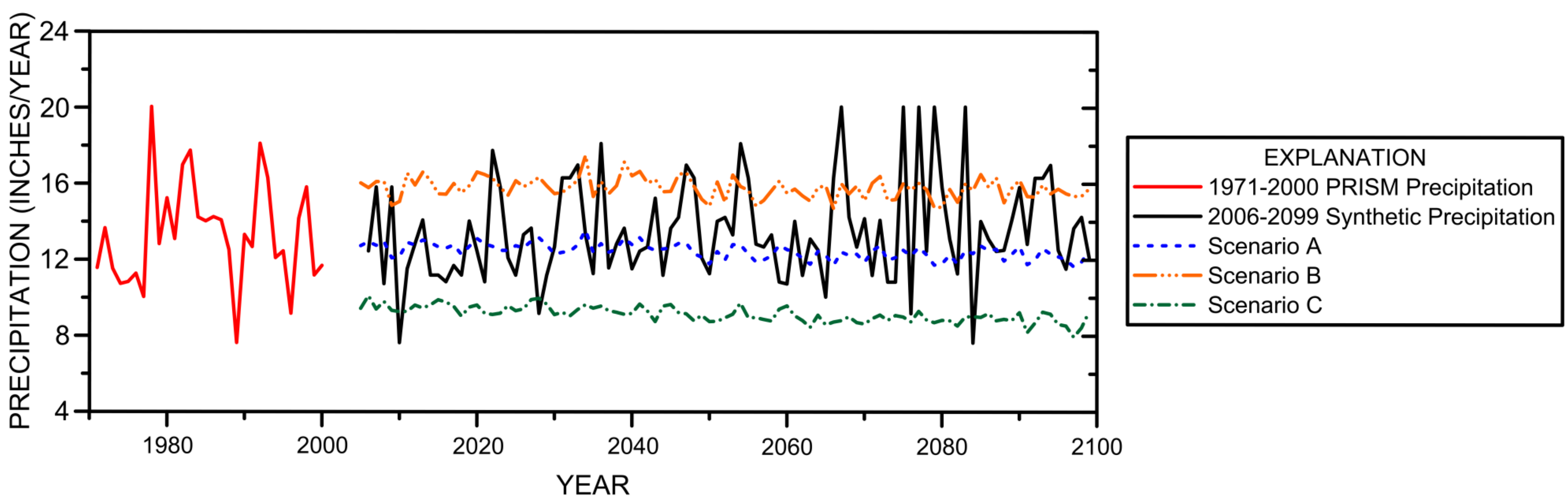


Figure 12. Precipitation values for 1971-2000 PRISM and Baseline, A, B, and C Scenarios. PRISM data were used to estimate recharge in the calibrated NARGFM. The Baseline scenario is precipitation absent forest restoration and climate change. Scenarios A, B, and C are the mean, mean +1 standard deviation, and mean -1 standard deviation of the IPCC A1B, A2, and B1 emission scenario precipitation projections plus changes from forest restoration.

3.9 RESULTS

To maintain consistency, all results are compared to the average for the calibrated simulation for the NARGFM, or the years 1910-2005. Some of these numbers deviate from reported values in Blasch et al. (2006) and results are therefore dependent on this difference. A comprehensive evaluation of the calibrated simulation of groundwater flow in Northern Arizona by the NARGFM can be found in the published USGS report (Pool et al., 2011). All values are reported in acre-feet per year (afy). All values are approximated, and rounded to three-significant figures. Variables given in the following graphs include the Baseline, A, B, and C scenarios, plus annual average for the initial period of simulation for the calibrated NARGFM (1910-2005)

In the interpretive model, 4FRI treatments from 2014-2023 simulated approximately 23,000 acre-feet of additional recharge to the Verde Valley sub-basin, or about 2,300 acre-feet/year (Figure 13). This is an estimated 2.8% increase in annual recharge from average conditions for the Verde Valley (~83,600 acre-feet/year). Because some of the 4FRI and non-4FRI (shelf-stock) treatments were located in the Coconino Plateau and Little Colorado Plateau sub-basins, it was assumed that these two sub-basins received additional recharge from forest restoration treatment, but they were not analyzed.

Recharge values (Figure 13) for Scenario A for the interpretive period (2006-2099) range from 76,400-84,000 afy, with an average value of 79,000 afy. This represents 5,000 afy or 5.74%/year less recharge than annual average conditions for the simulation period 1910-2005. Recharge values for Scenario B (2006-2099) range from 98,000-107,000 afy, with an average value of 99,800 afy. This represents 16,100 afy or

19.3%/year more recharge than annual average recharge (1910-2005). Recharge values for Scenario C (2006-2099) ranged from 54,900-62,800 afy, with an average value of 57,900 afy. This represents 25,700 afy or 30.8%/year less recharge than annual average recharge (1910-2005). Recharge decreased for all scenarios for the interpretive period (2006-2099), with the highest values coming during the 4FRI treatment period (2014-2023) and the lowest values coming at the end of the simulation period (2090-2099). Scenario B showed the highest amount of recharge for the Verde Valley sub-basin, while Scenario C showed the lowest. Scenario A was in between these two. This trend for recharge is similar for baseflow, well water level elevation, and storage change.

Stream baseflow at USGS stream gaging stations in the Verde Valley sub-basin was evaluated to discern responses of the Verde River and its tributaries to forest restoration treatments and different climate change scenarios (Figure 14). These gaging stations (and annual average baseflow for 1910-2005) were: Verde River near Clarkdale (39,000 afy), Verde River near Camp Verde (156,000 afy), Oak Creek near Sedona (20,600 afy), and Wet Beaver Creek near Rimrock (6,160 afy).

On average, baseflow for all stream gages decreased from the annual average for all interpretive scenarios, with the least decrease coming during first years of interpretive simulation (2006-2013) for Scenario B and the most decrease coming at the end of the simulation period (2090-2099) for Scenario C. Values given are averaged ranges for the interpretive period (2006-2099). Losses at the Verde River near Clarkdale ranged from 738-1,950 acre-feet, or 1.9-5% of annual average. Losses at the Verde River near Camp Verde ranged from 10,417-22,155 acre-feet, or 6.7-14% of annual average. From annual average, Oak Creek near Sedona gained 227 acre-feet of baseflow for Scenario B (1.1%)

and lost 1420 acre-feet (6.9%) for Scenario C; Scenario A had an average loss in baseflow of 605 acre-feet, or 2.9%. From annual average, Wet Beaver Creek near Rimrock showed gains for both Scenarios A (149 acre-feet or 2.4%) and B (389 acre-feet or 6.3%), but showed a loss for Scenario C (169 acre-feet or 2.7%).

Water-level data at seven wells were selected to analyze groundwater response to landscape change and climate change. These wells were pre-defined by Pool et al. (2011) as representative of the groundwater system in the Verde Valley sub-basin. These include five wells – (A-13- 05)05BDC, (A-14-05) 17AAC, (A-15-03)12ADB1, (A-15-04)04DDC1, and (A-16-03)22DCD – that are in the confined part of the Verde Formation of the alluvial basin-fill aquifer and two wells – (A-14-10)32DBD and (A-17-06)E30BBB – that are in the unconfined part of the Coconino aquifer. None of these wells were within the 4FRI treatment area but were assumed to show changes in the groundwater system that resulted from 4FRI treatments (Figure 12). No long-term water-level data were available for the Redwall-Muav aquifer in the Verde Valley sub-basin (Pool et al., 2011). Well data from two alluvial basin-fill wells – (A-13-05)05BDC and (A-14-05)17AAC – and one Coconino well aquifer well– (A-14-10)32DBD – are graphed to visualize changes in water-level altitude (Figure 15).

Generally, for the interpretive period (2006-2099) well levels declined in all wells from the last values of the calibrated model (2005). Losses ranged from a minimum of 1.0 foot at (A-13-05)05BDC and (A-16-03)22DCD for Scenario B to a maximum of 41 feet at (A-15-03)12ADB1 for Scenario C. The exception is (A-14-10)32DBD where well water-level elevation rose 27 feet for Scenario B. Mean standard deviation of estimated water-level elevations in wells located in the Verde Valley sub-basin is 10.6 feet for alluvial aquifer wells and 19.2 feet for wells located in the Coconino Aquifer. Results from three wells – (A-13- 05)05BDC, (A-15- 04)04DDC1, and (A-16-03)22DCD – fell within this standard deviation and were not considered significant changes. However, three wells – (A-14-10)32DBD, (A-15-03)12ADB1, and (A-17-06)E30BBB – showed significant changes, estimating changes of +26 to -31 feet, -39 to -41 feet, and -29 to -34 feet, respectively. One well – (A-14-05)17AAC – had values that were only significant for Scenario C (decline of 11 feet).

All scenarios suggest a decline in groundwater storage for the interpretive period (2006-2099) (Figure 16). Cumulative changes in storage for the Baseline, A, B, and C, Scenarios were -2.32 maf (million acre-feet), -2.54 maf, -1.73 maf, and -3.36 maf, respectively. Annual average changes in storage for the Baseline, A, B, and C Scenarios were -22,000 afy, -26,000 afy, -10,200 afy, and -42,700 afy, respectively. Generally, losses in storage decreased through time. There was no estimate available for pre-development (pre-1910) total water in storage for the Verde Valley sub-basin and therefore, percent changes per year cannot be established. Changes were lower than normal for stress period 12, or the years 2014-2023, and were assumed to be because of the additional water available for recharge following forest restoration treatments.

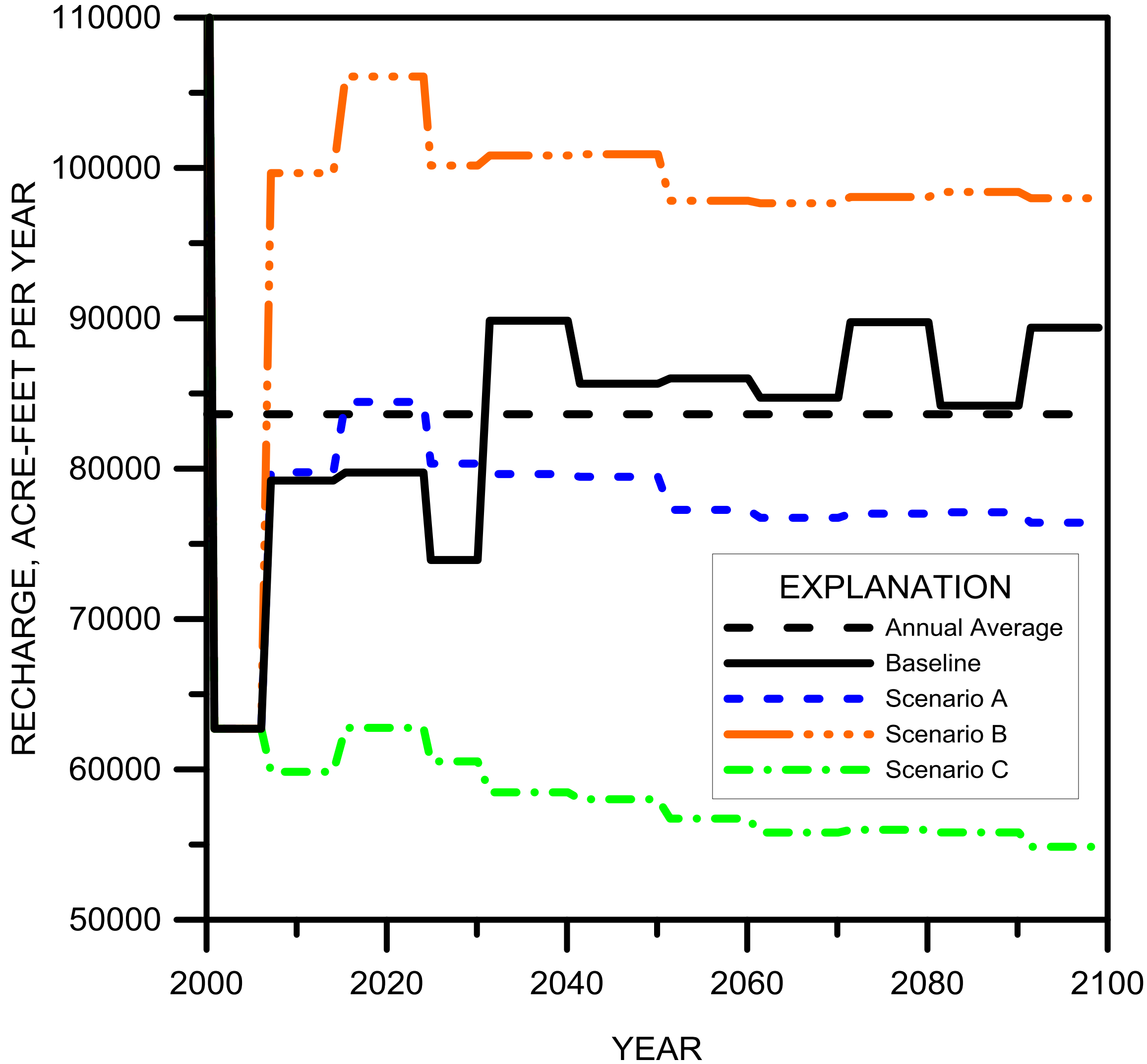


Figure 13. Changes in recharge in the Verde Valley sub-basin for the interpretive model scenarios. The Baseline scenario is precipitation absent forest restoration and climate change. Scenarios A, B, and C are the multi-model mean, mean +1 standard deviation, and mean -1 standard deviation of the IPCC A1B, A2, and B1 emission scenario precipitation projections plus changes from forest restoration. These are the same scenarios given for Figures 14-16.

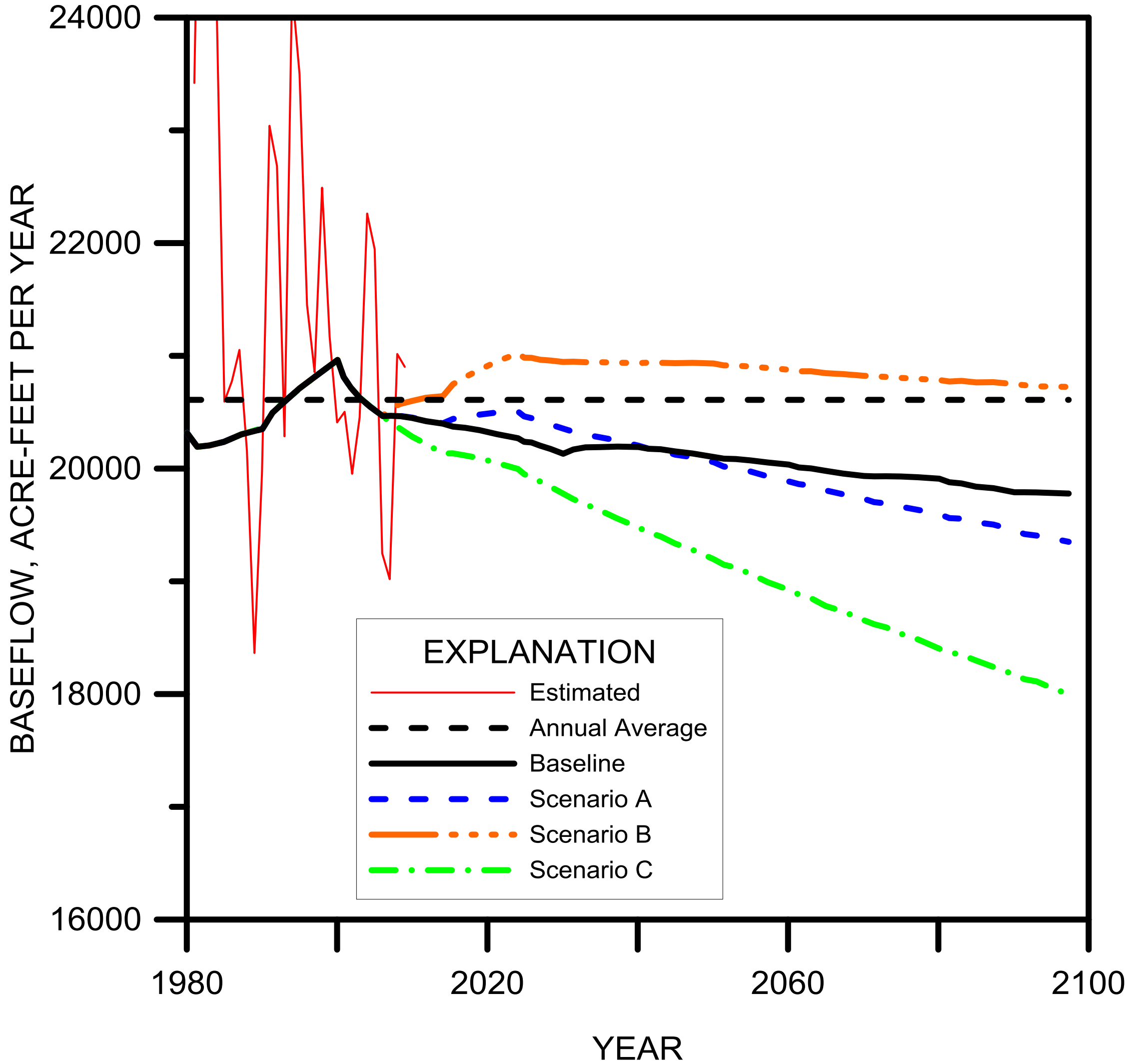
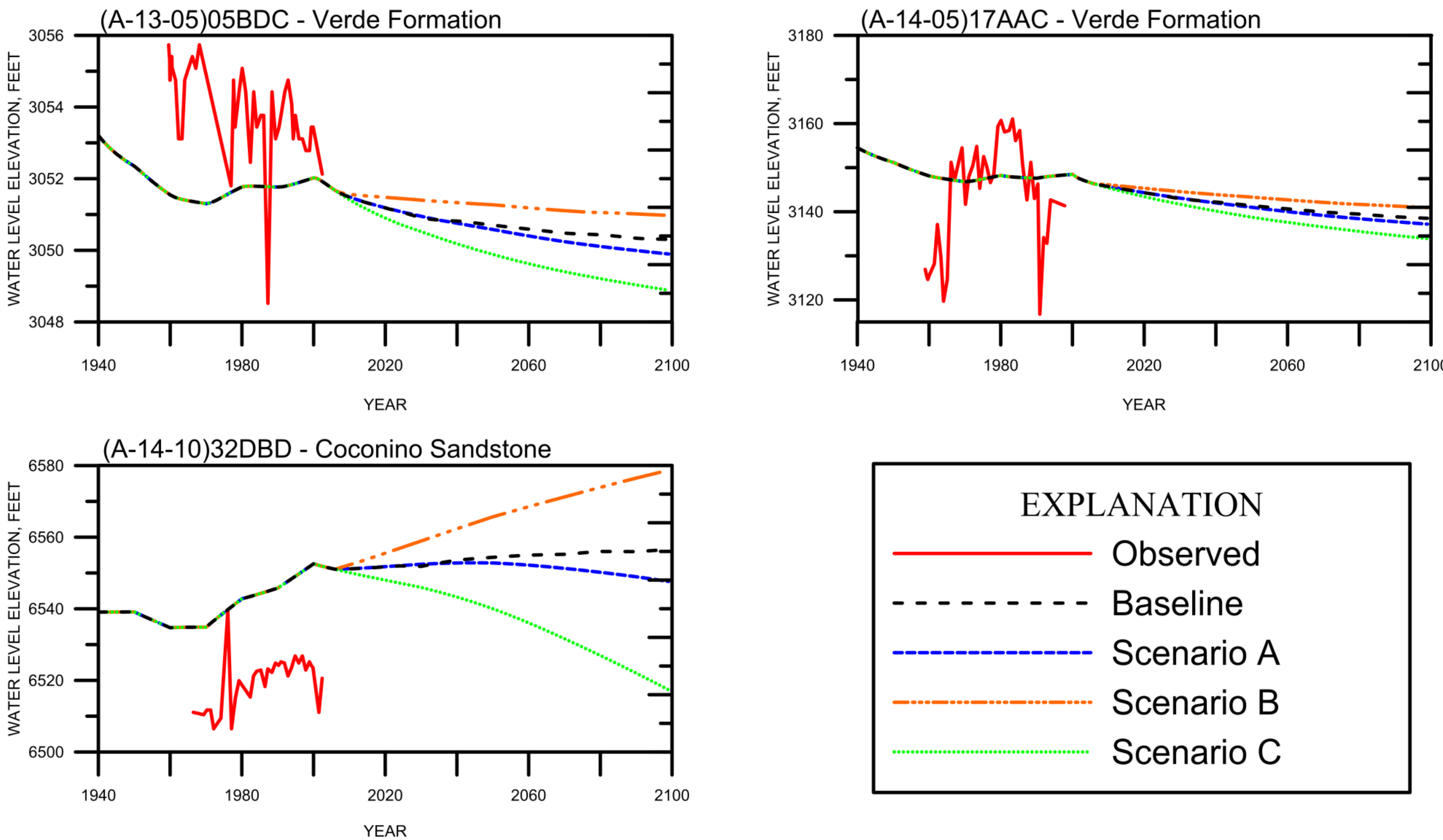


Figure 14. Observed and interpretive model simulated baseflow at Oak Creek near Sedona. Observed baseflow estimates provided by Natalie Coston (NAU Senior thesis, 2010). Coston data from NOAA, 2009.



Observed and interpretive model simulated groundwater levels at wells in the Verde Valley sub-basin. (A-13-05)05BDC and (A-14-05)17AAC are located in the Verde Valley near Camp Verde. (A-14-10)32DBD is located near the surface water and groundwater divides near Happy Jack (Pool et al., 2011). Values clipped to the year 1940-2099 for better resolution.

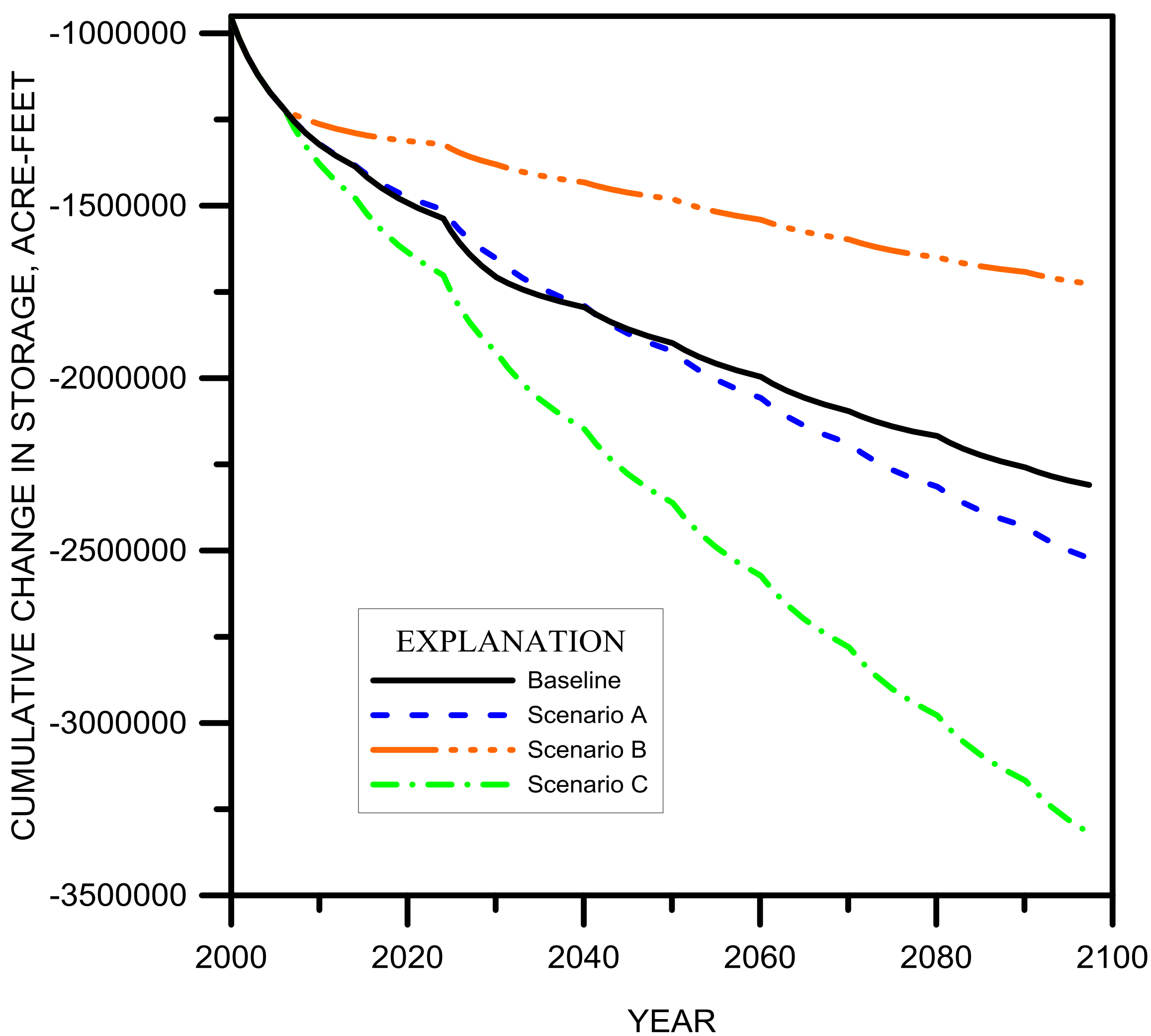


Figure 16. Changes in groundwater storage for the Verde Valley sub-basin.

3.10 DISCUSSION AND CONCLUSIONS

This interpretive groundwater-flow model was constructed to evaluate the changes to the groundwater-flow systems in Northern Arizona which might occur from changes in recharge due to upland forest restoration and anticipated climate change. All values for recharge, baseflow, water table elevation, and storage, are dependent on simulated, future precipitation trends, and are therefore highly variable. The increased recharge associated with 4FRI forest restoration treatments in stress-period 12 is relatively small compared to estimated changes in recharge from climate and is largely masked in the record. Because this is an interpretive model, simulated changes in recharge from 4FRI treatments were easily extracted by running the groundwater-flow model once with and once without the applied changes, isolating, and then analyzing individual stress periods. By doing this, we were able to identify changes in recharge from forest treatments. However, any increases in recharge from 4FRI treatments may be difficult to identify and may require a paired-watershed study to aid in distinguishing any changes associated with recharge.

The interpretive model did not include maintenance treatments for the first EIS area. Instead, the focus of the model was on the initial treatments. It was unclear how effective maintenance treatments would be, but it may sustain the hydrological benefits of reduced ET through frequent prescribed burns that may occur post-treatment. Therefore, benefits may last longer than those simulated with the interpretive model. Furthermore, because information on the second round of 4FRI treatments, which are expected to be largely in the Apache-Sitgreaves and Tonto National Forests, has yet to be fully developed, these future treatments, which would take place after the first EIS area was treated, were not included. However, it is anticipated that if treatments for the second EIS are similar to those for the first EIS, similar benefits may be possible.

The model suggests that recharge will decline through time for all scenarios. This is because precipitation projections show a decrease in the water available for recharge over time. Because the precipitation projections that were used were estimated from

IPCC emission scenarios, these declining trends are assumed to be caused by the effect that increased greenhouse gas emissions, such as carbon dioxide and methane, will have on the climate. Generally, climate models predict a climate that becomes warmer and drier through time. This is reflected in the declining recharge (Figure 13).

With less recharge, there is less water available to discharge to streams and wells. This can cause baseflow and water-level elevations to decline over time. These impacts are reflected in figures 14 and 15. While a wetter than average climate (Scenario B) may produce an increase in baseflow and water-level elevation, these increases are expected to be relatively short-lived because of declining recharge values throughout the interpretive simulation period (2006-2099). Blasch et al. (2006) reports that discharge upstream from the streamflow gages on the Verde River near Clarkdale and Camp Verde, Oak Creek near Sedona, and Wet Beaver Creek near Rimrock is likely sensitive to variations in recharge rates. Because of this, it is assumed that changes in baseflow will be affected by both forest restoration treatments and changes in precipitation from climate change.

Blasch et al. (2006) estimated a change of -39,000 acre-feet for the Verde Valley sub-basin for the year 2005, the last year simulated by the NARGFM (Pool et al. 2011). The changes in storage for the interpretive simulations fall above and below this value, depending on the scenario. However, in all cases, water is pulled from storage and cumulative storage change increases through time. This reflects an imbalance between water supply and demand. This imbalance is attributed to groundwater overdrafting through well pumping and surface water diversions. It is assumed that before the development of groundwater resources in the study area, or before 1938, the groundwater system was in equilibrium and there was no imbalance between water supply and demand. It was assumed that less water was pulled from storage over time because of groundwater capture of resources, especially of the Verde River and its tributaries.

This imbalance between supply and demand may result in future, unmet demands for water for both natural and human communities, which may significantly alter the ecology of the Verde River system, and may negatively impact human communities in the area. Communities will need to develop sustainable water management strategies to combat these issues. A more detailed analysis of these imbalances and possible solutions is included in Reclamation's Colorado River Basin Water Supply and Demand study (Reclamation, 2012) and the Arizona Department of Water Resources Water Resources Development Commission report (ADWR, 2011).

3.11 ACKNOWLEDGEMENTS

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CHAPTER 4 – DISCUSSION AND CONCLUSIONS

4.1 SUMMARY OF FINDINGS

This study had two objectives: 1) to determine, through a systematic review process, how forest restoration thinning and burning impacts the water budget of semi-arid, forested regions, and 2) to simulate how forest restoration thinning and burning and changing climatic conditions might impact groundwater recharge in Northern Arizona. The systematic review revealed that there are few studies that quantify the effects that removing trees have on groundwater recharge and even fewer that focus on the semi-arid, southwestern United States. Instead, the focus of most studies was on surface water in general and groundwater in more humid locations with relatively shallow-depth to the water table. This made it difficult to ascertain how 4FRI treatments in Northern Arizona might affect groundwater recharge to aquifers that are located at considerable depths (>1000 feet). As a result, a number of important assumptions were required.

Results from the systematic review suggest that a rough relationship exists between tree removal and water yield: when 5-100% of a conifer-dominated watershed has a treatment applied to it, annual water yield may increase from 0-50%, with the possibility for high results. These results were similar to those reported by Baker (2003). Because the groundwater results were inconclusive for semi-arid locations, I assumed that groundwater recharge was affected in a similar way to how Baker (2003) documents surface water yield being affected by basal area reduction. I used this relationship to establish zones of recharge-change based on basal area reduction in 4FRI and non-4FRI treatment areas. By applying recharge-change factors to these zones and simulating changes in precipitation with a similar recharge change factor, it was estimated that recharge increased by approximately 23,000 acre-feet to the Verde Valley sub-basin. This is approximately 2,300 acre-feet, or 2.8%, per year of treatment for ten years.

Regardless of increases in recharge from 4FRI treatments, water levels, baseflow, and groundwater available in storage continued to decline under pumping conditions that existed at the end of the calibrated model period (2005). Blasch et al. (2006) estimated a change of -39,000 acre-feet per year in storage for the Verde Valley during 2005. This declining trend continues into the future for all scenarios, with minor variations. This is attributed to surface water diversions and overdrafting of groundwater supplies, a practice that is likely not sustainable and may have – and has likely already had – detrimental impacts to the environment, future surface and groundwater supplies, and natural and human communities that depend on these supplies. Summing up these findings, it is estimated that 4FRI treatments may increase recharge to regional aquifers, but these effects are likely to be masked by decreases in precipitation and recharge from a drying climate, and decreases in water levels, stream baseflow, and storage associated with groundwater pumping and surface water diversions.

4.2 LIMITATIONS

The data and methods used for this project were considered adequate for the purpose of the study, but there were a number of limitations associated with the research. For example, the methods used to simulate changes in recharge from 4FRI treatments and climate change were based on a set of assumptions, the most important of which assumed that groundwater recharge was affected by tree removal in a similar way that surface water is affected. This relationship describes that when basal area in a semi-arid, ponderosa pine forest was reduced by 30-100%, water yields were observed to increase 15-40% (Baker, 2003). Treatments that reduced basal area by less than 30% were expected to show no increase in groundwater recharge. This assumption was made because the results from the systematic review were inconclusive as to how treatments in semi-arid, conifer-dominated forests would affect recharge.

As described in Chapter 3, this assumption was derived from a conceptual understanding of the hydrologic system in Northern Arizona and supported by multiple, converging lines of evidence. It is assumed that additional water will be available for recharge following forest restoration treatments due to decreasing evapotranspiration (Kolb, 2009) and increased snowpack (Stegman, 1996) following a reduction in basal area. Furthermore, Baker's (2003) results were reported on ponderosa pine watersheds in semi-arid climates, a scenario that matches the conditions of the 4FRI treatment area. In addition, afforestation has been shown to decrease groundwater recharge (Allan and Chapman, 2000). Finally, while the information collected for the systematic review was from low-elevation locations with a shallow-depth to the water table, 13 of the 15 studies reported increases in the water table following the removal of trees. All of these sources supported the assumptions I made in this study.

Another limitation is the reliability of the original recharge values built into the Northern Arizona Regional Groundwater-Flow Model, estimates which were derived from the Basin Characterization Model (Flint and Flint, 2008). The Basin Characterization Model (BCM) is a spatially distributed water-balance model that was developed to analyze how factors such as climate, topography, soils, geology, and vegetation affect recharge and runoff variability in the arid and semi-arid southwestern United States. Eight study-site basins, classified on the basis of climate, runoff, and in-place recharge, were analyzed to determine recharge at site-specific locations. Because of the variation between locations, a regional framework was developed so results from the eight study basins could be extrapolated across 194 basins in the region. The modelers assumed that these eight basins were representative of the entire study area. The BCM used the Parameter-elevation Regressions on Independent Slopes Model (PRISM) to model precipitation for the region of interest (PRISM Climate Group, 2012). PRISM uses point measurements of variables like precipitation and temperature to produce estimates of monthly, yearly, and event-based climatic parameters. Also built into the model are digital elevation models and expert knowledge of characteristics of complex climate systems in the semi-arid southwest, including rain shadows, coastal effects, and temperature inversions. PRISM data sets were initially produced for the period of record 1971-2000. Subsequently, a data set for the period of record 1940-2005 was made available. Both of these data sets were available as monthly or annual data, and as map graphics or gridded data. In the case of the BCM, average annual recharge was calculated from the first set of available data (1971-2000). The NARGFM used these estimates to calculate annual recharge and subsequently used BCM data sets produced from the 1940-2005 PRISM data to calculate recharge variability by decade.

As briefly described above, the NARGFM used a multi-model approach to estimate groundwater recharge and relied on data from the BCM that relied on data from the PRISM. Because of this approach, there is considerable potential for the accumulation of errors. The possibility of compounding uncertainties and assumptions can lead to results which may be inaccurate. Another limitation is that model results are often non-unique, meaning different models may produce the same result. This could mean that data are produced that appears accurate yet may come from an incorrect description of the natural system being modeled (Oreskes et al., 1994). Ideally, rigorous and comprehensive model calibration would minimize the potential for a false model to produce accurate results. An important point to remember is that models in general, and groundwater models specifically, can never be validated, only invalidated (Konikow and Bredehoeft, 1992). Therefore, the best way to determine the usefulness of a model is a comprehensive post-audit. I would recommend that the interpretive model for the hydrologic impacts of forest restoration treatments be recalibrated and analyzed in the future after the forest restoration treatments are complete. A more detailed list of limitations associated with the NARGFM can be found in its published report (Pool et al 2011).

There are important limitations associated with the WCRP's CMIP3 multi-model precipitation projections that were used. There are two general approaches used to downscale the output from global climate models: dynamical and non-dynamical approaches. Dynamical downscaling uses fine-scale, regional climate models to simulate climate over regions with a more localized terrain (Maurer et al., 2007). Non-dynamical downscaling statistically or empirically relates large-scale climate features to finer scale climates for the region. For the projections used here, a non-dynamical approach was used, including the Bias Correction and Spatial Disaggregation (BCSD) approach. Some of the limitations associated with climate modeling include simplification of the natural system being modeled, uncertainties about future greenhouse gas and aerosol emissions, economic and thus technological unpredictability, uncertainties in downscaling regional models to local environmental variations, the high variability of climate, especially precipitation, over small scales of time and space, and ability of models to predict extreme, or event-based, climates (Maslin and Austin, 2012).

Another limitation associated with this research was the method used to derive recharge-change factors for the precipitation projections. To find this recharge-change factor, two different climate data-sets were compared against each other. One set of data from the PRISM was described above. These data were produced for the period of record and provided the climate data that were used in the calibrated NARGFM to estimate annual average recharge and scaled, decadal variations in recharge. Against these data were compared the downscaled data from the WCRP's CMIP3 multi-model projections, as retrieved through Reclamation's research and development office. As described in Chapter 3, we used the multi-model mean from 16 models, then used the mean for the A1B, A2, and B1 climate scenarios, as well as the +/- 1 standard deviations to set our climate change boundaries. We assumed that the individual datasets were compatible. Finally, to find the recharge-change factor we compared precipitation data from the PRISM with precipitation data from the downscaled CMIP projections. The percent difference between the two was converted to a factor of difference and then applied to the NARGFM as either an increase or decrease in recharge to simulate an increase or decrease in regional precipitation. These are indirect methods for modeling recharge but there was no compatibility between software used to run the NARGFM and software used to manipulate the climate data sets.

Additional limitations include the timing of recharge to the regional aquifers, and a need for a re-calibration, post-audit, and sensitivity analysis of the NARGFM. The NARGFM simulates recharge as instantaneous and does not account for the delay that occurs from when additional rainwater infiltrates into the soil and that portion of water that percolates downward to regional aquifers. This is a process that can take anywhere from days to centuries and in some cases, millennia. Because recharge is not instantaneous, there is a likelihood that the additional recharge derived from treatments and climate change would not be seen in the system for many years. However, there is good reason to believe recharge may occur relatively quickly following 4FRI thinning and burning because these treatments occur along the Mogollon Rim, the area of primary recharge to regional aquifers in Northern Arizona (Parker, 2005). A re-calibration of the NARGFM to the years 2006-2013, a comprehensive post-audit, and a rigorous, quantitative sensitivity analysis were considered outside the scope of this project. These are considered necessary to increase the overall confidence and usefulness of the model but would require additional resources that were not available for this research. However, some of these features have been incorporated into sub-sections of the model including work done by the USGS in response to Prescott-area concerns about details of the Big Chino portion of the model, refinements made by AMEC to their Flagstaff Model for the City of Flagstaff, and possible, further refinements to the Flagstaff Model regarding pumping at Red Gap Ranch 40 miles east of Flagstaff.

A final important limitation includes the choice of my baseline scenario. This scenario was created from a synthetic precipitation record for the interpretive period (2006-2099). This record was estimated from values for the period of record 1971-2000, or the original period of PRISM precipitation values that were used to estimate annual average recharge for the calibrated NARGFM. A random sample of annual values was selected from this 30-year record and applied from 2006-2099 to estimate recharge values that we might expect in Northern Arizona absent landscape change and climate change. It was assumed that a 30-year record was sufficient for capturing annual and decadal variations in climate for the region. Therefore, the values we used for the synthetic precipitation record and for recharge values from 2006-2099 are considered reliable.

Because models are approximations of natural systems, with a number of assumptions built in, their primary value is heuristic. The results produced here are simulations of the groundwater-flow system in Northern Arizona, projected land use/land cover change associated with the Four Forest Restoration Initiative and non-4FRI treatments, and projected precipitations values based on IPCC climate change scenarios, and are not considered predictions of future recharge conditions, baseflow discharge, well water levels, and changes in groundwater storage. Instead, they are considered useful for identifying changes in the groundwater budget, in trend and magnitude, following forest restoration treatments and changes precipitation from climate change. They should be used in conjunction with others data such as those recovered from paired-watershed studies to help guide decision-making with respect to groundwater supply and demand issues, operations, and balancing the needs of both natural and human communities.

4.3 IMPLICATIONS

If groundwater outflow exceeds groundwater inflow, a decrease in well water levels, baseflow to streams, and groundwater storage may occur. Because both natural and human communities depend on these resources to survive, a reduction in these supplies will present a problem for both communities. A 2008 publication by the Arizona Water Institute, The Natural Conservancy, and Northern Arizona University detailed some of the likely ecological impacts that could result from reduced groundwater supplies (Haney et al., 2008). These impacts include decreased discharge at springs, change of streams from perennial to ephemeral conditions, increased depth to and fluctuations of the water table, and increased average annual depth to saturated soils. These impacts may reduce native vegetative diversity and abundance, and increase the abundance of non-native "weedy" species such as tamarisk. These changes in vegetation may change the structure and resiliency of native fish, bird, mammal, herpetofauna, and invertebrate populations along the Verde River, a number of which are listed as threatened or endangered (Haney et al., 2008). Concerns already exist about the effects that pumping groundwater from the Big Chino sub-basin may have on the flow of the Upper Verde River, where Verde headwater springs discharge and perennial flow of the Verde River begins. These and other issues have important implications for water rights and use in the study area.

Human populations are also likely to be impacted by these changes. Blasch et al. (2006) estimated approximately 46,400 acre-feet per year of water use and sub-irrigation in the Verde Valley sub-basin. These uses include surface water diversions, pumping wells, and transpiration from agriculture. Under current water use and recharge conditions, water levels and stream baseflow are expected to decline. This trend, as described in Chapter 3, is similar for all scenarios. The consequences of these results are that there will be an imbalance between water supply and demand. This may result in a significant amount of unmet demands for water users across the region.

4.4 RECOMMENDATIONS FOR FUTURE STUDIES

Collection of hydrologic data and elimination of data deficiencies are one of the most important avenues of future research. The NARGFM was built with these deficiencies and requires re-calibration with seven years of additional data (2006-2013). Additional refinements to the BCM, PRISM, and CMIP products would be useful. However, these would require input from a number of agencies and is likely outside the scope of future researchers who are attempting to quantify how land cover/land use and climate change affect the regional water budgets. Therefore a number of smaller-scope recommendations include incorporating future paired watershed study results into modeling assumptions. As described in Chapter 1, in addition to the systematic review and groundwater modeling associated with this research, a paired watershed study is also in development. The purpose of the paired watershed study is to collect water, mass, and energy balance data from 12 watersheds in Northern Arizona to quantify the benefits from 4FRI restoration treatment and maintenance scenarios. This will include groundwater recharge data. This study will help fill in the gaps in knowledge that was found with the systematic review completed for this study. A quantitative sensitivity analysis will also be useful for the NARGFM as it will help better identify which variables are critical to the reliability and usefulness of the model and should be scrutinized the most.

Another recommendation includes the application of different methods to simulate changes in recharge. For this study a recharge-change factor was used as an indirect method but in the future it may be beneficial to try and couple a groundwater model, vegetation model, and climate model. An example of a model that couples multiple processes is Hydrogeosphere (Therrien et al., 2004). This method would allow a more direct application of effects between variables. This will significantly increase the resources and personnel needed to determine impacts of land use/land cover and climate change but could significantly decrease the assumptions, limitations, and errors associated with the method used for this study. This may provide more reliable results that could then be used to make more informed adaptive-management decisions with regards to forest restoration thinning and burning and the maximization of surface water and groundwater discharge.

4.5 RECOMMENDATIONS FOR WATER MANAGEMENT IN THE SOUTHWESTERN UNITED STATES

A suggestion to the Forest Service for maximizing water availability can be summed up in the findings published by Reclamation’s Colorado River Basin Water Supply and Demand Study (Reclamation, 2012). The purpose of this study was to define current and future imbalances in water supply and demand in the Colorado River Basin and adjacent areas that will receive Colorado River water for the next 50 years. This area includes Northern Arizona and the Grand Canyon through which the Colorado River runs, as well as the Verde River, Salt River, and Gila River basins that feed into the Colorado River system. A median water supply and demand projection estimates an imbalance between supply and demand of 3.2 million acre-feet per year by the year 2060 for the entire Colorado River Basin. A more detailed report aimed at the Verde River was commissioned by The Nature Conservancy and published in 2011 (Limbrunner et al., 2011).

Potential strategies to resolve water supply and demand imbalances may include options that 1) increase water supply, 2) decrease water demand, 3) modify operations, and 4) use governance and implementation strategies related to water management and allocation (Reclamation, 2012). Options to increase water supply include desalination, reuse, development of local supplies, watershed management, and importation; options to decrease water demand include municipal, industrial, and agricultural water conservation, and water use efficiency; options to modify operations include evaporation control and water transfers, exchanges, and banking. These solutions are not considered exhaustive but met the criteria that were used to evaluate all options and are therefore considered representative. These criteria included technical, environmental, and social concerns like technical feasibility, energy needs, and recreation, respectively. Other concerns include costs, timing, and water quality.

When all options are considered, potential yield to the Colorado River Basin was estimated to be 5.7 million acre-feet per year by 2035 and 11 million acre-feet per year by 2060. When accounting for options that are not technologically feasible or have low estimates of reliability, this yield is reduced to 3.7 million acre-feet per year by 2035 and 7 million acre-feet per year by 2060. The latter figure is more than double the estimated imbalance of 3.2 million acre-feet per year. However, these figures are considered highly optimistic and are likely to be met with serious technical, economic, environmental, and social challenges. Nevertheless, the water supply and demand issues facing communities in the southwestern United States, like the estimations made here, are problems that will not solve themselves. Therefore strategies like these and others are needed to meet the required demands of both natural and human communities now and in the future.

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