Analysis of Current and Historical Surface Flows and Hydrologic Response to Restoration Treatments in the Upper Lake Mary Watershed, Arizona

Cory A. Miller

Professional Paper
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Forestry

Northern Arizona University

August 2007

Approved:

____

W. Wallace Covington, Ph.D.

____

Charles Denton, Coordinator

____

Andrea Thode, Ph.D.

EXECUTIVE SUMMARY

BACKGROUND

- Ponderosa pine and dry mixed conifer forests in the Southwest have undergone dramatic changes in forest structure, function, and composition since about 1870. These alterations are attributed to livestock grazing, logging, and fire suppression.
- Impacts of these forest changes include reduced tree vigor, forage quantity and quality, nutrient availability, and overall forest health.
- Fire risk has worsened and potential fire behavior has grown more severe due to (1) increased tree densities and canopy closure, (2) variability and continuity of vertical structure resulting in the presence of ladder fuels, (3) tree mortality due to competition, suppression, lack of soil moisture, and disease and insect outbreaks, and (4) increases in forest floor fuel loads.
- Effects on watershed processes include increases in evapotranspiration and interception, and decreases in infiltration, soil moisture, and surface runoff.
- Alterations due to anthropogenic activities such as these are evident in the Upper Lake Mary watershed located in the Coconino National Forest near Flagstaff, Arizona.
- Surface runoff into Upper Lake Mary has decreased even with similar precipitation amounts, suggesting that reduced surface flows could be due to expansion of overstory vegetation. These effects, together with extended drought and the risk of catastrophic wildfire posed by dense forest conditions, could potentially jeopardize the ability of the City of Flagstaff’s reservoir to produce adequate amounts of unpolluted water. As of July 2007, the reservoir was at 13.7% of its capacity.

OBJECTIVES

- Determine (1) presettlement and current forest conditions and structure in the Upper Lake Mary watershed, (2) current and presettlement surface water flows, and (3) effects of four forest management alternatives on surface flows, sedimentation, erosion, and risk of catastrophic wildfire.
- Provide the Coconino National Forest and the City of Flagstaff with management options, analysis, and results in a form that is directly useable to begin the NEPA process.

FORESTS AND WATER YIELD

- The removal of overstory vegetation results in increased water yields, peak flows, and low flows (base flows).
- Process changes that account for these increases include (1) reduction of overall evapotranspiration, (2) increased soil moisture and infiltration, and (3) decreased interception of precipitation by vegetation, especially snow.
- Even though water yield increases may not be statistically detectable, that does not mean they are not actually occurring.
- A minimum of 20% of the watershed area must be treated with at least 15% overstory removal to achieve augmented streamflows.
- Creation and enlargement of openings is key. Uniform thinnings are discouraged.

- Generally, 18-20 inches of annual precipitation are required to produce additional runoff through vegetation manipulation. The Upper Lake Mary watershed has historically exceeded this threshold.

ECOLOGICAL RESTORATION

- Ecological restoration treatments in ponderosa pine are designed to return forest structure, function, and composition to historic reference conditions, including the re-establishment of a frequent, low-severity fire regime.
- These treatments can counteract the temporal streamflow declines normally associated with thinning treatments, and can maintain and renew streamflow response.
- Uncertainty exists with regard to the effects of restoration treatments on snowpack spatial arrangement, distribution, and water content. Since up to 97% of streamflow in Arizona watersheds can be accounted for by melting snow, this indicates the need for further study in this area.

METHODS

- A forest inventory was conducted in the watershed to determine current and presettlement forest structure.
- The inventory area was stratified using logical combinations of Terrestrial Ecosystems Survey (TES) map units. This stratification system incorporates (1) soil physical and chemical properties, (2) climatic considerations, (3) topographic positions and slope, (4) vegetative, anthropogenic, and zootic influences, (5) productive and successional potentials, and (6) area geology.
- Water yields were calculated using the Baker-Kovner streamflow regression model developed from hydrologic studies in the Beaver Creek experimental watersheds.
- Soil erosion and sedimentation modeling was performed using information from the TES and previous studies.
- Water yields, erosion, and sedimentation were modeled for four management scenarios: (1) no action, (2) thinning 25% of basal area, (3) thinning 50% of basal area, and (4) ecological restoration. In addition, sedimentation and erosion were modeled for a severe wildfire.
- Additional effects of severe wildfire were assessed using GIS data and current literature.

RESULTS

- All inventory strata except Strata 1 and 3 are outside the historic range of variability for density and canopy cover as expressed by presettlement reference conditions.
- Inventory Strata 4 and 6 exhibit high potential for stand-replacing crown fires. Stratum 4 is of special concern, since these areas channel surface runoff from the watershed into Upper Lake Mary.
- Strata 6 and 8 have high densities of both live and dead standing trees.
- Water yields have decreased by as much as 29% since about 1870.
- If best management practices are observed, only the severe wildfire scenario will result in significant erosion and sedimentation.

- Other effects of severe wildfire include (1) reduced infiltration and increased erosion due to water repellent layers in the soil, (2) increases in dry ravel, slope failures, and debris torrents, (3) increases in peak flows that can result in destructive floods, and (4) decreases in water quality due to sediment, fire-retardant chemicals, heavy metals, and nitrate contamination.

CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

- No treatments are recommended for Strata 1 and 3.
- Treatment priority should be given to Strata 4, focusing on the slopes of the drainages that carry runoff into Upper Lake Mary. These treatments will provide reduced risk of catastrophic wildfire, watershed protection, and have good potential for increased water yields.
- Stratum 8 and the areas of 15-40% slope in Stratum 6 should be treated next, with attention given to removal of dead standing trees, restoration of aspen stands, and elimination of encroaching white fir.
- Enlargement of openings is recommended as a treatment strategy for Strata 2, 5, and 7. These areas compose 70% of the watershed area and offer good results in terms of water yield augmentation and fire protection.
- Ecological restoration treatments designed to mimic presettlement forest conditions can return surface water flows to presettlement levels, and can maintain and renew streamflow response to treatment.
- All thinning treatments offer protection from severe wildfires and increases in surface flows, with the greatest benefits from restoration treatments.
- Prescribed fire treatments should occur approximately every 5 years in order to maintain streamflow response.

INTRODUCTION

In the arid landscapes of the southwestern United States, water is perhaps the scarcest and most valuable resource. John Wesley Powell became convinced of water's vital importance to the region during his exploration of the West in 1869, and reported as much to Congress upon his return (Reisner 1993). Powell foresaw the need for reliable supplies of water in the Southwest for agricultural purposes and to slake the thirst of an ever-expanding populace; his predictions are proving to hold true now more than ever. The western U.S. is currently the fastest-growing region in the country, with Arizona and Nevada leading the nation in population growth rates (Bernstein 2006). Counties and municipal governments in the region are seeing their already meager water supplies taxed to the limit and are responding by re-evaluating their water and development policies. Often they are forced to search for additional sources of water to meet increasing demand, as in the case of the communities of the Verde River in north-central Arizona (Davis 2007).

The city of Flagstaff, Arizona is currently facing this very dilemma, which has been exacerbated in recent years by drought and by conditions in the surrounding forest. Flagstaff's population increased by 21.2% between 1990 and 2006 (USCB 2007). At the same time, the city has seen decreasing surface flows into Upper Lake Mary, its sole reservoir, even in years with similar precipitation amounts; the lake is currently at 13.7% of its capacity (Jack Rathjen, City of Flagstaff Water Production Manager, personal communication, 2007). This suggests that the reduced flow into the lake could be due to increasing overstory vegetation resulting from anthropogenic activities. Flagstaff's reservoir is located within the broader Lake Mary watershed, which also contains Lower Lake Mary, approximately 10 miles southeast of town. The watershed lies within the boundaries of the Coconino National Forest. In 1941, the city obtained a lease from the Coconino N.F. and constructed a dam, creating the reservoir called Upper Lake Mary (Blee 1988). The dam height was increased in 1951, which caused the reservoir capacity to double. Upper Lake Mary has historically provided on average over 40% of Flagstaff's drinking water, with the remainder from wells and springs (CFUD 2006). In addition to its importance as a vital water supply for the city, the Lake Mary area receives heavy recreational use at the lake itself, and within the watershed that provides surface runoff into the lake (Desta and Tecle 2004, personal observation). Of note is the fact that this watershed also provides valuable habitat for wildlife, especially migratory birds of prey and waterfowl. It is subject to seasonal closures for this reason (CNF 2007).

Like other northern Arizona ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests, the Upper Lake Mary watershed has undergone dramatic changes in forest structure since settlement by Europeans, which began about 1870. Large, old ponderosa pines have been removed, while saplings, seedlings, and poles have multiplied, often forming dense doghair thickets of small-diameter trees (Covington and Moore 1994). These changes, which are attributed to livestock grazing, logging, and suppression of natural wildfires, have noticeable impacts, such as reduced tree vigor, forage quality and quantity, nutrient availability, and overall forest health (Covington and Moore 1992, Covington et al. 1997, Allen et al. 2002). Other effects are increased tree densities, variability of vertical structure, fuel loads, risk of catastrophic wildfires, and susceptibility to insect and disease outbreaks (Cooper 1960, Covington and Moore 1992, Swetnam et al. 1999, Allen et al. 2002, Covington and Moore 1994, Covington et al. 1997). The Lake Mary watershed, like much of northern Arizona, is rated as having above normal fire potential for this fire season (SWCC 2007). In the absence of dramatic alterations in forest conditions or precipitation patterns, this rating is unlikely to change in the near future. The watershed exhibits high risk of crown fires along the canyons and drainages that collect and direct runoff into Lake Mary (Sisk et al. 2004). Changes in forest structure, density, and composition such as those described above are associated with alteration of watershed hydrological processes. Evapotranspiration and interception of precipitation are increased, while infiltration, soil moisture, and surface runoff are decreased (Bosch and Hewlett 1982, Covington et al. 1997, Stanley and Arp 2002, MacDonald and Stednick 2003). Wildfire that is outside the historic (natural) range of variability affects watershed processes to an even greater degree. Effects can include increases in dry ravel (downhill movement of soil caused by gravity), surface runoff, peak flows, and sedimentation of channels and basins; and reductions in infiltration due to hydrophobic soil layers, slope failures, and debris torrents in stream channels (Ice et al. 2004, Leao 2005). Such a disturbance could severely damage watershed function in Upper Lake Mary, and perhaps render it compromised or useless as a drinking water source for Flagstaff for a number of years.

Objectives

The specific objectives of this project are to determine, to the extent possible, (1) the presettlement and current forest conditions and structure in the Upper Lake Mary watershed, (2) the current and presettlement surface water flows, and (3) the effects of four forest management alternatives on surface flows, sedimentation, erosion, and risk of catastrophic wildfire. The study methods are chosen to provide Flagstaff and the Coconino National Forest with management options in a form that is directly useable to begin the NEPA process that must be completed before treatment can begin.

These methods provide the best available estimate when historic data on forest conditions and surface flows are not available. The following three sections (Forests and Water Yield, Snowpack, and Ecological Restoration) contain a discussion of the major principles and assumptions upon which this report is based.

Forests and Water Yield

In this report, the terms water yield, surface flow, surface runoff, and streamflow are synonymous and refer to "water that derives from precipitation and flows directly off the land surface or through subsurface paths to streams, and to some extent, to ground water aquifers" (Hibbert 1979, p. 7). Peak flows are the highest volumes and rates of flow that occur in a watershed or channel, and low flows, or base flows, are flows for perennial streams that continuously occur from groundwater discharge (Viessman and Lewis 2003)

Since paired catchment (watershed) studies were begun in earnest by the Swiss in 1890 there has been much interest in, and disagreement about, the effects of forest cover on watershed hydrology, particularly with respect to streamflow response to manipulation of overstory vegetation. Many studies have tackled this issue, and many comprehensive reviews of the topic are now available. It is generally agreed that the removal of forest overstory vegetation results in increases in surface flows, peak flows, and low flows (Rich and Thompson 1974, Ffolliott and Thorud 1974, Gary 1975, Leaf 1975, Hibbert 1979, Bosch and Hewlett 1982, Baker 1986, Austin 1999, Stanley and Arp 2002, MacDonald and Stednick 2003, Leao 2005). Increases in low flows are significantly less in terms of overall percentage of pre-treatment flows than increases in peak flows, but account for most of the water yield increase due to timber harvest (Austin 1999, Chang 2003). The main point of disagreement with respect to vegetation manipulation and water yield augmentation is the magnitude of the increase. For pine and eucalypt forest types, Bosch and Hewlett (1982) estimated a 1.57 inch (40 mm) increase in water yield for every 10 percent reduction in forest cover. Many studies included in this review were from areas of the United States and the world that receive substantially more precipitation than the Southwest. Water yields from treatments in northern Arizona should realistically be expected to be somewhat less. Better estimates can be made using results from experimental watersheds in northern Arizona, such as those at Beaver Creek. An analysis of the results from six such watersheds as reported by Baker (1986) shows that the average initial streamflow increase in these paired ponderosa pine catchments was .40 inches (10.16 mm) per 10% overstory removal, which includes the three watersheds treated with strip cuts. Note that this mean was calculated using results from both treatment types applied to these watersheds: “reduction of the forest overstory and creation of cleared openings” (Baker 1986, p. 68), which together describe the general nature of ecological restoration treatments; these treatments are explained in more detail in a following section.

Several factors contribute to the difficulty in detecting water yield increases with forest vegetation removal. Paired catchment studies provide the most significant results, but they are few and far between, and are difficult and expensive to locate and design. In addition, uncertainty in streamflow measurement in natural channels (as opposed to small research catchments) is probably about 10% (Macdonald and Stednick 2003). It must be said, however, that statistical significance of results and actual flow increases might in fact be two very different things. Ziemer (1986) opines that applying average runoff increase values obtained from small watersheds to larger areas overestimates potential water yield. Stanley and Arp (2002) summarize several studies that seem to support this idea, and show no statistically significant increase in water yield even with fairly substantial decreases in forest vegetation. However, MacDonald and Stednick (2003, p. 20) present a convincing argument:

> "These limitations in detecting change do not mean that changes in runoff won't occur in larger basins, or that there is no opportunity to alter runoff through forest management. Changes in runoff will occur with changes in the forest canopy, and a small percentage change imposed on a large area can equate to a large amount of water in absolute terms. The difficulty is that we cannot expect to measure these changes, so the effect of changes in forest management on runoff at larger scales will usually have to be quantified through hydrologic models, and presumed to be present even though the changes may not be statistically detectable at existing gauging stations."

Stanley and Arp (2002) present, in addition to the findings of no water yield increase with forest cover reduction mentioned above, an even greater number of study summaries with results that support the idea that decreases in forest cover result in increases in water yield, and the vast majority of reviews and experiments that have been conducted in this field agrees (Rich and Thompson 1974, Ffolliott and Thorud 1974, Gary 1975, Leaf 1975, Hibbert 1979, Bosch and Hewlett 1982, Baker 1986, Stanley and Arp 2002, MacDonald and Stednick 2003, Leao 2005). An important point is that, in general, a minimum of 20% of the watershed area must be treated with 15% removal of the overstory for significant streamflow increases to occur (Bosch and Hewlett 1982, Stanley and Arp 2002, MacDonald and Stednick 2003). It is the creation and enlargement of openings that produce additional surface flows; for example, a uniform thinning must be applied to 50% of a given area before streamflow increases are observed (Hibbert 1979).

The water budget continuity equation represents the hydrologic theory underlying most common methods of streamflow estimation and models the inputs and outputs of the hydrologic cycle (Chang 2003, Viessman and Lewis 2003). A water budget, or water balance, for a particular area can be quantified by a simplified form of this equation, which is the basis for all hydrologic modeling (Viessman and Lewis 2003):

$$P - R - ET - G = \Delta S$$

Where:

P = Precipitation

R = Surface runoff

ET = Evapotranspiration

G = Groundwater Flow

ΔS = Change in storage (water stored in soil and underground)

Water balances for a given watershed are usually accounted for on a yearly basis. Rearranged and ignoring change in storage, since there is little change in soil moisture and groundwater in adjacent years in forested areas (MacDonald and Stednick 2003), the equation becomes:

$$R = P - ET - G$$

Any decrease in evapotranspiration therefore results in increased runoff. Overstory removal results in increased surface flow in the Southwest and in many other parts of the world due in large part to the corresponding reduction in evapotranspiration (Hibbert 1979, Baker 1986, Bosch and Hewlett 1982, Stanley and Arp 2002). If evaporation and transpiration are considered separately, runoff will increase because there are fewer trees to transpire water, provided there is no simultaneous increase in evaporation from soil and other surfaces (MacDonald and Stednick 2003). The amount of water that actually evaporates and is transpired (actual evapotranspiration) from plant surfaces is usually less than the potential evapotranspiration for a geographic area; the limiting factor is soil moisture (Stanley and Arp 2002, Haque 2003). Generally, potential evapotranspiration is inversely related to precipitation, due to lower amounts of energy available for evaporation at higher elevations, higher latitudes, and areas with fewer sunny days (Hibbert 1979).

The theoretical annual precipitation threshold for producing additional runoff from forest overstory treatments is 18-20 inches (450-500 mm) (Bosch and Hewlett 1982, MacDonald and Stednick 2003). It is thought that precipitation amounts below this threshold yield little additional water even with very intensive and widespread forest treatments within a watershed. Significant water yield increases through overstory removal can be observed where annual precipitation is greater than 18 inches (450 mm) and annual potential evapotranspiration is greater than 15 inches (380 mm), because these conditions promote plant growth and therefore increased evapotranspiration (Hibbert 1979). It makes sense that removal of vigorously growing plants, especially overstory trees, under these conditions would greatly reduce evapotranspiration and result in increased runoff. It must be said, however, that the precipitation in northern Arizona is highly variable with respect to timing and distribution of both rain and snow, which directly affects streamflow timing and amounts (Baker 1986). One or more late-season winter storms could produce heavy snowfall followed by a warm period or by rain-on-snow events. It is certainly conceivable that these scenarios could produce significant surface flows even in years where annual precipitation amounts are below the 18 inch (450 mm) threshold. In fact, slight increases have been observed in Arizona drainages where mean annual precipitation received is at the lower end of the threshold range, although extensive treatments ranging from 83% removal for the pinyon-juniper type and 100% chemical control for chaparral were required

(Clary et al. 1974, Hibbert 1979, Bosch and Hewlett 1982). Arizona and the Southwest are currently suffering an extended drought, which could result in streamflow deficits larger than any increases that could be obtained through forest management activities. However, offsetting those deficits to some degree with even modest streamflow increases is certainly more desirable than having no counterweight at all. Again, it is important to note that a lack of statistically significant and detectable increases does not mean that increases are not actually occurring. With respect to precipitation, it is also important to note that overstory removal and creation of openings result in "progressively larger increases in annual runoff as precipitation increases" (MacDonald and Stednick 2003, p. 7).

Snowpack

Manipulation of overstory vegetation, in addition to contributing to increased streamflow through reduced evapotranspiration, also influences surface runoff timing and amounts through its effects on the winter snowpack. Winter precipitation is responsible for a majority of the streamflow throughout the Colorado River Basin, with up to 97% of streamflow accounted for by winter precipitation in the Beaver Creek watershed in Arizona (Hibbert 1979, Baker 1986). Studies from the 1970's conducted in Colorado and Arizona indicate that the creation of small patchcut openings 2-8 tree heights in diameter or stripcuts was essential for water yield improvement (Brown et al. 1974, Rich and Thompson 1974, Gary 1975, Leaf 1975, Baker 1986). It was thought that this type of treatment affected the distribution of snow by wind, and that interception of snow by the overstory vegetation, while greatly reduced, did not play a crucial role in augmented streamflows (Gary 1975, Leaf 1975, Hibbert 1979). However, more recent studies have shown that it is in fact the reduction in interception rates by overstory vegetation that affects snow water equivalent and streamflow, and not the accumulation of snow into openings as earlier thought (MacDonald and Stednick 2003). Snow water equivalent, which is the actual amount of water in snowfall and varies spatially and temporally, can account for up to 60% of total evapotranspiration (Stanley and Arp 2002). Wind distribution of snow and spatial arrangement of vegetation, while less influential than once believed, are still important factors in streamflow production. Most results from early studies in this area remain unchallenged, although the size limitation of the created openings to 2-8 tree heights in diameter has been shown to be less important than the overall reduction in interception. Generally, the creation of openings results in increased accumulation of snow in the openings, with a corresponding decrease in the snowpack in adjacent unharvested areas; these changes can last 30 years or longer (Gary 1975, Leaf 1975). The greater snow accumulation in openings results in reduced soil moisture deficit, which carries over from year to year, so that runoff from snowmelt occurs earlier in the season (Rich and Thompson 1974, MacDonald and Stednick 2003). The following year, less water is required for soil moisture recharge and more surface water is available Stednick and Troendle 2004). Snowmelt rates in the created and enlarged openings are faster than in adjacent untreated stands (Gary 1975, Stanley and Arp 2002). When combined with the greater accumulation of snow in the openings, this means that the snowpack under the forest canopy and the snowpack in the openings melt completely at about the same time (Rich and Thompson 1974, Leaf 1975, MacDonald and Stednick 2003).

Reductions in overall evapotranspiration and interception rates and changes in snowpack distribution are the dominant factors with respect to water yield increases from forest treatments. However, the amount and timing of runoff also depends on numerous other factors that influence vegetative cover and snowpack characteristics including slope, aspect, and soil properties; and on factors that directly affect timing and magnitude of surface flows such as hydraulic connectivity with groundwater, watershed shape, and type, timing, and seasonal distribution of precipitation (Ffolliott and Thorud 1974, Gary 1975, Baker 1986, Black 1997, Leao 2005).

Ecological Restoration

Ecological restoration is a broad framework of concepts and treatment methods meant to restore structure, function, and composition in failing or unhealthy ecosystems. Restoration practitioners consider ecosystems holistically, and attempt to find a point in history that is compatible with the evolutionary environment and history in a particular area, and to design treatments that are mutually beneficial to ecosystems and humans alike (Moore et al. 1999, Friederici 2003a, SERI 2004). This historical reference point is assumed to be within the natural or historic range of variability for the area; the term “reference conditions” refers to both the reference point and the range of natural conditions that encompasses it (Fulé et al. 1997, SERI 2004). Applying historical knowledge to ecological problems can be a practical and useful approach, because it can indicate when current conditions are “highly anomalous” (Swetnam et al. 2002), it can serve as a basis for comparison with current conditions, and it can guide management approaches and decisions (Fulé et al. 1997, Moore et al. 1999, Allen et al. 2002, SERI 2004).

The exact replication of presettlement forest structure is not always practical, desirable, nor even possible in many ecosystems and areas within ecosystems, in part because many of the pathways and processes are poorly understood (Moore et al. 1999, Allen et al. 2002). The southwestern ponderosa pine forests are one exception, due to extensive research focused on restoration of this forest type (Allen et al. 2002, Friederici 2003a). This research has resulted in increased understanding of presettlement forest structure, function, and composition and how these have been changed by livestock grazing, fire suppression, and logging practices since the arrival of European settlers beginning in the late 1860's through the beginning of the 20th Century (Cline 1976, Swetnam et al. 1999, Pyne 2001). Dendrochronological and other evidence support findings of frequent surface fires prior to the arrival of Europeans, in the range of 2-20 years (Covington and Moore 1994b, Fulé et al. 1997, Moore et al. 1999, Swetnam et al. 1999). Large, high-intensity, high-severity fires were infrequent to rare; suppression of the natural fire regime, coupled with unsustainable land-use practices, resulted in the loss of most of the old ponderosa pines and the development of thick, dense stands of small-diameter trees (Covington and Moore 1994a, Fulé et al. 1997, Covington et al. 1997, Swetnam et al. 1999). These dense pole stands and doghair thickets are strewn across entire landscapes, are prone to catastrophic, stand-replacing crown fires outside the natural range of variability, and have replaced the small groups of trees and large grassy openings that used to characterize southwestern ponderosa pine forests (Cooper 1960, Covington and Moore 1994a, Covington and Moore 1994b, Covington et al. 1997, Fulé et al. 1997, Moore et al. 1999, Allen et al. 2002). As noted in the introduction, there are a myriad of other detrimental effects on ecosystem health and processes that have resulted from these structural changes. A primary goal of ecological restoration is to reverse these effects. Ecological restoration treatments in ponderosa pine and other Southwestern ecosystems historically adapted to frequent, low-severity wildfires have been shown to have numerous positive effects. Removal of forest overstory and restoration of open, park-like stands have resulted in decreased risk of catastrophic fire and improved understory abundance and diversity, soil nutrient availability, individual tree vigor and radial growth rates, and overall forest health (Covington et al. 1997, Feeney et al. 1998, Stone et al. 1999, Korb and

Springer 2003, Friederici 2003b, Selmants et al. 2003, Zimmerman 2003, Fulé et al. 2005, Skov et al. 2005).

Reference conditions based on presettlement evidence in the ponderosa pine forest type are useful because these forests experienced ecological changes on an unprecedented scale following settlement (Covington and Moore 1994a, Covington et al. 1997, Swetnam et al. 1999, Moore et al. 1999, Allen et al. 2002). The physical evidence of presettlement forest structure currently exists in the forest today in the form of stumps, logs, and old-growth trees (Fulé et al. 1997). Earlier evidence has been erased by the surface fires that once swept through on a frequent basis, so "structure at the time of settlement is the latest and best estimate of forest structure consistent with the evolutionary environment for a particular site" (Moore et al. 1999, p. 1270). Allen et al. (2002) recommend using "local", site-specific reference conditions in order to determine the natural range of variability for proper development of restoration prescriptions. The use of presettlement wood to determine forest structure reference conditions is a widely-accepted method that is very site-specific and leads to localized ecological restoration prescriptions. Site-specificity in restoration design is important because of the high variability in structure of both current and presettlement forests. Moore et al. (1999) discuss structural and compositional variability and the need to account for them when planning restoration activities. They note as an example of this variability that presettlement ponderosa pines typically grew much denser on coarse-textured versus fine-textured soils.

The changes in overstory density that have occurred over the last century have altered total evapotranspiration and other hydrologic processes. Effects in watersheds that have become dense with trees include decreases in streamflows, peak flows, and base flows (Covington et al. 1997, Allen et al. 2002). Wildfires outside the natural range of variability resulting from forest structure changes can cause increased erosion, floods, downstream deposition of sediment and debris, and the development of impermeable soil layers (hydrophobicity) (Campbell et al. 1977, Huffman et al. 2001, Allen et al. 2002, Gottfried et al. 2003, Ice et al. 2004). Ecological restoration treatments can help to reverse these effects, and can counteract the temporal nature of forest treatments on hydrologic processes, particularly streamflow, which are known to decline with time following treatment due to vegetative regrowth (Baker 1986, MacDonald and Stednick 2003). Not only will restoration treatments improve streamflow by reducing evapotranspiration and increasing snowmelt rates, they will maintain this response through the re-introduction of frequent, low-intensity surface fires. This fire regime will prevent the regrowth of understory species, particularly Gambel oak (*Quercus gambelii* Nutt.), that would interfere with the streamflow response and cause the increased water yields to disappear after 7-10 years in the absence of fire (Baker 1986). Although it is assumed that ecological restoration in Southwestern ponderosa pine would affect the snowpack in such a manner as to positively influence streamflow, the effects of the creation of relatively large openings (70-80% of a given area) on snow accumulation and distribution by wind are unknown and merit further study.

Forest overstory removal results in increased streamflows due to direct effects on evapotranspiration, interception, and snow accumulation and distribution. When implemented as part of ecological restoration treatments, forest thinnings can help to reverse the structural, functional, and compositional changes that have occurred in southwestern ponderosa pine and mixed conifer stands since European settlement. The City of Flagstaff and the Coconino National Forest could potentially realize these benefits in the Upper Lake Mary watershed if a minimum of 20% of the watershed area is treated.

METHODS

Study Area

The Upper Lake Mary watershed is located approximately 10 miles (16.1 km) south of Flagstaff (Figure 1). The northern boundary extends along the top of Anderson Mesa, which is across Lake Mary Road from the lake itself. The southern boundary is a line running roughly from Coulter Hill southeast to Mormon Mountain (Figure 2). As delineated by the Coconino National Forest, the Upper Lake Mary watershed contains 34,044 acres (13,777.6 ha). Upper Lake Mary lies within a graben, which is a valley formed by a down-dropped block of rock bounded by normal faults, or horsts (Blee 1988, Press and Siever 1994). The two normal faults parallel the lake along its length within several hundred feet of its shores. The Anderson Mesa fault, which is north of the lake, is displaced approximately 250 ft. (76.2 m) above the Lake Mary graben. The Lake Mary fault, which is south of the lake, is displaced about 100 ft. (30.5 m) (Blee 1988, Desta and Tecle 2004). The lake-capacity is 15,620 acre-feet with a surface area of 876 acres (345.5 ha) and an elevation of 6828.5 ft. (2081.3m) at lake-full stage. Upper Lake Mary has relatively high seepage and evaporation losses, due to an arid, low-humidity climate and fractured bedrock in the fault zones (Blee 1988).

The dominant overstory vegetation in the watershed is ponderosa pine interspersed with numerous clumps of Gambel oak and some areas with quaking aspen (*Populus tremuloides* Michx.). Gambel oak is located throughout the watershed, occurring at all but the very highest elevations. Quaking aspen and mixed conifer stands occur at generally higher elevations in the southern part of the watershed, primarily on and near Mormon Mountain. Mixed conifer species in the watershed include white fir (*Abies concolor* (Gord. and Glend.) Hildebr.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Rocky Mountain maple (*Acer glabrum*), ponderosa

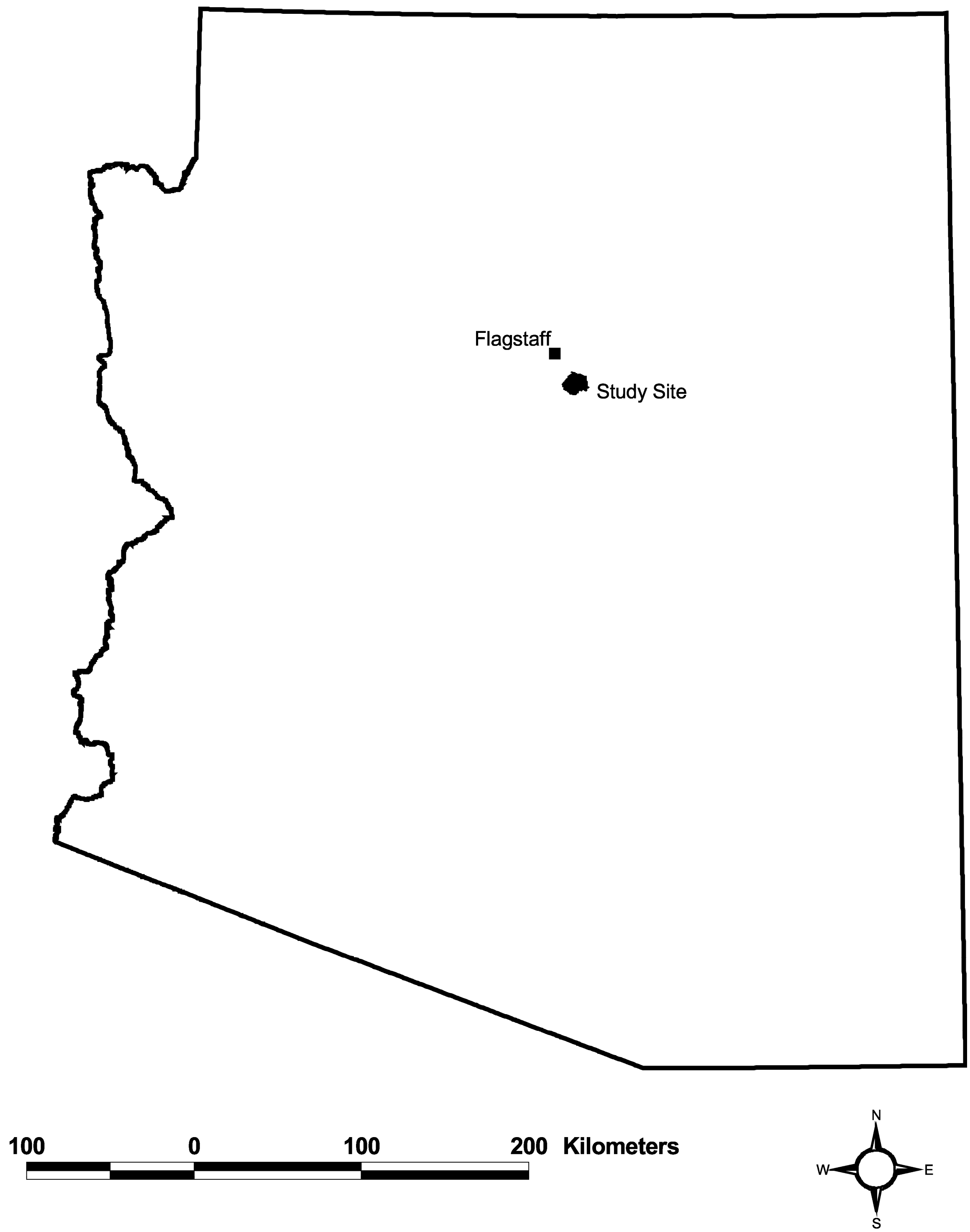


Figure 1. Map showing location of the Upper Lake Mary watershed study site and proximity to Flagstaff.

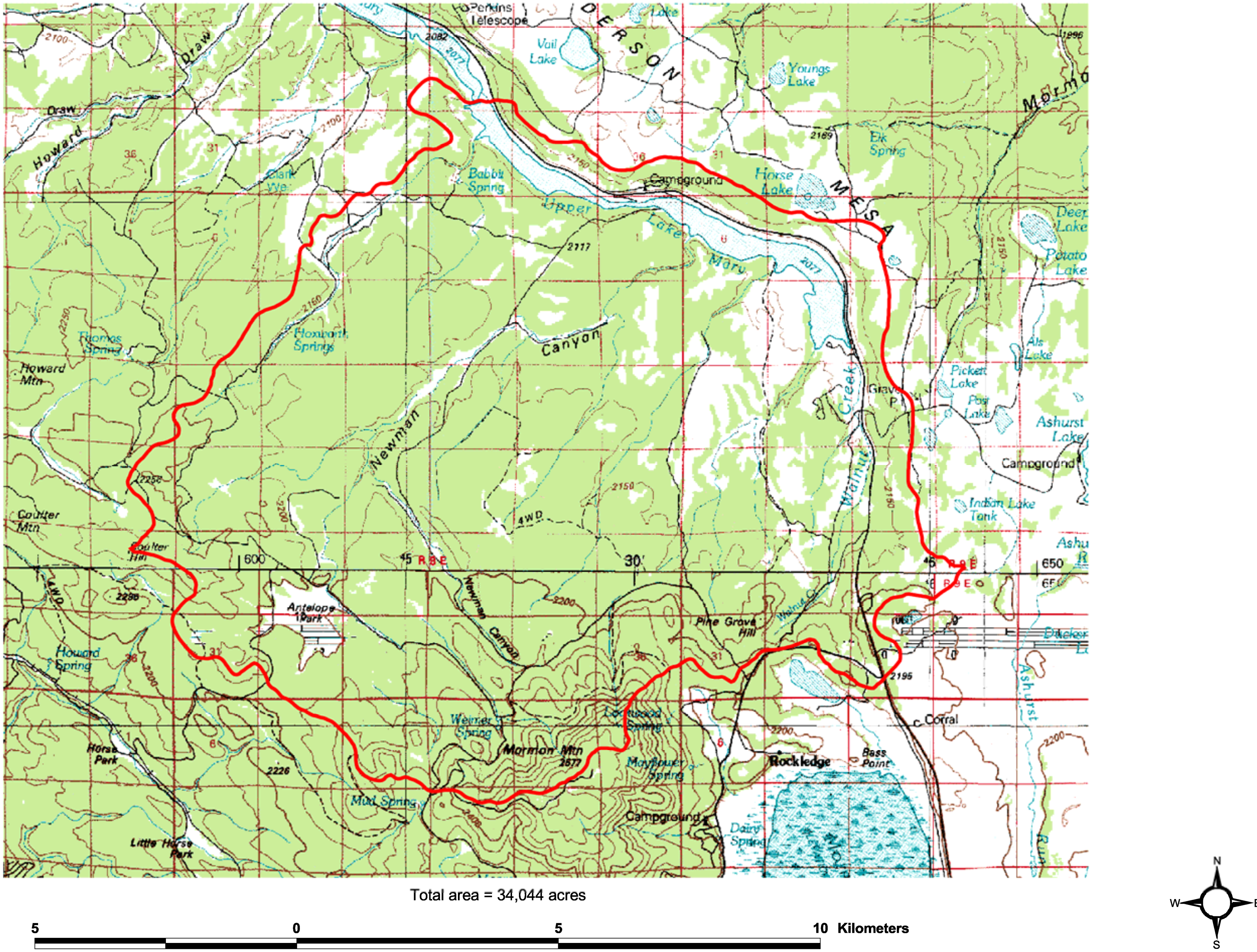


Figure 2. Topographic map of Upper Lake Mary watershed.

pine, Gambel oak, and quaking aspen. Ground cover consists primarily of native bunch-grasses, although exotic, invasive species are present to a limited extent. Annual precipitation in the Upper Lake Mary watershed ranges from 20 - 32 inches annually, with a winter precipitation range of 14.5 – 23.3 inches (OCS 1997, PRISM 1997, NRCS 2007). Surface runoff into Upper Lake Mary is intermittent and usually occurs during spring snowmelt or during rain-on-snow events; there are no perennial streams in the watershed (Blee 1988). Inflow to the reservoir results from precipitation that falls onto the lake surface, runoff from the slopes of the two normal faults, and runoff funneled into the lake by a series of drainages, the largest of which is Newman Canyon (Desta and Tecle 2004, Figure 3). Montmorillonitic soils with a clayey-skeletal or fine texture comprise 94% of the watershed area (TES 1995). Soils with this texture, particle size, and mineralogy have a sizable clay component and tend to swell rather than infiltrate runoff. These soils belong to hydrologic soil group D, which has the lowest infiltration rates and highest surface runoff potential of the four hydrologic soil groups (Mockus 1972, TES 1995).

Knowledge of historical timber harvest records can aid in the determination of presettlement forest structure. Although records of timber volumes extracted are incomplete, the Coconino National Forest Supervisor's Office Timber Sale Atlas contains records of late 19th and early 20th century harvests in the Upper Lake Mary watershed. This information was analyzed using photographs of the atlas maps (Table 1). Figure 4 shows an example of one of these photographs with selected features highlighted. Due to its proximity to Flagstaff and railroad lines, as well as topographic accessibility, the area was subject to heavy logging characterized by extensive high-grading between the late 19th and early 20th centuries (Cline 1976, Mike Manthei, Timber Staff, Coconino National Forest, personal communication, 2007). Numerous railroad spurs were

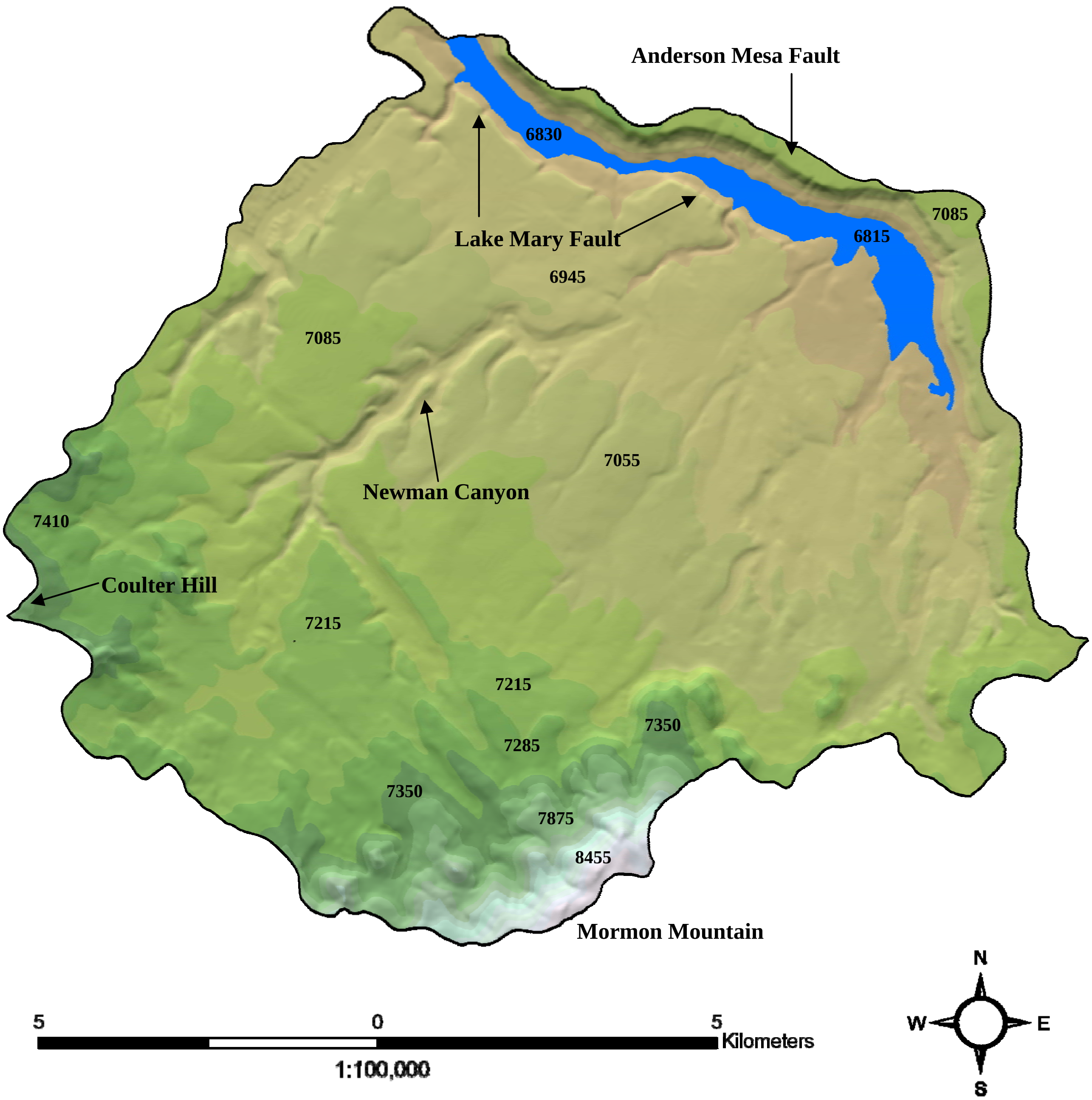


Figure 3. Painted relief map of the Upper Lake Mary study area showing major topographic features and elevations (feet).

Table 1. Results of analysis of historic timber harvests by section in the Upper Lake Mary watershed.

Township	Section	Percent of Section in Watershed	Acres of Section in Watershed	Percent Harvested	Acres in Watershed Harvested	Year(s) Harvested	Reason If Not 100% Harvested	Remarks
T.18N R.8E	1	25.0	160.0	0.0	0.0	N/A	Inaccessible (slope)	
	2	92.0	588.8	25.0	147.2	1920	Inaccessible (slope)	
	3	100.0	640.0	70.8	453.3	1916, 1920, 1924	Inaccessible (slope)	
	4	81.3	520.5	100.0	520.5	1916	N/A	
	5	13.0	83.2	100.0	83.2	1915-1916	N/A	
	10	8.3	53.3	0.0	0.0	N/A	Inaccessible (slope)	
	11	3.2	20.2	0.0	0.0	N/A	Inaccessible (slope)	
T.19N R.7E	24	38.0	243.2	100.0	243.2	1913	N/A	Railroad spurs indicate logging on pvt. land (Coulters Ranch)
	25	13.0	83.2	100.0	83.2	1913, 1914, 1915, 1934, 1944	N/A	
T. 19N R.8E	1	100.0	640.0	70.0	448.0	1919	Lake	
	2	100.0	640.0	81.5	521.6	1919	Lake, park, timber too sparse	
	3	100.0	640.0	100.0	640.0	Prior to 1903	N/A	Not cut under U.S. Forest Service regulations
	4	99.0	633.6	75.0	475.2	Prior to 1903, 1922	Timber too sparse	NW4: Not cut under U.S. Forest Service regulations
	5	35.4	226.8	100.0	226.8	Prior to 1903	N/A	Not cut under U.S. Forest Service regulations
	7	13.2	84.5	100.0	84.5	Prior to 1903	N/A	Not cut under U.S. Forest Service regulations
	8	79.3	507.5	87.5	444.1	Prior to 1903, 1914	Unclear	Portions not cut under U.S. Forest Service regulations
	9	100.0	640.0	100.0	640.0	Prior to 1903	N/A	Not cut under U.S. Forest Service regulations
	10	100.0	640.0	95.0	608.0	1919, 1922	Park	
	11	100.0	640.0	90.0	576.0	1919, 1922	Park	
	12	100.0	640.0	77.5	496.0	1919	Parks, timber too sparse	
	13	100.0	640.0	45.0	288.0	1921, 1923	Parks, timber too sparse	
	14	100.0	640.0	100.0	640.0	1919	N/A	
	15	100.0	640.0	90.0	576.0	1919	Park	
	16	100.0	640.0	90.0	576.0	1914, 1919	Park	
	17	100.0	640.0	100.0	640.0	Prior to 1903	N/A	Not cut under U.S. Forest Service regulations
	18	80.4	514.8	100.0	514.8	1913, 1914	N/A	
	19	100.0	640.0	100.0	640.0	1912, 1913, 1914-1915	N/A	
	20	100.0	640.0	100.0	640.0	1914-1916	N/A	

Table 1 (cont.). Results of analysis of historic timber harvests by section in the Upper Lake Mary watershed.

Township	Section	Percent of Section in Watershed	Acres of Section in Watershed	Percent Harvested	Acres in Watershed Harvested	Year(s) Harvested	Reason If Not 100% Harvested	Remarks
T. 19N R.8E (cont.)	21	100.0	640.0	100.0	640.0	1916, 1920	N/A	
	22	100.0	640.0	95.0	608.0	1920, 1921	Park	
	23	100.0	640.0	90.0	576.0	1919. 1921	Park	
	24	100.0	640.0	68.8	440.0	1921, 1922	Timber too sparse	
	25	100.0	640.0	100.0	640.0	1921, 1922	N/A	
	26	100.0	640.0	100.0	640.0	1921	N/A	
	27	100.0	640.0	100.0	640.0	1920, 1921	N/A	
	28	100.0	640.0	100.0	640.0	1916, 1920	N/A	
	29	100.0	640.0	70.0	448.0	1914-1916	Park	
	30	91.0	582.4	100.0	582.4	1915	N/A	
	31	54.3	347.5	100.0	347.5	1915-1916	N/A	
	32	96.0	614.4	70.0	430.1	1915-1916	N/A	
	33	100.0	640.0	95.0	608.0	1916	Park	
	34	100.0	640.0	100.0	640.0	1916, 1920, 1921	N/A	
	35	100.0	640.0	100.0	640.0	1921	N/A	
	36	87.0	556.7	100.0	556.7	1921, 1922, 1923	N/A	
T. 19N R.9E	4	27.1	173.4	0.0	0.0	N/A	Parks, woodland	
	5	79.4	508.2	10.0	50.8	1922	Lake, parks, woodland	
	6	100.0	640.0	35.6	227.8	1922	Lake, parks, timber too sparse	Private land or silvicultual plots - not harvested
	7	100.0	640.0	15.2	97.3	1922	Parks, timber too sparse	
	8	100.0	640.0	16.7	106.7	1922, 1923	Lake, parks, timber too sparse	Private land or silvicultual plots - not harvested
	9	43.0	275.2	0.0	0.0	N/A	Parks, woodland, timber too sparse, protected area	
	16	68.0	435.2	27.0	117.5	1923	Parks, timber too sparse, protected area	
	17	100.0	640.0	90.5	579.2	1922	Parks	
	18	100.0	640.0	65.0	416.0	1922	Parks, timber too sparse	
	19	100.0	640.0	90.0	576.0	1922	Parks	
	20	100.0	640.0	94.5	604.8	1922	Parks	
	21	75.0	480.0	70.0	336.0	1922, 1923	Parks, timber too sparse	
	27	10.0	64.0	0.0	0.0	N/A	Parks, timber too sparse, private land	

Table 1 (cont.). Results of analysis of historic timber harvests by section in the Upper Lake Mary watershed.

Township	Section	Percent of Section in Watershed	Acres of Section in Watershed	Percent Harvested	Acres in Watershed Harvested	Year(s) Harvested	Reason If Not 100% Harvested	Remarks
T. 19N R.9E (cont.)	28	84.4	540.2	75.0	405.1	1923	Park, timber too sparse	
	29	100.0	640.0	96.1	615.0	1923	Parks	
	30	100.0	640.0	100.0	640.0	1922, 1923	N/A	
	31	63.0	403.2	100.0	403.2	1922, 1923	N/A	
	32	47.5	304.0	100.0	304.0	1923	N/A	
	33	34.0	217.6	33.3	72.5	1923	Parks, timber too sparse	
T.20N R.8E	27	21.0	134.1	70.0	93.9	1900	Lake, parks	Not cut under U.S. Forest Service regulations
	28	7.3	46.7	0.0	0.0	N/A	Protected area	
	33	17.2	110.1	100.0	110.1	Prior to 1903	N/A	Not cut under U.S. Forest Service regulations
	34	92.0	588.8	47.6	280.3	1901, 1903	Lake, parks, protected areas	
	35	73.1	468.1	25.0	117.0	1903	Lake, parks, timber too sparse	Not cut under U.S. Forest Service regulations
	36	40.0	256.0	0.0	0.0	N/A	Parks, timber too sparse	
T.20N R.9E	31	24.0	153.6	0.0	0.0	N/A	Park, timber too sparse	
Percentage of Total Acres Harvested	**77.7**	**Total Acres in Watershed**	**34018.9**	**Total Acres Harvested**	**26435.4**			

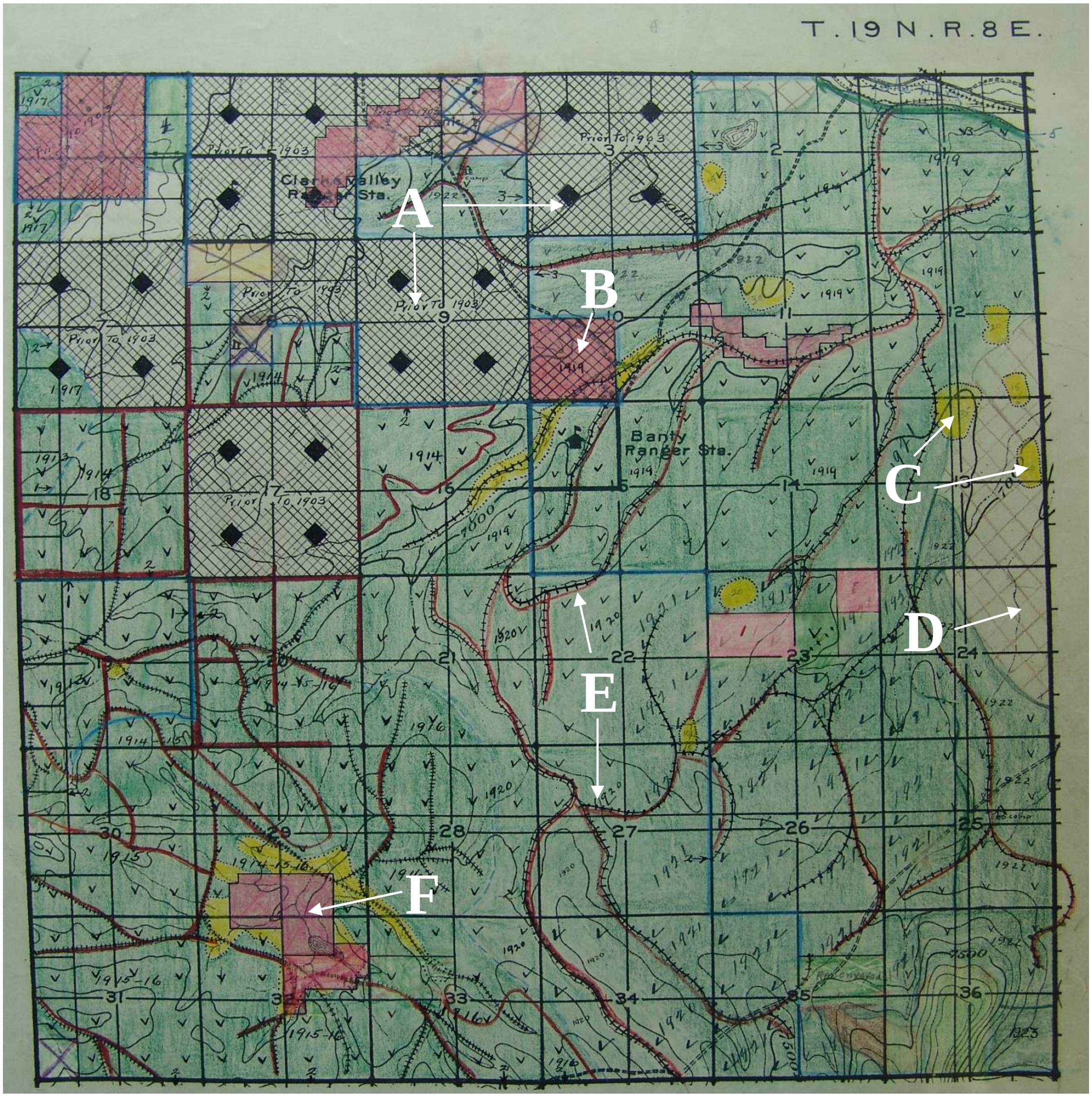


Figure 4. Timber sale map from Coconino National Forest Supervisor's Office Timber Atlas.

A. Areas with this cross-hatched symbol were harvested prior to 1903, and were typically clear-cut of all mature timber with no seed trees left.
B. Experimental silvicultural plots.
C. Parks and meadows.
D. Mature timber, too scattered to harvest.
E. Railroad spurs constructed to remove timber.
F. Private, university, or other alienated timber lands.

constructed into the watershed, which facilitated widespread logging activity (Figure 4). Remnants of these spurs are still present in many areas (Figure 5). Intense logging operations occurred between 1900 and 1924, with limited timber sales continuing through the early 1940's. There have been no timber sales in the watershed since then, and few large-scale management activities, inventories, or silvicultural or other data collected and / or archived. Planimetric analysis of the timber atlas maps reveals that 77.7%, or 26,435.4 acres (10,698 ha), of the Upper Lake Mary watershed was harvested between 1900 and 1924. 3,152 acres, or 9.3% of the watershed area, were cut prior to the establishment of the U.S. Forest Service, and were clearcut of all mature timber with no seed trees left. The remaining areas were high-graded, meaning that nearly all merchantable timber was removed without regard for regeneration or how harvesting scheme might weaken the local gene pool by removing the healthiest, most vigorous trees (Mike Manthei, Timber Staff, Coconino National Forest, personal communication, 2007). These harvesting activities, combined with suppression of natural wildfires, have resulted in conditions that are similar to conditions in numerous other stands of ponderosa pine on northern Arizona. Overstory density has increased dramatically, shifting from old and large trees to numerous younger, smaller, suppressed trees. However, the Upper Lake Mary watershed still contains many openings, parks, and meadows, and the doghair thickets and degree of canopy closure do not appear quite as extensive as in some other areas of the Coconino National Forest. In addition, the watershed contains many young Gambel oak clumps, with up to 30% of the canopy cover by oak in some areas. Timber harvests of the type that occurred in the Upper Lake Mary watershed impact forest regeneration and successional trajectories following disturbances. Fulé et al. (1997) described conditions similar to those found currently in the watershed, and hypothesized that heavy logging eliminated seed sources and prevented the establishment of

Figure 5. Remnants of early 1900's era railroad spurs used to harvest timber in the Upper Lake Mary watershed.

seedlings even during good seed years. This could be one reason why there are so many oak stems in the Lake Mary area (Fulé et al. 1997, Figure 6).

Forest Inventory

A forest inventory was conducted in order to determine, to the extent possible, current and presettlement forest densities. The inventory was conducted using a two-stage list sampling design. This method is appropriate for large areas when it is not possible to collect data in every stand, and it is preferred over collecting data at a few points in all stands (Shiver and Borders 1996). The inventory area was stratified using Terrestrial Ecosystems Survey (TES) map unit combinations. Randomly located 10-acre (4.05 ha) blocks were allocated to each inventory stratum according to the percentage of the watershed within that unit. The field crew sampled 3,4, or 5 points within each block depending on the total number of points to be sampled within a particular stratum. A total of 338 points were sampled in 81 randomly located blocks. Point samples of basal area and percent cover were taken at each point, and presettlement evidence counts were recorded within a 1/10th acre (0.04 ha) plot at each sample point. In each plot, the number of stumps, stump holes, snags, logs, and live presettlement trees was recorded. A tally was made only if a determination could be made that the base of the presettlement tree, either live or dead, was or used to be within the plot. Stump holes were counted only if an adjacent stump was not present. Live trees were tallied if core samples showed the tree was alive in 1870. For trees that were not cored, diameter at breast height (dbh) measurements of greater than 24 inches (610 mm) for ponderosa pine and 30 inches (762 mm) for white fir or Douglas-fir were considered to indicate live presettlement trees. The 24-inch threshold for ponderosa pine was determined from 52 core samples taken in the field on all strata except Strata 1 and 3. This is an

Figure 6. Clumps of Gambel oak (*Quercus gambelii*) are abundant in the Upper Lake Mary watershed.

acceptable method to tally live presettlement trees in a specific area when it is not possible to core all yellow pines within the 1/10th acre plots (Charlie Denton, Coordinator, Ecological Restoration Institute, Northern Arizona University, personal communication, 2007). Of the 52 core samples, eight were of presettlement age but less than 24 inches. There were no post-settlement trees greater than 24 inches (610 mm) among the core samples, so this threshold was determined to be valid. The 30-inch (762 mm) threshold for live presettlement white-fir and Douglas-fir was similarly determined from 30 core samples taken in the field. I estimated fuel loading from coarse woody debris for the area around each sample point (USDA-FS 1997). I also estimated the relative abundance of ground cover species in the 1/10th acre plot and in the surrounding area. Photographs were taken facing north and south from each plot center (point).

TES Map Units and Combinations

The Terrestrial Ecosystems Survey consists of a systematic assessment, classification, and mapping of terrestrial ecosystems found in Region 3 (USDA Forest Service Southwestern Region) (USDA – FS 1991, TES 1995). It is an integrated survey and hierarchical with respects to classification levels and mapping intensities. A terrestrial ecosystem represents the combined influences of climate, soil, and vegetation; the TES correlates these factors with soil temperature and moisture and categorizes them along an environmental gradient (USDA-FS 1991). Indicator plants have been determined for specific climatic regimes, and timing and amount of precipitation are also assessed and used to differentiate the gradients. Interpretations based upon TES incorporate (1) soil physical and chemical properties, (2) climatic considerations, (3) topographic positions and slope, (4) vegetative, anthropogenic, and zootic influences, (5) productive and successional potentials, and (6) geology (TES 1995, USDA-FS 1991). The

Terrestrial Ecosystems Survey therefore forms the initial ecological basis for other types of surveys such as this forest inventory. Initial assessment of the 18 map units present in the Upper Lake Mary watershed indicated that many of the map units had similar characteristics and properties that would cause them to respond similarly to disturbances (fire) or management activities (thinning or restoration). In order to simplify the analysis, like map units were grouped into logical combinations (Table 2, Figure 7).

Water Yield Calculations

Water yield estimates were calculated using the Baker-Kovner streamflow regression model. This model was developed from observations made in 12 of the experimental watersheds at Beaver Creek (Brown 1974), which is located approximately 20 miles (32 km) south of the Upper Lake Mary watershed. An initial model used precipitation, insolation (solar radiation, expressed as a decimal fraction), trees per acre, basal area, soil, and geology as parameters. Since not all variables were independent, the regression was later modified. It was determined that of all the variables considered, winter precipitation (October – April), potential insolation, timber density as described by basal area, and the interactions between these parameters correlated best with annual streamflow (R2 = 0.69). The regression equation is of the form:

$$S = -5.72 + 0.83P + 0.42R - 0.24RP^{0.92} - 0.007P^{2}\,[1 - \exp - (B/45)]^{3}$$

Where:

S = Annual streamflow in inches

P = Winter precipitation in inches

R = Insolation expressed as a decimal fraction

B = Basal area in ft^2/acre

Table 2. Terrestrial Ecosystems Survey map unit combinations used as basis for forest inventory stratification. Logical combinations were created based on similarity of vegetation, soil chemical and physical properties, and other ecological characteristics.

Stratum	TES Units Combined	Area (acres)	Basis for Combination
1	50,53,55	1386.23	Units have similar TES classification and are found within similar landscape positions (valley plains and basins)
2	523	682	Moderately deep, medium to fine-textured soils found on elevated plains, 0-15% slope, within PIPO-PJ units
3	515	476.9	Pushed (chained) area associated with high sun cold climate, found on elevated plains, 0-15% slope
4	524, 537, 565, 584	5606.71	Shallow to moderately deep, medium to fine-textured soils found on 15-40% slopes within PIPO-PJ and PIPO-QUGA units
5	536, 557, 582, 586	12819.55	Moderately deep to deep, fine-textured soils found on elevated plains, 0-15% slope, within PIPO-QUGA and PIPO-FEAR units
6	575, 613, 654	1611.1	Shallow to moderately deep, medium- to fine-textured soils on 15-80% slopes within mixed conifer units
7	585	10017.43	Shallow to moderately deep, fine-textured soils found elevated plains, 0-15% slope, within PIPO-QUGA units
8	653	425.01	Moderately deep to deep, fine-textured soils, 0-15% slope, within mixed conifer units

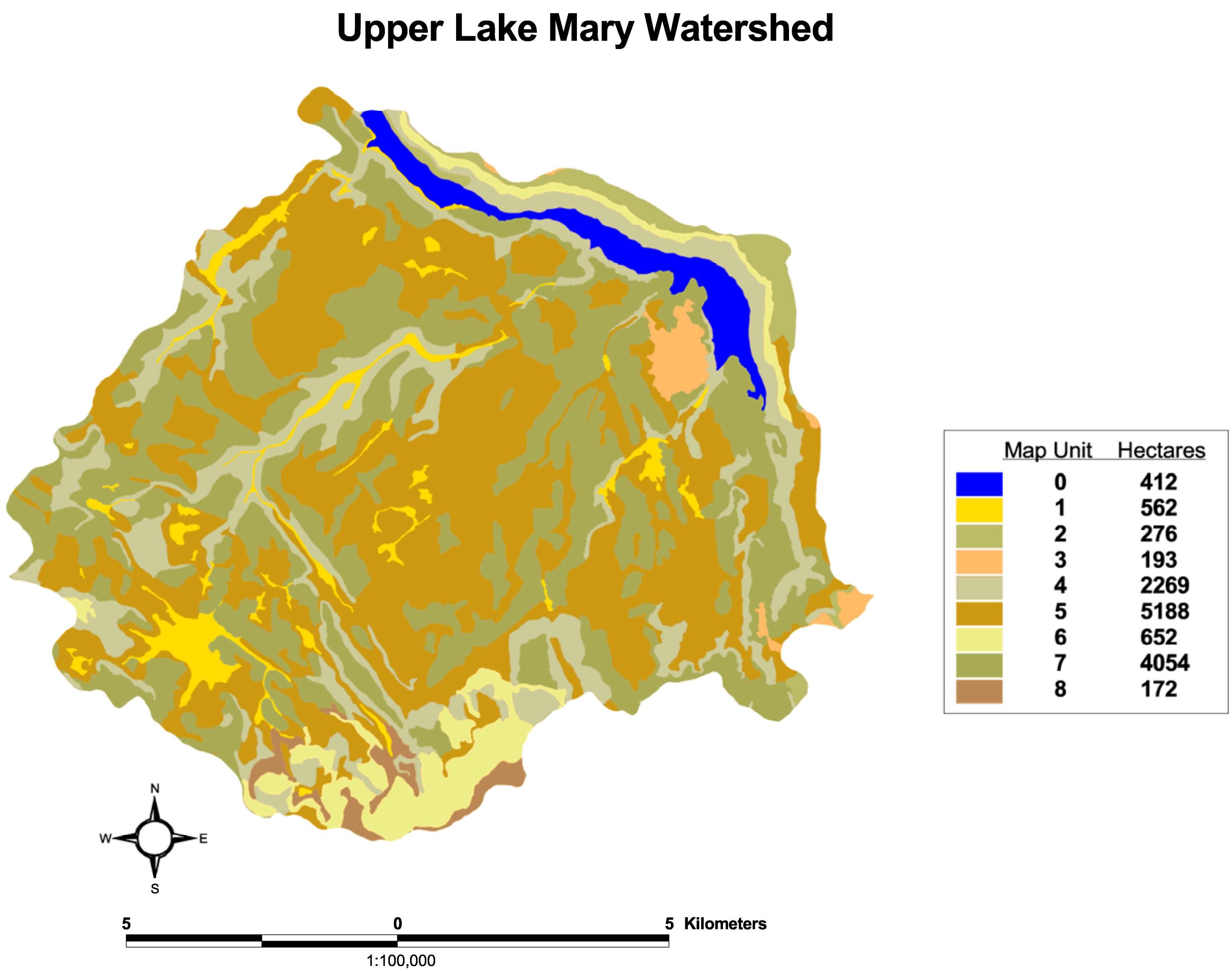


Figure 7. Map of the Upper Lake Mary watershed showing TES map unit combinations.

Insolation was indexed at 0.7 for all water yield estimates in this analysis, which is the estimated average potential insolation for Beaver Creek and for most of northern Arizona's ponderosa pine forests (Brown 1974, Dave Brewer, Program Coordinator, Ecological Restoration Institute, Northern Arizona University, personal communication, 2007). Average annual precipitation and winter precipitation values were determined for each map unit combination and for the entire watershed using an online GIS precipitation tool provided by Oregon State University's PRISM Group (OCS 1997, PRISM 1997). Annual and winter precipitation values were calculated according to the percentage of the watershed in each precipitation class in order to assess the accuracy of the estimation methods. Precipitation class midpoints were used to prepare estimates. Winter precipitation values were quantified by month, then weighted by the total area in each precipitation class.

Basal area for four management alternatives was calculated for each map unit from the inventory results. The management alternatives were selected to provide a range of options and for comparison of water yield results. The first alternative is no action, or leaving the watershed forest in its current condition. Thinning of the forest overstory to 75% of current basal area (25% thin) and 50% of current basal area (50% thin) are the second and third alternatives. The fourth option is ecological restoration, which includes re-introduction of the natural fire regime. Ecological restoration treatments are based on presettlement evidence, so the percentage of basal area removed for each stratum differs. Restoration basal area is assumed to be the same as presettlement basal area, which was estimated for each stratum using inventory results and results from previous studies at Camp Navajo west of Flagstaff, Mt. Trumbull on the Arizona Strip north of the Grand Canyon, and from various permanent plots in the Coconino National

Forest (Fulé et al. 1997, Waltz et al. 2004, Moore et al. 2004). Diameter distributions from these studies were standardized and averaged in 4-inch (101.6 mm) classes[1]. The resulting average diameter distribution was then applied to the number of presettlement trees per acre measured for each stratum. I calculated individual tree basal area for the midpoint of each diameter class, multiplied this figure by the number of trees in that class, then summed the resulting basal areas for each diameter class for each map unit combination. Current basal area and presettlement trees per acre measurements and presettlement basal area calculations were compared to the results from previous studies; all values were within the ranges presented therein (Covington and Moore 1994a, Covington et al. 1997, Fulé et al. 1997, Waltz et al. 2004, Moore et al. 2004). Water yields were calculated and compared for each map unit combination using the Baker-Kovner streamflow regression model. Although developed for ponderosa pine, it was assumed this model would also be acceptable for the mixed conifer type. The Baker-Kovner streamflow regression should underestimate water yields in mixed conifer stands, since these stands receive more precipitation and produce greater water yields per acre than ponderosa pine (Rich and Thompson 1974, Ffolliott and Thorud 1974, Leaf 1975, Hibbert 1979). I compared surface flows for current conditions (no action) and each of the 3 remaining action alternatives. Presettlement and restored basal areas were considered to be the same for purposes of comparison.

Sedimentation and Erosion Modeling

Current, potential, and tolerance soil losses in each stratum were determined based on current

---

[1]Diameter distributions for Moore et al. (2004) prepared by Charlie Denton, Ecological Restoration Institute, Northern Arizona University.

ground cover conditions as described in the TES. Weighted averages for each soil loss were calculated according to the percentage of total stratum area occupied by each original TES map unit and the percentage of total watershed area occupied by each inventory stratum. The amount of bare soil in each stratum due directly to erosional and operational effects of the three active management alternatives was estimated using a combination of results from previous studies (Rice et al. 1972, Rich and Thompson 1974, Rice et al. 2004), soil information from the TES, and observations made in the field about the likely sizes and positions of landings, skid trails, and roads. Bare soil values in acres for each stratum and management alternative were multiplied by the potential soil loss tolerance provided in the TES. The remainder of the area for each alternative in each stratum was multiplied by the TES current soil loss tolerance. Erosion and sediment values were averaged over ten years. Annual soil loss in each stratum was determined by adding the potential soil loss values for two years to the current soil loss tolerances for eight years, then dividing by ten to obtain yearly values.

In the modeling of soil erosion and sedimentation the following assumptions were made:

- A 25% thin would expose bare mineral soil on 5% of the area, 50% thin would expose 15%, and ecological restoration 25% (Rice et al. 1972).
- Sediment delivery ratios of (1) 1% under current conditions, (2) 2% for 25% thinning treatments, (3) 3% for 50% thinning treatments, (4) 4% for ecological restoration, and (5) 10% under a wildfire scenario (Greg Kuyumjian, Hydrologist, Santa Fe National Forest personal communication, 2007).
- With respect to wildfire all strata except 1 and 3 are projected to have a high potential for severe overstory removal. The existing basal areas are beyond the historic range of variability with respect to density and canopy closure, and, although there are numerous

large and small openings, continuous stands can still be found throughout the watershed. The only exceptions are a few large upland benches dominated by Strata 5 and 7.

- The projected soil erosion at potential soil loss, tolerance soil loss and current soil loss for a stratum is a weighted average. Therefore the TES map unit that dominates the strata will have the most influence on the overall erosion rate. The increased soil erosion will also be a weighted average and will occur for 2 years after which time it will decrease to current levels (Rice et al. 1972).
- Proper application of best management practices will reduce soil erosion back to pretreatment levels within 2 years. Rice et al. (1972) noted several impacts on erosion including: (1) compared to road construction the logging operation usually results in minor erosion, (2) in the majority of operations most of the area is left undisturbed, (3) seldom is more that 30 percent of the bare soil exposed, and (4) surface erosion that does occur comes from localized areas.
- In the modeling of wildfire, where basal areas are high I project 30 percent will burn hot (all litter and overstory removed), 20 percent moderate (some litter and overstory remaining), and the remaining 50 percent light or none. These assumptions are based on (1) analysis of the inventory data for each stratum, and (2) examination and comparison of topographic, fire risk, density, canopy cover, and strata location maps for the Upper Lake Mary watershed.
- With respect to erosion rate and wildfire, the potential soil loss will relate to a severe fire, tolerance soil loss to a moderate fire, and current soil loss to a light burn. This will run for 2 years and then fall back to pre-burn levels.

- This is a relative index of soil erosion and not an absolute. The further from the TES parameters, the more unlikely the number is correct. For example, if the average slope was found to be 3% within a map unit, the model will not fit as well for areas that are on 10% slope.

Wildfire Risk and Effects

The risk and effects of wildfires outside the historical range of variability in the Upper Lake Mary watershed were assessed using maps created using data from ForestERA (Sisk et al. 2004) that show potential fire behavior, current basal areas, and percent canopy cover. These maps were compared to USGS quadrangle maps to determine potential fire behavior in different areas of the watershed. General effects of severe wildfires on hydrology, particularly in the southwestern United States, that are likely to also occur in the Upper Lake Mary watershed were assessed by reviewing current literature on the topic.

RESULTS AND DISCUSSION

Forest Inventory

The overstory structure sample design (basal area, presettlement evidence) was chosen for maximum efficiency. It does not provide information on contemporary diameter or age distributions, nor does the inventory design account for spatial distribution of presettlement trees. However, basal area is a logical and objective measure of stand density, and it is the basis for many silvicultural prescriptions (Avery and Burkhart 1994). Inventory results by stratum can be found in Tables 3-7. A comparison of strata results from Tables 3, 4, and 5 shows that current

Table 3. Current basal area (BA) means and standard deviations (SD) for inventory strata that did not contain mixed conifer, in the Upper Lake Mary watershed. BA and SD are in ft^2/ac. PIPO=ponderosa pine, QUGA=Gambel oak, Juniper=*Juniperus* species.

Combo #	Original Map Units	Area (acres)	% of total area	PIPO BA Mean	PIPO BA SD	QUGA BA Mean	QUGA BA SD	Juniper BA Mean	Juniper BA SD	Total BA Mean	Total BA SD
1	50,53,55	1386.23	4.20	41.33	75.39	21.33	67.81	0	0	62.67	94.38
2	523	682.00	2.07	104.00	97.43	0.00	0.00	10	19.44	114.00	92.40
3	515	476.90	1.44	6.67	11.55	0.00	0.00	0	0	6.67	11.55
4	524, 537, 565, 584	5606.71	16.98	186.50	80.69	17.00	36.95	0	0	203.50	79.34
5	536, 557, 582, 586	12819.55	38.82	160.46	110.60	13.85	34.49	0	0	174.31	112.37
7	585	10017.43	30.33	141.55	92.07	11.84	24.16	0	0	153.4	98.4

Table 4. Current basal area (BA) means and standard deviations (SD) for inventory strata with mixed conifer in the Upper Lake Mary watershed. BA and SD are in ft^2/ac. PIPO=ponderosa pine, QUGA=Gambel oak, ABCO=white fir, POTR=quaking aspen, PSME=Douglas-fir, ACGL=Rocky Mountain maple.

Combo #	Original Map Units	Area (ac)	% of total area	PIPO BA Mean	PIPO BA SD	QUGA BA Mean	QUGA BA SD	ABCO BA Mean	ABCO BA SD	POTR BA Mean	POTR BA SD	PSME BA Mean	PSME BA SD	ACGL BA Mean	ACGL BA SD	Total BA Mean	Total BA SD
6	575,613,654	1611.10	4.88	62.76	73.24	26.21	36.29	40.69	53.31	0.00	0.00	11.03	35.29	2.07	11.14	142.76	75.35
8	653	425.01	1.29	85	58.31	22.5	32.84	45	75.4	25	47.51	2.5	7.07	0	0	180	94.42

Table 5. Presettlement (Preset) evidence from the Upper Lake Mary watershed by forest inventory stratum. Means and standard deviations (SD) are number per 1/10th acre plot. Historic TPA's and BA's were highest in mixed conifer (Strata 6 and 8). Strata 2 and 4 have undergone dramatic changes in terms of percent increase between presettlement and current basal areas. TPA=trees per acre, BA=basal area (ft^2/acre).

Combo #	Original Map Units	Preset Mean	Preset SD	Preset TPA Dead	Preset TPA Live	Total Preset TPA	Current BA	Preset BA
1	50,53,55	1.80	2.40	18.0	0.0	18.0	62.7	27.9
2	523	0.8	0.92	7.0	1.0 (PIPO)	8.0	114.0	12.6
3	515	0.0	0.0	0.0	0.0	0.0	6.67	0.0
4	524, 537, 565, 584	3.10	1.84	16.7	1.75 (PIPO)	18.4	203.5	28.6
5	536, 557, 582, 586	3.41	2.67	30.6	3.46 (PIPO)	34.1	174.31	52.86
6	575,613,654	3.93	2.62	28.3	3.79 PIPO 5.86 ABCO 1.38 PSME 11.03 Total	39.3	142.8	61.1
7	585	3.1	2.3	27.4	3.3 (PIPO)	30.7	153.4	47.6
8	653	4.9	3.7	46.3	2.5 (PIPO)	48.8	180.0	75.8

Table 6. Means and standard deviations (SD) of coarse woody debris (CWD) and percent canopy cover measurements by stratum (current conditions). Strata 6 and 8 show high levels of CWD and percent canopy cover. Stratum 4 has the highest mean CWD of all ponderosa pine strata, and the highest overall percent canopy cover.

Combo #	**Original Map Units**	**CWD Mean (tons/ac)**	**CWD SD**	**% cover Mean**	**% cover SD**
1	50,53,55	4.00	5.77	25	33.71
2	523	2.05	1.32	37.7	21.64
3	515	0.77	0.46	3.08	4.11
4	524, 537, 565, 584	7.72	4.29	73.00	17.16
5	536, 557, 582, 586	6.96	3.90	59.55	23.31
6	575,613,654	20.59	11.40	71.28	18.19
7	585	6.98	3.89	54.91	22.74
8	653	15.49	6.88	61.28	26.52

Table 7. Basal area (BA) means and standard deviations (SD) of dead standing trees. Both strata are mixed conifer; Stratum 6 occurs on 15-80% slopes and Stratum 8 is found on 0-15% slopes. BA and SD are in ft^2/ac. PIPO=ponderosa pine, QUGA=Gambel oak, ABCO=white fir, POTR=quaking aspen.

Combo #	Original Map Units	PIPO BA Mean	PIPO SD	ABCO BA Mean	ABCO SD	POTR BA Mean	POTR SD	Total BA Mean	Total SD
6	575,613,654	4.83	15.73	9.66	23.68	13.10	35.97	27.59	58.65
8	653	0.00	0.00	0.00	0.00	50.00	86.85	50.00	86.85

basal area is more than double presettlement basal area in all map unit combinations. All strata are outside the range of natural variability as expressed by presettlement reference conditions. Strata 2, 4, 5, 6, 7, and 8 are also outside the range of natural variability for canopy cover. Canopy cover in Arizona's ponderosa pine forests was historically about 20% on similar soils (Covington and Moore 1994a, Covington et al. 1997). Strata 2 and 4 are particularly striking, with basal area increases of 900% and 700%, respectively (Table 5). Stratum 1, which contains parks, grasslands, and meadows, was historically open, with 18 trees per acre and basal area of 27.9 ft^2/acre (6.4 m^2/ha) (Table 5). In the contemporary watershed forest, this stratum has 62.7 ft^2/acre (14.4 m^2/ha), indicating that tree encroachment into meadows has occurred. No presettlement Gambel oak stumps were found in this stratum, or indeed within the entire inventory area. However, oak now accounts for 1/3 of the basal area in Stratum 1 (Table 3). Stratum 4 is at very high risk of catastrophic wildfire. This stratum had similar presettlement overstory density to Stratum 1, but now has a basal area of 203.5 ft^2/acre (46.7 m^2/ ha) and 73% canopy cover, the highest among all strata (Tables 5 and 6). Coarse woody debris is also higher in this map unit combination than in any other ponderosa pine stratum. This stratum, a portion of which occurs on the slopes of the canyons draining the watershed into Upper Lake Mary, historically had the lowest overstory density of the forested ponderosa pine strata, possibly due to increased fire intensity and frequency related to its topographic position. This stratum is located where active crown fires are likely to occur (Figures 7 and 8). If a fire occurs on one or more of the ephemeral drainages feeding Upper Lake Mary, severe reduction in water quality is likely to result. Stratum 3 had the lowest current and presettlement basal areas (Table 5). This stratum was most likely open grassland with scattered large pinyon pine (*Pinus edulis* Engelm.) and juniper (*Juniperus* spp.). The TES categorized it as a chained area, meaning that trees were

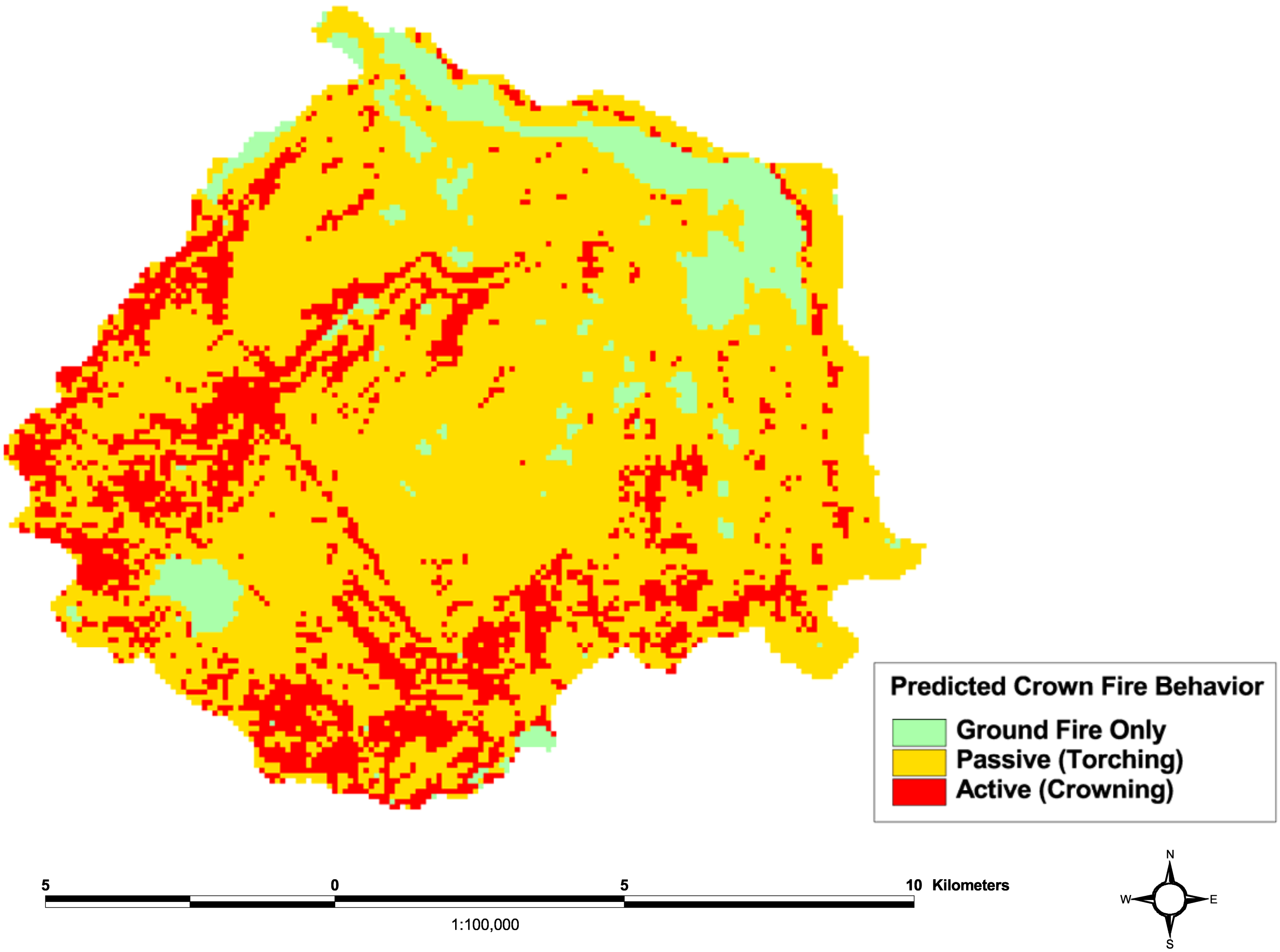


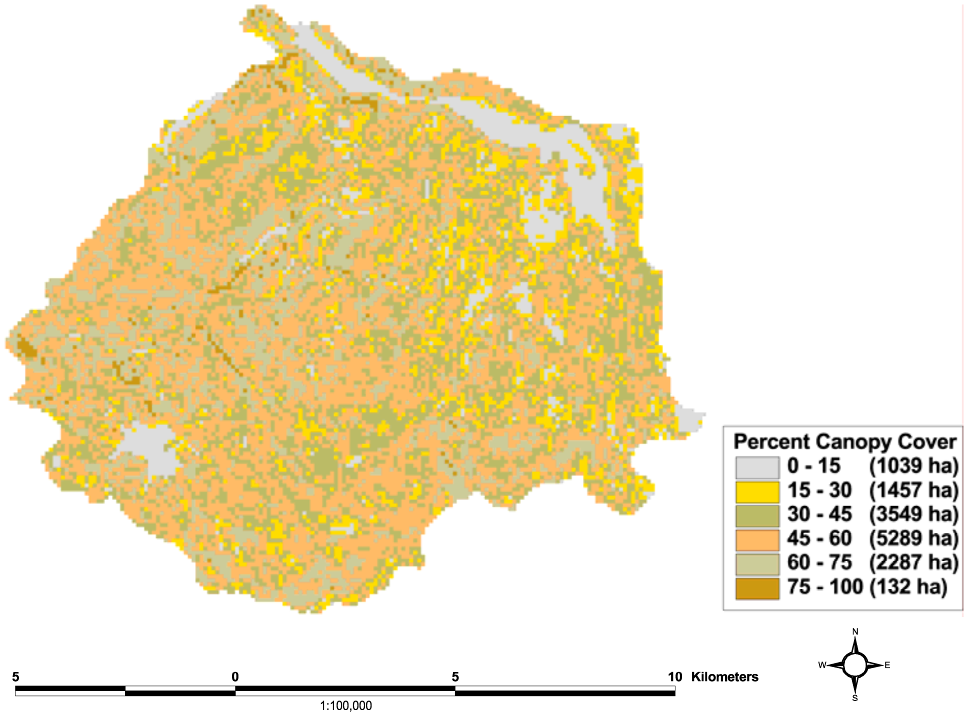
Figure 8. Map of Upper Lake Mary watershed showing predicted crown fire behavior. Note that active crown fire behavior is predicted along the drainages that carry water into Upper Lake Mary. Map prepared from low-resolution (90m or 2 pixels/acre) data provided by ForestERA, Northern Arizona University (Sisk et al. 2004). Active crown fire behavior is predicted on moderately steep to steep slopes and areas with high tree densities. Both conditions are found in the drainages that run from southwest to northeast and direct surface flows into the lake.

pushed or pulled from the ground with bulldozers, pairs of which often ran parallel with a heavy chain between. The purpose was to create livestock forage, although it was of limited benefit in this regard. The mixed conifer strata (6 and 8) show marked differences between current and presettlement basal areas (Table 5). In addition, they were the only strata to have greater than one snag (dead standing tree) per plot (Table 7). Although dead standing trees were not located in every plot in these strata, certain areas within these strata are at high risk for catastrophic wildfire. These areas have extremely high densities of both live and dead standing trees, and most of the strata area shows relatively high levels of coarse woody debris (Figure 9).

Basal area and percent canopy cover maps produced using data from Northern Arizona University's ForestERA laboratory generally agree with these findings, although the data are low resolution (90m or 2 pixels per acre) and tend to underestimate both parameters (Figure 10). In most cases, inventory data standard deviations are high, indicating the data were highly variable. This could be due in part to sampling error introduced in the stratification process, as previously discussed. However, it is my opinion that the steps taken to stratify the watershed for inventory actually reduced sampling error and that the high variability in the data is due to the fact that forest conditions in the watershed are highly variable. This variability in forest structure was observed during inventory data collection within 10-acre (4.1 ha) experimental blocks and often even within the 1/10th acre plots. Strata 5 and 7, which contain most of the watershed area, exhibit this characteristic variability (Figure 11). Although basal areas in each of these two strata are relatively high, canopy cover ranges only between 55 and 60 percent.

Because of high variability in forest structure within relatively small areas, some of the ecological effects of doghair thickets and dense pole stands could be easily observed (Figure 12). When compared with adjacent openings, stands of doghair thickets had much deeper litter and

Figure 9. Dead standing trees, dense forest overstory conditions, high levels of coarse woody debris, and the presence of ladder fuels characterize much of the mixed conifer strata in the Upper Lake Mary watershed.



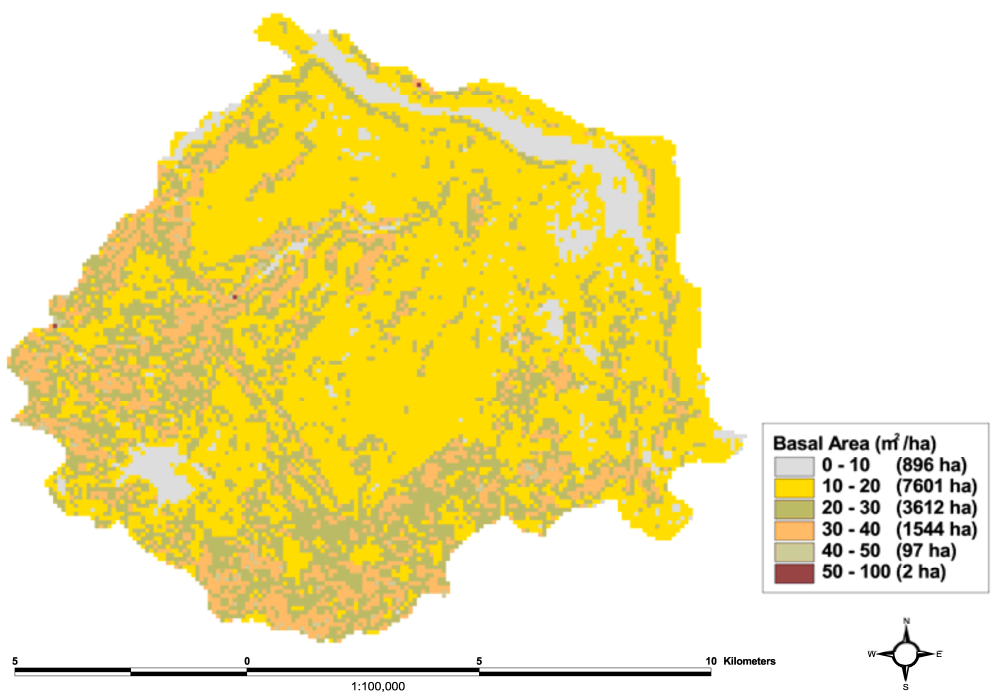


Figure 10. Basal area and percent canopy cover maps of the Upper Lake Mary watershed, created from Forest ERA data (Sisk et al. 2004). These data show that 38% of the watershed has basal areas greater than 87 ft^2/acre (20 m^2/ha), and 18% has canopy cover greater than 60%. The data are low-resolution (90m or 2 pixels/acre) and forest inventory results indicate that they tend to underestimate both basal area and percent cover. The maps show that basal areas and canopy cover are highest in the drainages that carry water into Upper Lake Mary and in the areas of higher elevation in the southern portions of the watershed. These results are consistent with inventory findings.

Figure 11. Overstory structure in the Upper Lake Mary watershed is highly variable. Despite the presence of doghair thickets and dense pole stands that have formed since European settlement, numerous openings still exist.

Figure 12. Doghair thickets and dense pole stands in the Upper Lake Mary watershed contain suppressed trees and have high degrees of canopy closure. Herbage production in these stands is very low.

duff on the forest floor. This fact, combined with low levels of light penetration, undoubtedly contributes to the marked declines in herbage production observed within thickets. Trees within thickets were mostly suppressed and often snow-bent, and thickets contained most of the coarse woody debris less than 20 inches (508 mm) in diameter that was observed in the watershed. Forest floor fuels of this size burn faster than similar amounts of larger fuels, contain less moisture, and can carry wildfires quicker and farther. Native grasses are abundant in the watershed, except within doghair thickets. The presence of exotic invasive species and forest pathogens was judged to be minimal and confined to a few areas. Quaking aspen decline was observed in Stratum 8 (Figure 13). Aspen stands are being replaced by ponderosa pine, with a white fir understory. White fir encroachment is heavy within Strata 6 and 8, and is present to a more limited extent in Strata 2, 5, and 7.

TES Map Units and Combinations

The use of TES map units as forest inventory strata is a method that provides numerous advantages over traditional forest stratification techniques based on overstory vegetative characteristics alone. The map units can be used to plan and evaluate land management activities based on the limitations and potentials of ecosystem components (TES 1995). It is reasonable to assume that vegetation will be similar within map units because they are classified according to ecological factors that affect things like vegetation type, structure, and density. The map unit combinations used as the basis for forest inventory stratification in this study were delineated based on similar ecological conditions and gradients. I considered these ecological classifications when creating the combinations; TES map units were combined based on vegetation characteristics, slope, production capability, erosion potential, and soil classification.

Figure 13. Aspen decline in inventory Stratum 8 in the Upper Lake Mary watershed. All aspen in these two photographs are dead, and there is very little regeneration.

Soil erosion and sedimentation modeling was performed using TES information and inventory results for the different map unit combinations or strata.

Although forest inventory stratification based on TES map units or map unit combinations can provide more information than stratification based on vegetative characteristics alone, there are certain limitations. This stratification system could introduce sampling error, because stands sampled are not representative of other stands within that map unit or combination (Shiver and Borders 1996). However, I felt that with such a large number of original TES map units, combining units that were similar with respect to slope, vegetative characteristics, and soil physical properties would reduce the overall number of samples required without introducing significant error. Clary et al. (1966), in a study conducted in the Beaver Creek Watershed, determined that if two or more soil types are arranged in a pattern related to the shape of the land surface and the nature of the soil materials that the standard error of herbage production and timber site index can be reduced. This study reported that the standard error for herbage production and timber site index declined by 43 percent and 30 percent, respectively. However, the authors did make note that the reduction in standard error for the area depends on the distribution or weighting of the strata. If one or two strata dominate, which was the case in this study, then the actual reduction in standard error will be less than obtained in the sample.

Changes in Water Yield

Average winter precipitation weighted by percent of total area within each precipitation class for the entire Upper Lake Mary watershed was estimated at 26.14 inches (664 mm). Average winter precipitation weighted by percent of total area within each stratum was estimated at 25.93 inches (658.6 mm). Further estimates based on strata results were therefore assumed to be valid.

The watershed receives 18.9 inches (480.1 mm), or 72.9%, of its precipitation in the winter months (Table 8). This is contrasted with the Beaver Creek experimental watersheds, which receive 67.5% of total precipitation in the winter months. The model used to calculate water yields was developed from Beaver Creek data, which illustrates one limitation of this analysis.

Figure 14 shows, for each stratum, water yield changes at average winter precipitation resulting from the four management alternatives. Current basal area is low in Stratum 1 and reflects tree encroachment into parks and meadows. Stratum 3 has very little current basal area. Water yields in strata 1 and 3 would therefore be little changed following treatment. Strata 2, 4, 5, 6, 7, and 8 offer the best opportunities for water yield increases through vegetation management. Increases in water yield at average winter precipitation range from 3%-6.6% for 25% reduction in basal area, 10.5%-19% for 50% reduction, and 17%-28.9% for ecological restoration. Figure 15 shows water yield changes that would occur following treatment for a range of winter precipitation values. As precipitation and thinning intensity increase, water yield increases resulting from treatments become progressively larger. Acre-feet of surface flows resulting from treatments for each stratum are found in Figure 16. Ecological restoration treatments yield the best results in terms of increased water yield across all map unit combinations, except Strata 3, where minimal increases are predicted for all management alternatives. Vegetative regrowth following the 25% and 50% thinning treatments will reduce streamflow response over time and cause it to return to pre-treatment levels within about 10 years (Baker 1986). Re-introduction of the natural fire regime as a component of restoration treatments will prevent such rapid regrowth of the understory and extend streamflow response, possibly indefinitely.

Although it was not modeled or quantified for this report, groundwater recharge will most likely occur from forest treatments. Upper Lake Mary lies in a fault zone of fractured bedrock and is subject to seepage losses. Hydraulic connectivity between the surface waters of the lake and the underlying aquifer probably exists, as evidenced by water quality tests conducted by the City of Flagstaff. Test results show that surface water from the lake and water from one of the city's wells in the Lake Mary Well-field are virtually indistinguishable from one another (Ron Doba, Utilities Director, City of Flagstaff, personal communication, 2007).

Sedimentation and Erosion Modeling

The Upper Lake Mary watershed, like the Beaver Creek study conducted by Clary et al. (1966), is dominated by a few strata. Strata 4, 5, and 7 are comprised of nine TES map units and represent 28,445 acres or 86 percent of the watershed. If individual TES map units are assessed roughly 26,660 acres or 80 percent of the study area is accounted for by units 582, 584, 585, and 586. The remaining 20 percent of the watershed is comprised of 14 map units that account for 6,370 acres, though some of the highest potential for significant erosion and sedimentation is found within these units.

Results of erosion and sedimentation modeling are found in Tables 9 and 10. When averaged over ten years, the soil loss tolerance is not exceeded even with the highest value attained in the wildfire scenario. Although not in the tables, the modeling shows that for both ecological restoration and wildfire the soil loss tolerance will be exceeded in Strata 4 and 6 for at least several years. These strata have the highest potential for declines in water quality from ecological restoration treatments or from wildfire. This indicates that special care in sale administration needs to be taken when treating these moderately steep and steep slopes. It is

Table 8. Average annual and winter precipitation by inventory stratum, Upper Lake Mary watershed. Average precipitation values were weighted by percent of total area in each stratum. Winter precipitation was assumed to be 72.9% of annual precipitation in all areas (see Methods section of text).

Stratum	**Percent of total area**	**Average annual precipitation (inches)**	**Annual precipitation weighted by % of total area (inches/area)**	**Average winter precipitation (inches)**	**Winter precipitation weighted by % of total area (inches/area)**
1	4.20	26	1.09	18.95	0.80
2	2.07	25.5	0.53	18.59	0.38
3	1.44	22	0.32	16.04	0.23
4	16.98	26	4.4	18.95	3.22
5	38.82	25.75	10.0	18.77	7.29
6	4.88	30	1.5	21.87	1.07
7	30.33	25.5	7.7	18.59	5.64
8	1.29	30	0.39	21.87	0.28
	Average precipitation (inches)		**Annual 25.93**		**Winter 18.90**

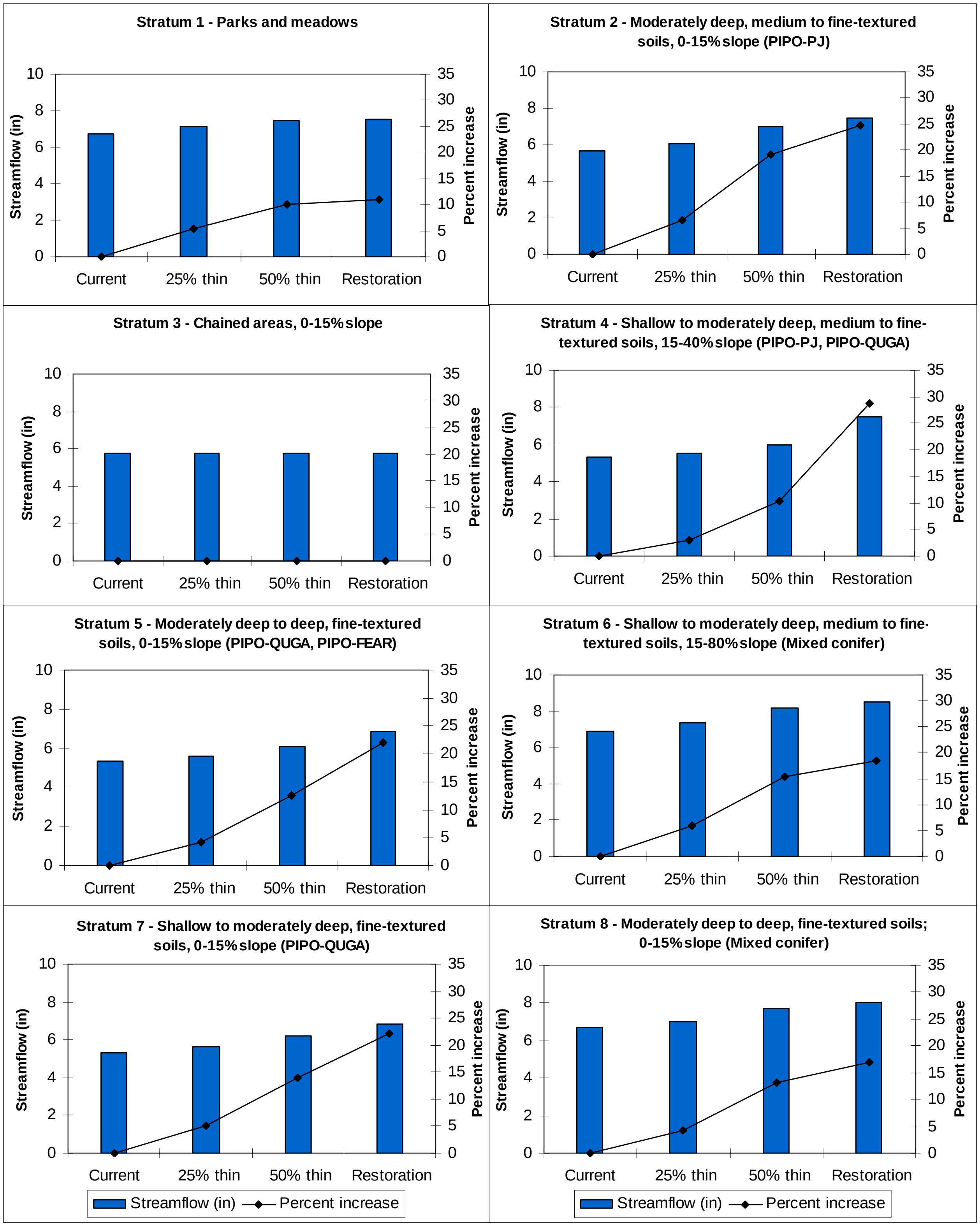


Figure 14. Changes in streamflow at average winter precipitation resulting from four forest management alternatives by inventory strata (TES map unit combinations) in the Upper Lake Mary, Arizona watershed. Water yield increases in Strata 1 and 3 are minimal for all management alternatives. Water yields in the remaining six strata are greater as thinning intensity increases. PIPO – ponderosa pine, PJ – pinyon-juniper, QUGA – Gambel oak, FEAR – Arizona fescue.

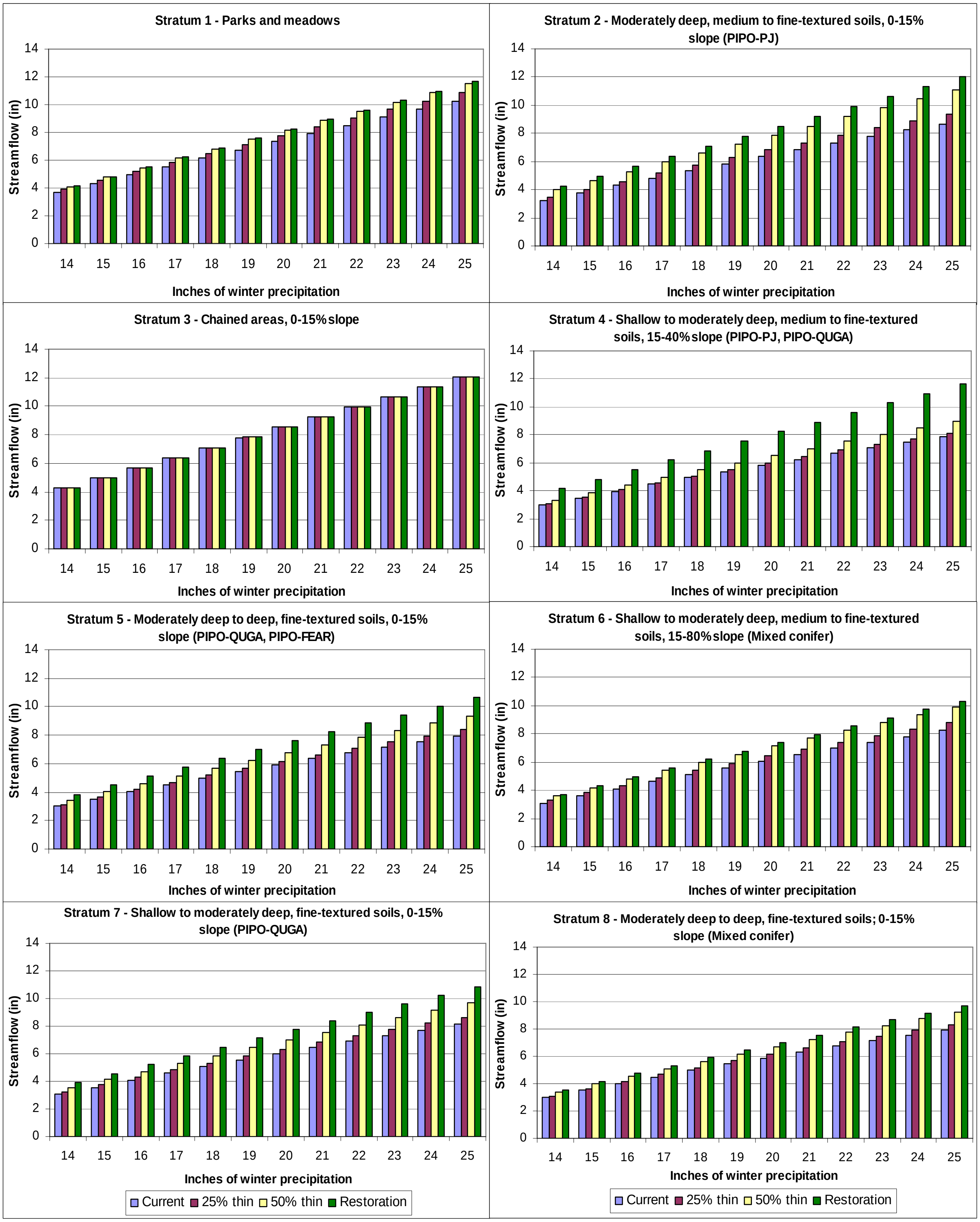


Figure 15. Changes in streamflow for four forest management alternatives and a range of winter precipitation values by inventory strata (TES map unit combinations) in the Upper Lake Mary, Arizona watershed. All strata except Stratum 3 show progressively larger increases in water yield with increasing winter precipitation, although the increases in Stratum 1 are minimal.

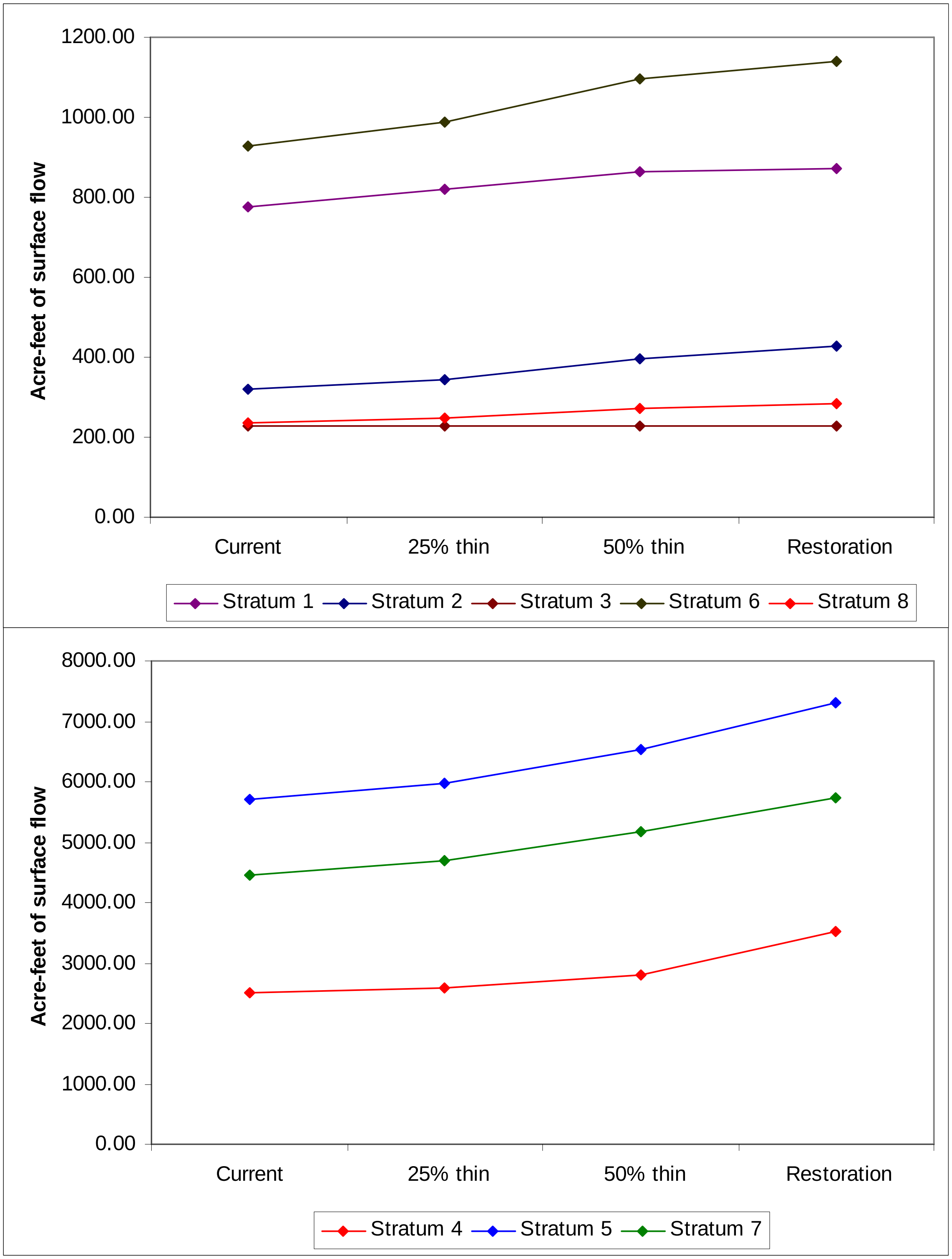


Figure 16. Annual acre-feet of surface flow for each inventory stratum and management scenario in the Upper Lake Mary watershed. Larger values are associated with strata that occupy a greater percentage of the watershed. Greater relative responses to thinning in a particular stratum indicate high current densities and stocking levels.

highly likely that the rate shown for sedimentation after a wildfire would decrease after several years to pretreatment levels, especially on the 0 to 15% slopes. Based on the results found in Tables 9 and 10, it is reasonable to assume a tenfold increase in sediment delivery into Upper Lake Mary following the wildfire scenario described above.

Effects of Wildfire on Hydrology

The effects of wildfire on hydrologic processes depend much more on fire severity, or the amount of fuel consumed and the overall effects of the fire, than on fire intensity, which is a measure of heat release. Burning of volatile organic compounds in vegetation can cause reduced infiltration and water repellency in soils (Ice et al. 2004, DeBano et al. 2005). These effects can last for months or in some cases, for a year or more (Huffman et al. 2001). Increases in surface erosion and dry ravel often occur following wildfires, and slope failures and debris torrents can further degrade hydrologic function (Ice et al. 2004). Severe wildfire in the mixed-conifer vegetation type results in significant increases in sedimentation and erosion, and a single catastrophic wildfire can produce thousands of tons of excess sediment over a period of thousands of years due to the environmental changes it causes (Megahan and King 2004). For severe wildfires in the ponderosa pine type, significant increases in erosion can be expected, as well as an initial spike in streamflow of 30% or more (Brown et al. 1974). In the Stermer Ridge watersheds of central Arizona, peak flows following the Rodeo-Chediski fire were found to be as much as 90 times pre-fire peak flows (Gottfried et al. 2003, Ice et al. 2004). The highest known post-fire peak flow in southwestern ponderosa pine was recorded on the severely burned watershed in 2002; this flow was 2,350 times the size of pre-fire peak flows (Gottfried et al.

2003, Ice et al. 2004). Floods of these magnitudes can be at least as destructive as the severe fire itself. Stream habitat, wildlife and fisheries populations, cultural resources, and human developments can all be severely damaged by flooding following severe wildfires (Neary et al. 2005a). Water quality can also be seriously impacted by a severe wildfire. Increased sedimentation and nitrates and introduction of heavy metals from soils and chemicals used to fight the fire are of primary concern (Neary et al. 2005b). In addition, nutrient cycles can be interrupted or radically changed, with increased concentrations of nitrogen, phosphorous, calcium, magnesium, potassium, and in some cases, phosphorous occurring after severe fires (Ice et al. 2004). Nitrate concentrations from burned foliage can reach contamination levels following catastrophic wildfires, a situation exacerbated by the fact that many fire retardant chemicals contain large amounts of nitrogen (Neary et al. 2005b).

CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

Reductions in forest overstory density in southwestern ponderosa pine and mixed conifer offer numerous benefits in terms of increased streamflows, improvements in forest health, and reduced risk of catastrophic wildfire. In the Upper Lake Mary watershed, all forested areas are outside the historic range of variability for overstory density as expressed by presettlement reference conditions, and all inventory strata except Strata 1 (parks and meadows) are outside the historic range of variability for canopy cover. Changes in water yield, sedimentation, and erosion were modeled in this analysis; one passive and three active forest management alternatives were considered. Water yield improvements were greater with increasing thinning intensity, as was reduction in risk of catastrophic wildfire. The former can be accounted for by a variety of factors, of which reduced evapotranspiration is primary. The latter effect is due

Table 9. Projected erosion in the Upper Lake Mary watershed by inventory stratum for four management alternatives. Values are averaged over ten years. No treatments exceed the soil loss tolerances in this time frame, although ecological restoration treatments and severe wildfire exceed the tolerances in the first few years following treatment in Strata 4 and 6. Stratum 3 (chained areas), which is not recommended for treatment, has very low tree density and it is unlikely that either crown or ground fires will occur in these areas.

Stratum	Area (acres)	Slope (%)	Erosion Hazard	Tolerance Soil Loss (tons/yr)	Current Soil Loss (tons/yr)	25% Thin (tons/yr)	50% Thin (tons/yr)	Restoration (tons/yr)	Severe Wildfire (tons/yr)
1	1,396	0 to 5	Slight	4,972	824	866	898	931	1,000
2	682	0 to 15	Slight	1,849	194	196	204	213	225
3	477	0 to 15	Moderate	425	542	N/A	N/A	N/A	N/A
4	5,607	15 to 40	Severe	15,123	5,069	5,690	6,961	8,231	10,136
5	12,819	0 to 15	Slight	37,826	1,782	1,872	2,141	2,408	2,817
6	1,611	15 to 120	Severe	5,164	1,949	2,236	2,839	3,440	4,342
7	10,017	0 to 15	Slight	18,242	811	844	909	973	1,070
8	425	0 to 15	Moderate	1,153	69	96	136	174	233

Table 10. Projected sediment deliveries in the Upper Lake Mary watershed by inventory stratum for four management alternatives. Values are averaged over ten years. Values for the three active management alternatives are relatively low in all strata. Significant sedimentation from these treatments is not expected, especially if best management practices are followed. Sediment rates for severe wildfire are much higher than current sediment rates and sediment rates for the three active management scenarios. Sedimentation of these magnitudes could impede watershed function, especially if the fire occurs in Stratum 4 and/or Stratum 6.

Stratum	Current Soil Loss (tons/yr)	Projected Sediment Rate (tons/yr)	25% Thin (tons/yr)	Projected Sediment Rate (tons/yr)	50% Thin (tons/yr)	Projected Sediment Rate (tons/yr)	Restoration (tons/yr)	Projected Sediment Rate (tons/yr)	Severe Wildfire (tons/yr)	Projected Sediment Rate (tons/yr)
1	824	8	866	17	898	27	931	37	1,000	100
2	194	2	196	4	204	6	213	9	225	23
3	542	5	N/A	5	N/A	5	N/A	5	N/A	5
4	5,069	51	5,690	114	6,961	209	8,231	329	10,136	1,014
5	1,782	18	1,872	37	2,141	64	2,408	96	2,817	282
6	1,949	20	2,236	45	2,839	85	3,440	138	4,342	434
7	811	8	844	17	909	27	973	39	1,070	107
8	69	1	96	2	136	4	174	7	233	23

mainly to decreased fuel loads, ladder fuels, and degree of canopy closure. If left untreated, wildfire outside the natural range of variability is likely in the watershed. Such an event could greatly reduce water quality in Upper Lake Mary, especially for the first few years following the fire.

Specific findings and recommendations of this analysis include:

- The precipitation threshold for surface water production, generally thought to be 18-20 inches (450-500 mm) annually, is exceeded in all areas of the Upper Lake Mary watershed.
- At least 20% of the watershed must be treated under all active management scenarios in order for streamflow increases to occur.
- Inventory strata 1 (parks and meadows) and 3 (chained areas) show little water yield response to thinning treatments, partly because current basal areas are relatively low in comparison to other strata. Low treatment priority is assigned to Stratum 1. Although restoration of parks and meadows is a desirable forest management activity in terms of process restoration and forest health improvement, this stratum is currently at low risk for wildfires outside the natural range of variability. In addition, water yield increases following forest treatment are minor. No treatments are recommended for Stratum 3. Treatments in this stratum would have little effect on potential for catastrophic wildfire, restoration of structure and processes, or water yield.
- Treatment priority should be given to Stratum 4 (shallow to moderately deep, medium to fine-textured soils, 15-40% slope), focusing on the slopes of the drainages that transport overland surface flows into Upper Lake Mary. This stratum is the farthest from its reference conditions, and offers good potential for water yield increases and fire risk

reduction from thinning treatments. Treatments in this stratum are critical because of high tree density, canopy cover, and forest floor fuel loads. Due to its landscape position, this stratum has the greatest potential to affect water quality in Upper Lake Mary should a severe wildfire occur. Severe wildfire in Stratum 4 would result in erosion exceeding the soil loss tolerance for several years, with projected sediment delivery rates of 2,505 tons per year. Ecological restoration treatments on Stratum 4 would approach the soil loss tolerance. Care must therefore be taken to follow best management practices to minimize erosion and sedimentation caused by harvesting activities. Annual surface flow increases for the three active management options range from approximately 3% to 29%. Total annual surface flow production in Stratum 4 ranges from 2,579 acre-feet for the 25% thin alternative to 3,513 acre-feet following ecological restoration.

- The areas of 15-40% slope within Stratum 6 (shallow to moderately deep, medium to fine-textured soils, 15-80% slope in mixed conifer) should be treated next. High tree densities, canopy cover, and fuel loads (both on the forest floor and in the form of dead standing trees) indicate that this stratum is also at risk for catastrophic wildfire. Such a fire would cause the soil loss tolerance to be exceeded for several years, with projected sediment delivery rates of 1,075 tons per year. Ecological restoration treatments in Stratum 6 would approach the soil loss tolerance, but these effects can be minimized through proper application of best management practices. During harvesting operations, dead standing trees should be removed in addition to live trees in the areas where they are present in order to reduce fire risk. Treatment is not recommended on the portions of Stratum 6 above 40% slope. In order to mitigate spotting during a wildfire, treated areas surrounding untreated steep slopes should be at least 1 mile wide. Yearly water yield increases range from 6% following 25% reduction in basal area to 18.5% for ecological restoration treatments. Total annual surface flow production increases in Stratum 6 would range from 987 acre-feet to 1,139 acre-feet.

- Soil loss tolerance is not exceeded in Strata 2, 5, 7, or 8 for any of the management alternatives, nor is it exceeded in the severe wildfire scenario. This is partly due to the fact that these strata occur on 0-15% slopes. Sediment delivery rates are relatively high for Strata 5 and 7, due to the fact that these are the largest strata in the watershed.
- Treatment is next recommended for Stratum 8 (moderately deep to deep, fine-textured soils, 0-15% slope in mixed conifer) because of high levels of coarse woody debris and dead standing trees, the removal of which will reduce overall fire risk in the watershed. Aspen decline is of concern in this stratum; dead standing aspen and white fir should be cut, as should live ponderosa pine where it is replacing aspen. If possible, fences should be constructed to encourage aspen reproduction and prevent browsing of seedlings. Annual surface flow increases in Stratum 8 range from just over 4% (25% thin) to nearly 17% (restoration). Total yearly water yield increases in this stratum are low because of the limited size of this stratum. They range from 247 acre-feet to 285 acre-feet for the three active management alternatives.
- The remaining strata (2, 5, and 7) occupy 70% of the watershed. These strata offer very good results in terms of both water yield increases and reduction of fire risk, but treatments here are not as crucial for watershed protection as in the other strata with higher treatment priorities. Large openings are included in Stratum 1, but small parks, meadows and other openings also occur in Strata 2, 5, and 7. Restoration of these areas

should be a primary consideration in all treatment areas, as well as removal of white fir encroachment wherever it occurs.

- Of these three remaining strata, Stratum 2 (moderately deep, medium to fine-textured soils, 0-15% slope in ponderosa pine with pinyon-juniper) would provide the largest percentage gains in water yield following forest treatments, but the smallest increases in total water production because of its limited size. Annual percentage increases range from nearly 7% to nearly 25% for the three active management options, with total surface flows ranging from 343 acre-feet to 426 acre-feet.
- Annual water yield increases in Stratum 5 (moderately deep to deep, fine-textured soils, 0-15% slope) range from 4% to 22% for the three active management alternatives. Total annual water production following forest treatments is sizable, since this stratum occupies over 38% of the watershed. These values range from 5,961 acre-feet to 7,318 acre-feet.
- In Stratum 7 (shallow to moderately deep, fine-textured soils, 0-15% slope), modeling of the three thinning scenarios shows that yearly streamflow increases would be between 55 and 22%, while the total yearly surface flow production would be between 4,700 acre-feet and 5,727 acre-feet.
- Encroaching white fir occurs mainly in Strata 6 and 8, although it is not limited to these areas. Primarily seedlings and saplings, these trees should be removed where they are replacing other species in ponderosa pine, aspen, and mixed conifer stands. This will improve forest health, reduce competition, and help to reverse some of the effects of 100 years of wildfire suppression. Since white fir is not fire adapted, and because the encroaching trees from heavy thickets of ladder fuels, removal of them will also reduce fire risk and hazard.

Ecological Restoration and Maintenance of Water Yield Response

Ecological restoration treatments result in the largest decreases in basal area and therefore the greatest increases in surface flows in this analysis. A caveat is that uncertainty exists with respect to the effects of restoration treatments on snowpack and therefore surface flows. While surface flow increases and reduction of fire risk can be achieved to a lesser extent by the 25% thin and 50% thin management alternatives, these options are not self-sustaining in terms of these effects. Vegetative regrowth in the absence of fire in the years following treatments generally limits long-term water yield response in ponderosa pine until eventually, the initial water yield increases are entirely lost (Baker 1986). Ecological restoration can provide sustained water yields and reduced fire risk in addition to the other benefits it offers, such as improved forest health and ecological processes. However, prescribed fire treatments applied in approximately five-year intervals will most likely be necessary to maintain water yield response. Intervals greater than five years could lead to reduction in initial surface flow response following thinning treatments.

The Upper Lake Mary watershed is a prime candidate for restoration treatments. Stands of very dense poles and doghair thickets are not continuous across the landscape, native understory species are abundant, and the presence of exotic species is limited. If thinning activities are planned and located strategically, treatment costs on a per acre basis should be relatively low, especially if activity planning is centered around the numerous large and small forest openings in the watershed. Thinning treatments will restore overstory structure, and restoration of processes and composition should follow with reintroduction of a fire regime within the natural range of variability. In addition, ecological restoration treatments will provide the greatest increases in water yield, and the highest level of protection against catastrophic wildfires of the four management alternatives considered. In their presentation of a broad perspective of restoration in ponderosa pine, Allen et al. (2002) conclude that treatments should focus on restoring natural processes and reduce the threat of crown fires, and that priority in ecological restoration treatments should be given to areas near human developments and important watersheds.

LITERATURE CITED

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12(5): 1418-1433.

Austin, S.A. 1999. Streamflow response to forest management: a meta-analysis using published data and flow duration curves. M.S. thesis, Department of Earth Resources, Colorado State University, Fort Collins, Colorado. 121 pp. plus appendices.

Avery, T.E and H.E. Burkhart. 1994. Forest measurements. McGraw-Hill, Inc., New York. 408 pp

Baker, M.B. Jr. 1986. Effects of ponderosa pine treatments on water yield in Arizona. Water Resources Research 22(1): 67-73.

Bernstein, R. 2006. Louisiana loses population; Arizona edges Nevada as fastest-growing state. US Census Bureau Press Release, December 22, 2006. http://www.census.gov/Press-Release/www/releases/archives/population/007910.html, accessed 7-16-07.

Black, P.E. 1997. Watershed functions. Journal of the American Water Resources Association 33(1): 1-11.

Blee, J.W.H. 1988. Determination of evaporation and seepage losses, Upper Lake Mary near Flagstaff, Arizona. USGS Water Resources Investigations Report 87-4250, Tucson, Arizona. 39 pp.

Bosch, J.M. and J.D. Hewlitt. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55:3-23.

Brown, H.E., M.B. Baker, Jr., J.J. Rogers, W.P. Clary, J.L. Kovner, F.R. Larson, C.C. Avery, and R.E. Campbell. 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service Research Paper RM-129. 36 pp.

Campbell, R.E., M.B. Baker, Jr., P.F. Ffolliott, F.R. Larson, and C.C. Avery. 1977. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service Research Paper RM-191. 12 pp.

Chang, M. 2003. Forest hydrology: an introduction to water and forests. Boca Raton, Lousiana: CRC Press. 373 pp.

[CFUD] City of Flagstaff Utility Department. 2006. Report to the Water Commission: water and wastewater operation plan, Flagstaff, Arizona. 58 pp.

Clary, W.P., P.F. Ffolliott, and A.D. Zander. 1966. Grouping sites by soil management areas and topography. USDA Forest Service Research Note RM-40, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 4 pp.

Clary W.P., M.B. Baker, Jr., P.F. O'Connell, T.N. Johnsen, Jr., and R.E. Campbell. 1974. Effects of pinyon-juniper removal on natural resource products and uses in Arizona. Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service Research Paper RM-128. 28 p.

Cline, P. 1976. They came to the mountain: the story of Flagstaff's beginnings. Flagstaff, Arizona: Northern Arizona University with Northland Press. 364 pp.

[CNF] Coconino National Forest. 2007. Current conditions. http://www.fs.fed.us/r3/coconino/conditions/index.shtml, accessed July 16, 2007.

Cooper, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. Ecological Monographs 30(2): 129-64.

Covington, W.W. and M.M. Moore. 1992. Post-settlement changes in natural fire regimes: implications for restoration of old-growth ponderosa pine forests. USDA Forest Service General Technical Report RM-213, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 19 pp.

Covington, W.W. and M.M. Moore. 1994a. Southwestern ponderosa pine forest structure changes since Euro-American settlement. Journal of Forestry 92(1): 39-47.

Covington, W.W. and M.M. Moore. 1994b. Postsettlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. Journal of Sustainable Forestry 2 (1): 153-181.

Covington, W.W., P.Z. Fule, M.M. Moore, S.C. Hart, T.E. Kolb, J.N. Mast, S.S. Sackett, and M.R. Wagner. 1997. Restoring ecosystem health in ponderosa pine forests of the southwest. Journal of Forestry 95(4):23-29.

Davis, T. 2007. The battle for the Verde: will a new pipeline dry up one of the West's last free-flowing streams? High Country News 39 (9): 10-16.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 2005. Soil physical properties. In: Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. USDA Forest Service General Technical Report RMRS-GTR-42-volume 4, Rocky Mountain Research Station, Fort Collins, Colorado. 250 pp.

Desta, A. and A. Tecle. 2004. Water balance in Upper Lake Mary. Hydrology and water resources in Arizona and the Southwest: proceedings of the 2004 Meetings of the Hydrology Section, Arizona-Nevada Academy of Science, Glendale, Arizona. 9 pp.

Feeney, S.R., T.E. Kolb, W.W. Covington, and M.R. Wagner. 1998. Influence of thinning and burning restoration treatments on presettlement ponderosa pines at the Gus Pearson Natural Area. Canadian Journal of Forest Resources 28: 1295-1306.

Ffolliott, P.F. and D.B. Thorud. 1974. Vegetation management for increased water yield in Arizona. Tucson, Arizona: University of Arizona Agricultural Experiment Station Technical Bulletin 215. 38 pp.

Friederici, P. 2003a. Part 1: the context for restoration. In: Friederici P, ed. Ecological restoration of southwestern ponderosa pine forests. Washington: Island Press. p. 3-6.

Friederici, P. 2003b. Healing the region of pines: Forest restoration in Arizona's Uinkaret Mountains. In: Friederici P, ed. Ecological restoration of southwestern ponderosa pine forests. Washington: Island Press. p. 231-250.

Fulé, P.Z., D.C. Laughlin, and W.W. Covington. 2005. Pine-oak forest dynamics five years after ecological restoration treatments, Arizona, USA. Forest Ecology and Management 218: 129-145.

Fulé, P.Z., W.W. Covington, and M.M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications 7(3): 895-908.

Gary, H.L. 1975. Watershed management problems and opportunities for the Colorado Front Range ponderosa pine zone: the status of our knowledge. Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service Research paper RM-139. 32 pp.

Gottfried, G.J., D.G. Neary, M.B. Baker, Jr., and P.F. Ffolliott. 2003. Impacts of wildfires on hydrologic processes in forest ecosystems: two case studies. In: Renard, K.G., S.A. McElroy, W.J. Gburek, H.E. Canfield, and R.L. Scott, eds. First Interagency Conference on Research in the Watersheds, October 27-30, 2003. Benson, AZ: U.S. Department of Agriculture, Agricultural Research Service. P. 668-673.

Haque, A. 2003. Estimating actual areal evapotranspiration from potential evapotranspiration using physical models based on complementary relationships and meteorological data. Bulletin of Engineering, Geology, and the Environment 62(1): 57-63.

Hibbert, A.R. 1979. Vegetation management for water yield improvement in the Colorado River Basin. Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service report, in cooperation with the Water and Vegetation Management Subcommittees of the Pacific Southwest Interagency Committee. 58 pp.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrological Processes 15: 2877-2892.

Ice, G.G., D.G. Neary, and P.W. Adams. 2004. Effects of wildfire on soils and watershed processes. Journal of Forestry 102 (6): 16-20.

Korb J.E. and J.D. Springer. 2003. Understory vegetation. In: Friederici P, ed. Ecological restoration of southwestern ponderosa pine forests. Washington: Island Press. p. 231-250.

Leaf, C.F. 1975. Watershed management in the central and southern Rocky Mountains: a summary of the status of our knowledge by vegetation types. Fort Collins, Colorado: Rocky Mountain Forest and range Experiment Station, USDA Forest Service Research Paper RM-142. 28 pp.

Leao, D.S. 2005. Water yield and peak discharges resulting from forest disturbances in a northern Arizona watershed. Flagstaff, Arizona: Master's thesis, Northern Arizona University.

MacDonald, L.H. and J.D. Stednick. 2003. Forests and water: a state-of-the-art review for Colorado. Fort Collins. Colorado: Colorado State University. 65 pp.

Megahan, W.F. and J.G. King. 2004. Erosion, sedimentation, and cumulative effects in the northern Rocky Mountains. In: Ice, G.G. and J.D Stednick, eds. A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD. p. 201-222.

Mockus, V. 1972. Hydrologic soil groups. Chapter 7 in National Engineering Handbook, Part 630: Hydrology. USDA/NRCS, Washington, D.C. 12 pp.

Moore, M.M., W.W. Covington, and P.Z. Fulé. 1999. Reference conditions and ecological restoration: a southwestern ponderosa pine perspective. Ecological Applications 9(4): 1266-78.

Moore, M.M., D.W. Huffman, P.Z. Fulé, W.W. Covington, and J.E. Crouse. 2004. Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests. Forest Science 50(2): 162-176.

[NRCS] Natural Resources Conservation Service. 2007. Arizona annual precipitation map. http://www.ncgc.nrcs.usda.gov/products/datasets/climate/data/precipitation-state/az.html, accessed July 10, 2007.

Neary, D.G., P.F. Ffolliott, and J.D. Landsberg. 2005a. Fire and streamflow regimes. In: Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. USDA Forest Service General Technical Report RMRS-GTR-42-volume 4, Rocky Mountain Research Station, Fort Collins, Colorado. 250 pp.

Neary, D.G., J.D. Landsberg, A.R. Tiedemann, and P.F. Ffolliott. 2005b. Water quality. In: Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. USDA Forest Service General Technical Report RMRS-GTR-42-volume 4, Rocky Mountain Research Station, Fort Collins, Colorado. 250 pp.

[OCS] Oregon Climate Service. 2007. PRISM data explorer. http://mistral.oce.orst.edu/www/mapserv/nn/index.phtml, accessed July 10, 2007.

Press, F. and R. Siever. 1994. Understanding earth. W.H. Freeman and Company, New York. 682 pp.

[PRISM] PRISM Group, Oregon State University. 2007. Annual precipitation map created from PRISM data. http://prism.oregonstate.edu/, accessed July 11, 2007.

Pyne, S.J. 2001. Year of the fires: the story of the great fires of 1910. New York: Penguin Books. 322 pp.

Reisner, M. 1993. Cadillac desert: the American West and its disappearing water. New York: Penguin Books. 582 pp.

Rice, R.M., J.S. Rothacher, and W.F. Megahan. 1972. Erosional consequences of timber harvesting: an appraisal. In: Proceedings of the National Symposium on Watersheds in Transition, Fort Collins, Colorado, June 1972. p. 321-329.

Rice, R.M, R.R. Ziemer, and J. Lewis. 2004. Evaluating forest management effects on erosion, sediment, and runoff: Caspar Creek and northwestern California. In: Ice, G.G. and J.D. Stednick, eds. A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD. p. 223-238.

Rich, L.R. and J.R. Thompson. 1974. Watershed management in Arizona's mixed conifer forests: the status of our knowledge. Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, USDA Forest Service Research Paper RM-130. 15 pp.

Selmants, P.C., A. Elseroad, and S.C. Hart. 2003. Soils and nutrients. In: Friederici P, ed. Ecological restoration of southwestern ponderosa pine forests. Washington: Island Press. p. 231-250.

Shiver, B.D., and Borders, B.E. 1996. Multistage sampling – inventorying large acres. Chapter 8 in sampling techniques for forest resource inventory. Wiley and Sons, New York. pp. 230-267.

Sisk, T.D., H.M. Hampton, B.G. Dickson, Y. Xu, M.M. Howe, and J. Palumbo. 2004. Forest Ecological Restoration Analysis (ForestERA) Project: Data derived from foundational data layers. http://www.forestera.nau.edu/index.htm, accessed July 17, 2007.

Skov, K.R, T.E. Kolb, and K.F. Wallin. 2005. Difference in radial growth response to restoration thinning and burning treatments between young and old ponderosa pine in Arizona. Western Journal of Applied Forestry 20: 36-43.

[SERI] Society for Ecological Restoration International Science and Policy Working Group. 2004. The SER international primer on ecological restoration. Society for Ecological Restoration International, Tucson, Arizona. 15 pp.

[SWCC] Southwest Coordination Center. 2007. Seasonal fire potential map. http://gacc.nifc.gov/swcc/predictive/outlooks/seasonal/2007/swa2007_seasonal-outlook_NSAW_exec.pdf, accessed May 11, 2007.

Stanley, B. and P.A. Arp. 2002. Effects of forest harvesting on basin-wide water yield in relation to percent of watershed cut: a review of literature. University of New Brunswick, Fredericton, New Brunswick. 35 pp.

Stednick, J.D. and C.A. Troendle. 2004. Water yield and timber harvesting practices in the subalpine forests of the central Rocky Mountains. In: Ice, G.G. and J.D. Stednick, eds. A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD. p. 169-186.

Stone, J.E., T.E. Kolb, and W.W. Covington. 1999. Effects of restoration thinning on presettlement *Pinus ponderosa* in northern Arizona. Restoration Ecology 7(2): 172-182.

Swetnam, T.W., C.D. Allen, and J.T. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9(4): 1189-1206.

[USCB] U.S. Census Bureau Population Finder. 2007. http://factfinder.census.gov/home/saff/main.html?_lang=en, accessed July 16, 2007.

[USFS] U.S.D.A. Forest Service. 1991. Watershed and air management. Forest Service Manual 2500, Region 3 Supplement 2500-91-1. USDA-FS Region 3, Albuquerque, New Mexico.

[TES] USDA Forest Service. 1995. Terrestrial ecosystems survey of the Coconino National Forest. U.S. Government Printing Office, Washington, D.C. 405 pp.

[USFS] USDA Forest Service. 1997. Photo series for quantifying forest residues in the southwestern region. USDA-FS Southwestern Region, Albuquerque, New Mexico. 227 pp.

Viessman Jr., W. and G. L. Lewis. 2003. Introduction to hydrology. Prentice Hall, Upper Saddle River, New Jersey. 612 pp.

Waltz, A.E.M., P.Z. Fulé, W.W. Covington, and M.M. Moore. 2003. Diversity in ponderosa pine forest structure following ecological restoration treatments. Forest Science 49(6): 885-900.

Ziemer, R.R. 1986. Water yield from forests: an agnostic view. Proceedings of the California Watershed Management Conference, West Sacramento, California. 5 pp.

Zimmerman, G.T. 2003. Fuels and fire behavior. In: Friederici P, ed. Ecological restoration of southwestern ponderosa pine forests. Washington: Island Press. p. 126-143.

ACKNOWLEDGEMENTS

Grateful acknowledgement is given to Joe Crouse, Northern Arizona University Ecological Restoration Institute for all maps and GIS work; Wally Covington, Northern Arizona University Ecological Restoration Institute for providing this opportunity and for guidance along the way; Mike Manthei and Katherine Sanchez-Meador, Coconino National Forest for historical watershed information, Aregai Tecle, Northern Arizona School of Forestry and Paul Trotta, Northern Arizona University College of Engineering and Natural Sciences for helpful advice and guidance; Andi Thode, Northern Arizona University School of Forestry for in-depth editorial advice; and Northern Arizona University Ecological Restoration Institute's "Old Growth Club": Charlie Denton, Dennis Lund, and Dave Brewer for project and editorial advice. Additional thanks to Dave Brewer for help with project design, data collection, and erosion and sediment modeling. This project was funded by the Ecological Restoration Institute, Northern Arizona

University and the Watershed Research and Education Program, College of Engineering and Natural Sciences, Northern Arizona University.