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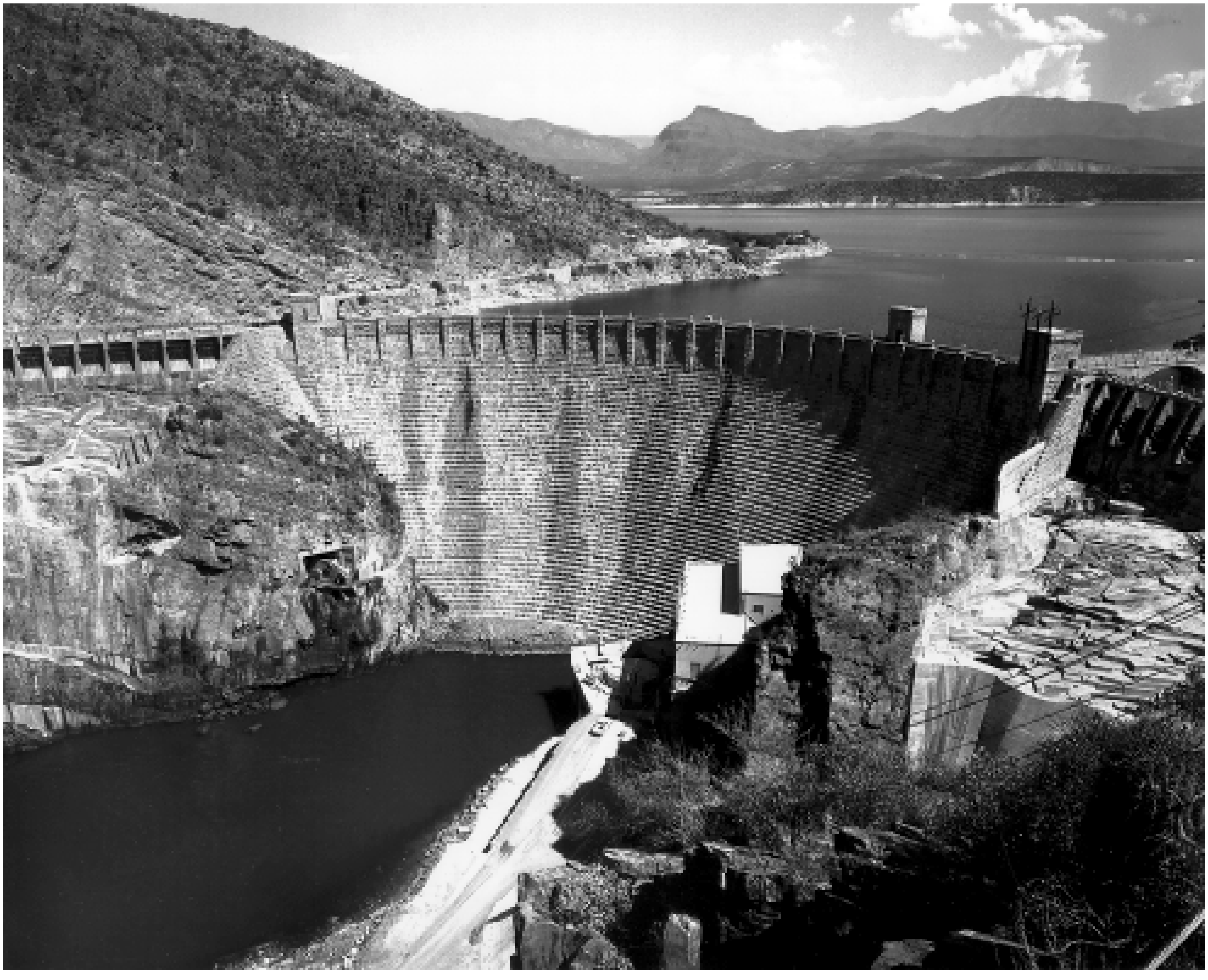
History of Watershed Research in the Central Arizona Highlands

Malchus B. Baker, Jr., Compiler



Abstract

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The Central Arizona Highlands have been the focus of a wide range of research efforts designed to learn more about the effects of natural and human induced disturbances on the functioning, processes, and components of the region's ecosystems. The watershed research spearheaded by the USDA Forest Service and its cooperators continues to lead to a comprehensive understanding of the region's ecology, and to formulation of management guidelines that meet the increasing needs of people in the region, and throughout the Southwestern United States. This report assembles the pertinent details of all watershed research accomplished by the USDA Forest Service and its cooperators in the region and provides highlights of the results. An extensive literature cited section is included for additional information. Information on the current status of the 5 major research area is also provided.

Keywords: watershed management, water yield, hydrology, mixed conifer, ponderosa pine, pinyon-juniper, chaparral, riparian, vegetation treatment

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Cover photo (circa 1960): Roosevelt Dam on the Salt River, AZ, was the first reservoir to capture and store Arizona water.
Photo courtesy of Salt River Project History Services.

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Contents

Chapter 1

Chapter 2

Chapter 3

Chapter 7

Chapter 8

Chapter 1

Central Arizona Highlands

Peter F. Ffolliott

Introduction

The Central Arizona Highlands are a distinct biogeographic, climatic, and physiographic province that forms a diverse ecotone between the larger Colorado Plateau to the north and the Sonoran Desert ecoregions to the south (figure 1). The Highlands coincide approximately with the Arizona Transition Zone identified by ecologists, geologists and others. This region is one of the last in the Southwestern United States that was settled by European immigrants.

With its unique and diverse landscape, the Central Arizona Highlands has been the focus of a wide range of research efforts designed to learn more about the effects of natural and human induced disturbances on the functioning, processes, and components of the region's ecosystems. Spearheaded by the USDA Forest Service and its cooperators, this research continues to lead to a comprehensive understanding of the ecology of the region, and to formulation of management guidelines that meet the increasing needs of people in the region and throughout the Southwestern United States.

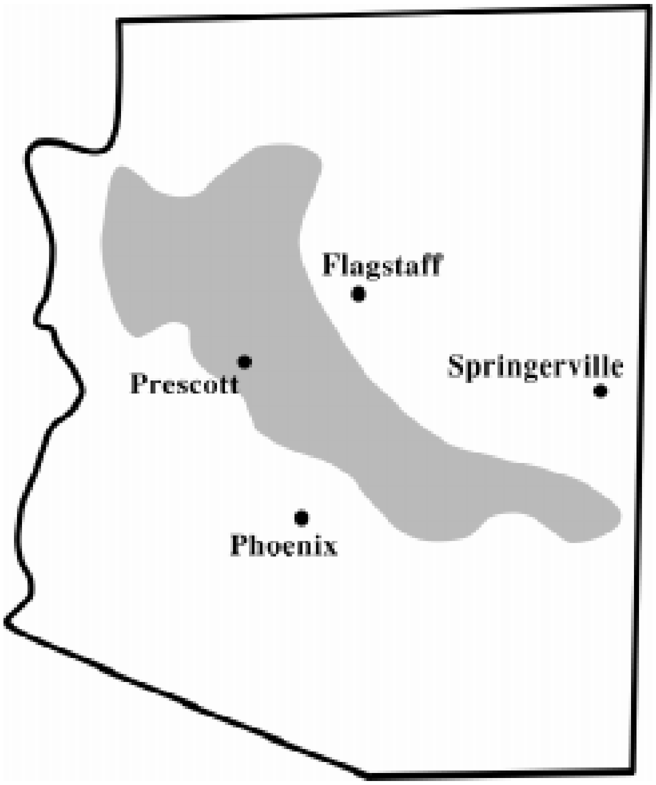

Figure 1. The Central Arizona Highlands.

Climate

The Central Arizona Highlands, similar to other areas in the state, are characterized by a cyclic climatic regime of winter precipitation, spring drought, summer precipitation, and fall drought. Precipitation usually comes from the northwest in the winter and from the southeast in the summer. Winter precipitation, often snow at higher elevations, is associated with frontal storms moving into the region from the Pacific Northwest. Surface thermal heating in the winter is less pronounced than in the summer; upslope air movement is relatively slow; cloudiness is common; and precipitation is usually widespread and relatively low in intensity.

The major source of moisture for summer rains is the Gulf of Mexico. This moisture moves into the Highlands from the southeast, passes over highly heated and mountainous terrain, rises rapidly, cools, and condenses. Summer storms, primarily convectional, are often intense and local rather than widespread. Summer rains typically begin in early July, breaking the prolonged spring drought and providing relief to the hot weather of June and July.

Winter precipitation is more variable than summer in amount and time of occurrence from year-to-year. However, yearly variations in precipitation generally decrease with increases in elevation. Spring drought is often more detrimental to most plants and animals in the region than fall drought, due to the higher temperatures and wind conditions during the beginning of the growing season.

Vegetation Types

Vegetation types in the Central Arizona Highlands include mixed conifer forests, ponderosa pine forests, mountain grasslands, pinyon-juniper woodlands, and chaparral shrublands. The elevational and precipitation regimes for these vegetation types are in figure 2. These ecosystems contain: water, timber, forage, recreation opportunities, and habitats for a variety of big and small game animals, rodents, and game and non-game birds. A diversity of riparian ecosystems occur in, or adjacent to, stream systems and their floodplains throughout the region.

Mixed Conifer Forests

Seven coniferous and one deciduous tree species in a variety of mixtures characterize these high elevation forests. These species include Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), white fir (*Abies concolor*), corkbark fir (*A. lasiocarpa* var. *arizonica*), ponderosa pine (*Pinus ponderosa*), southwestern white pine (*P. strobiformis*), and quaking aspen (*Populus tremuloides*). Relatively little herbaceous vegetation is produced under dense overstories in these forests. As a consequence, carrying capacities for livestock and wildlife, which graze these forests in summer, are low in relation to other vegetative types in the region. Mixed conifer forests contain: water, timber, forage, recreation opportunities (camping, hunting, picnicking, hiking, and site-seeing), and habitats for a variety of big and small game animals, rodents, and game and non-game birds.

Annual precipitation in high elevation mixed conifer forests (above 9,500 ft) ranges from 30 to 45 inches and is usually in excess of potential evapotranspiration (figure 2). As a result, streams originating in this area are often perennial. Streams originating in low elevation mixed conifer forests (8,000 to 9,500 ft) are mostly intermittent. Snowmelt runoff is a significant source of annual runoff.

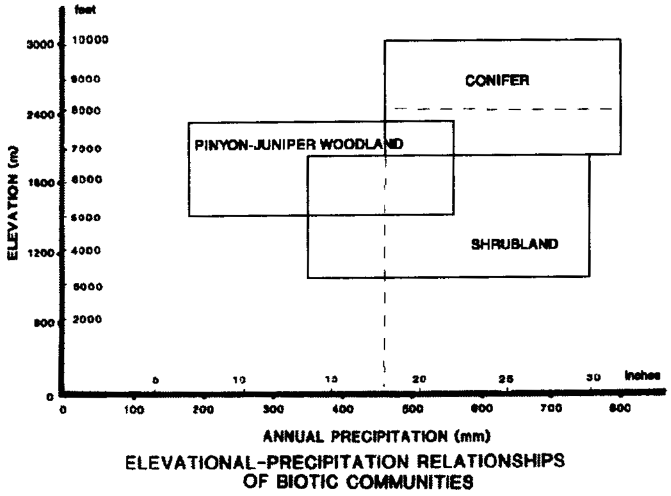

Figure 2. Precipitation-elevation relationships for vegetation types in the Central Arizona Highlands.

Soils, which vary in origin, are medium to moderately fine textured. Soil materials (regolith) are usually deep, allowing deep water penetration and storage. Mixed conifer forests are found over a range of slope and aspect combinations, although slope steepness is generally greater than in other vegetative types.

Ponderosa Pine Forests

Most of the ponderosa pine forests are at elevations between 5,500 and 8,500 ft on the Mogollon Plateau (figure 2). Although ponderosa pine trees dominate these forests, they often contain Douglas-fir, quaking aspen, and southwestern white pine at high elevations, and alligator juniper (*Juniper deppeana*) and Colorado pinyon (*Pinus edulis*) and its singleleaf form (*P. edulis* var. *fallax*) at low elevations. Gambel oak (*Quercus gambelii*) is scattered throughout. Grasses and grasslike plants, forbs, and half-shrubs grow beneath ponderosa pine overstories. Ponderosa pine forests are a valuable source of water, timber, forage, and recreation. Carrying capacities for livestock and wildlife, which graze these rangelands from late spring to early autumn, are relatively high. A diversity of wildlife species use these forests for cover and food, both seasonally and yearlong.

High transpiration rates and soil moisture deficiencies can curtail the growth of plants in ponderosa pine forests, which receive 20 to 30 inches of annual precipitation (figure 2). High elevation forests tend to have greater frequencies and amounts of precipitation than low elevation forests; although this can be altered by storm patterns and topography. Usually only a small amount of summer rain is converted into streamflow. Winter precipitation is the major source of runoff.

Basalt and cinders are the most common parent materials (57%), although sedimentary soils (43%) are also found throughout these forests. Topography is characterized by extensive flat, rolling mesas, intermixed with steeper, mountainous terrain, and a diversity of slope and aspect combinations.

Mountain Grasslands

Mountain grasslands, small in aggregate area, are scattered throughout the mixed conifer and ponderosa pine forests. While tree species are not usually part of these communities, isolated trees or shrubs occur through invasion from the adjacent forests on cinder cones and elevated places within the grasslands. The forest edge, where the 2 habitats come together, is a well delineated ecotone. Characteristic grasses are timothy (*Phleum pratense*), Arizona fescue (*Festuca arizonica*), mountain muhly (*Muhlenbergia montana*), pine dropseed (*Blepharoneuron triholepis*), black dropseed (*Sporobolus interreptus*), mountain brome (*Bromus marginatus*), and the introduced Kentucky bluegrass (*Poa pratensis*). Many of these species have high forage value for livestock and wildlife species. Recreation is a valuable resource of these high elevation grasslands because they are intermixed with mixed conifer and ponderosa pine forests.

Annual precipitation ranges from 30 to 45 inches, with almost 50% occurring during the summer season. The general weather patterns of mountain grasslands coincide with those in the adjacent coniferous forests.

Soils are usually fine-textured alluviums that are frequently and easily compacted and often have poor drainage. Mountain grasslands occupy relatively level terrain compared to most of the adjacent forests.

Pinyon-Juniper Woodlands

These coniferous woodlands are below the ponderosa pine forests, at elevations between 4,500 to 7,500 ft (figure 2). Colorado pinyon is found throughout, with singleleaf pinyon (*Pinus monophylla*) occurring on limited areas. North of the Mogollon Rim, Utah juniper (*Juniperus osteosperma*), Rocky Mountain juniper (*J. scopulorum*), and one-seed juniper (*J. monosperma*) are intermixed with pinyon, while alligator juniper and Utah juniper are south of the Mogollon Rim. Annual and perennial grasses and grass-like plants, forbs, half-shrubs, and shrubs abound beneath the woodland overstories. Recreation, a resource of these woodland areas, is limited by summer temperatures and the relative lack of water. These woodlands are also an important source of firewood. Livestock, which spend their summers at higher elevations, graze in the woodlands in winter. These woodlands are also seasonal and yearlong habitats for many wildlife species.

There are wide fluctuations in weather patterns throughout the pinyon-juniper woodlands. Annual precipitation varies from 12 to 24 inches. Winter precipitation is usually rain with occasional snow. Evapotranspiration rates are relatively high in the growing season. Only during the coldest months of December through February is precipitation greater than the evapotranspiration rates.

Soils are derived from basalt, limestone, and sandstone parent material. Pinyon-juniper woodlands generally occupy extensive areas of gently rolling topography. With the exception of steep canyon walls, few slopes exceed 20% to 25%. All aspects are well represented.

Chaparral Shrublands

Chaparral shrublands occur on rough, discontinuous, mountainous, terrain south of the Mogollon Rim. Chaparral stands consist of a heterogenous species mix in many locations, but often only 1 or 2 species dominate. Shrub live oak (*Quercus turbinella*) is the most prevalent species, while true (*Cercocarpus montanus*) and birchleaf mountainmahogany (*C. betuloides*), Pringle (*Arctostaphylos pringlei*) and pointleaf (*A. pungens*) manzanita, yellowleaf (*Garrya flavescens*), hollyleaf buckthorn (*Rhamnus crocea*), desert ceanothus (*Ceanothus greggii*), and other shrub species are included in the chaparral mixture of shrub species. Annual and perennial grasses, forbs, and half-shrubs are present, particularly where the overstory canopy is open or only moderately dense. Although the recreational value (hiking, camping, and hunting) of chaparral is lower than that of higher elevation vegetation types, its close proximity to major population centers provide it with an advantage. Research has also determine that chaparral areas are major sources of water if vegetation control is exercised. Chaparral rangelands are often grazed year-long by livestock, because evergreen plants common to the shrublands provide a continuous forage supply. A variety of wildlife species are found in chaparral shrublands, with comparatively high populations often concentrated in fringe areas.

Average annual precipitation varies from about 15 inches at the lower limits of the chaparral shrublands (3,000 ft) to over 25 inches at the higher elevations (6,000 ft) (figure 2). Approximately 60% of the annual precipitation occurs as rain or snow between November and April. The summer rains fall in July and August, which are the wettest months of the year. Annual potential evapotranspiration rates can approach 35 inches (Hibbert 1979).

Chaparral soils are typically coarse-textured, deep, and poorly developed. Granites occur on more than half of the shrublands. The topography is characterized by mountain ranges dissected by steep-walled gorges and canyons. Slopes of 60% to 70% are common. All aspects are represented.

Riparian Ecosystems

Three riparian ecosystems, delineated by elevation, are recognized in the Central Arizona Highlands. Riparian vegetation that occurs along the flood plain of stream channels are typically composed of herbaceous species of *Carex*, *Eleocharis*, *Juncus*, and *Scirpus* and produce the characteristic dark green edge along the channel systems. Woody plants, including saltcedar (*Tamarix pentandra*), sycamore (*Platanus wrightii*), and cottonwood (*Populus fremontii*), that are often associated with riparian ecosystems are typically found higher up on the terraces next to the flood plains.

In ecosystems below 3,500 ft, many of the ephemeral streams have broad alluvial floodplains that can support herbaceous plants and terraced bottoms that often support high densities of deep-rooted trees including saltcedar, sycamore, cottonwood, palo verdes (*Cercidium spp*.), and other species.

Riparian ecosystems between 3,500 and 7,000 ft contain the greatest number of plant species and the greatest canopy cover. Besides the characteristic herbaceous plants along the flood plain, cottonwood, willow (*Salix spp*.), sycamore, ash (*Fraxinus velutina*), and walnut (*Juglans major*) are typically found on the terraces, with 3 or 4 species often occurring together.

Above 7,000 ft, herbaceous species of *Carex*, *Eleocharis*, *Juncus*, and *Scirpus* predominate along the edge of the stream channels. Willow, chokecherry (*Prunus virens*), boxelder (*Acer negundo*), Rocky Mountain maple (*A. glabrum*), and various coniferous tree species occupy the higher terraces.

Because of the abundance of water, plants, and animals, riparian areas provide valuable recreation opportunities as well as forage for livestock and wildlife in an otherwise arid environment. Riparian ecosystems are prime habitats for many game and non-game species of wildlife and fish.

Collectively, climatic characteristics of riparian ecosystems exhibit a wide range of conditions due to large elevational differences and distributions of associated mountain ranges and highlands. The key characteristic of the riparian system is the availability of water throughout the year or at least during the growing season.

Soils at the higher elevations generally consist of consolidated or unconsolidated alluvial sediments from parent materials of the surrounding uplands. Soil depths vary in riparian ecosystems, depending upon the stream gradient, topographic setting, and parent materials. Soils on the flood plains at lower elevations consist of recent depositions, tend to be uniform within horizontal strata, and exhibit little development. The alluvial soils in all ecosystems are subject to frequent flooding and, as a consequence, are characterized by a range of textures. Riparian ecosystems vary from narrow, deep, steep-walled canyon bottoms, to intermediately exposed sites with at least one terrace or bench, to exposed, wide valleys with meandering streams.

Initial Research Emphasis

One situation that conditioned and circumscribed people's behavior throughout Arizona and the Southwestern United States was the perennial shortage of water. The expected but variable supplies of surface water have long since been appropriated. Electricity and electric pumps enabled access to previously unavailable groundwater sources, while the favorable climate resulted in an increase in agriculture and urbanization. As a consequence, nearly all of the increased water supplied to this rapidly growing area was pumped from underground basins. This has caused a steady decline in regional water tables, which, in turn, has affected local economies. Many acres that formerly supported agriculture have been abandoned, converted to housing developments, or switched to an alternate source of water, such as the Central Arizona Project (CAP) water that became available in the late 1980s. However, the water situation, especially in the heavily populated areas, has had little affect on people's behavior, except for the farmer (Wilson 1997). Within any user group (household, municipal, commercial, industrial, or agriculture), the willingness to pay for water varies significantly depending on the benefits obtained from its use. For example, as the price of water increases, the quantity demanded by various users changes because of differences in their ability to purchase water. Household users have the highest willingness to pay and one of the lowest quantities demanded (about 2 to 3 acre-ft / acre / yr assuming 4 families per acre). On the other hand, the willingness of farmers to pay is far less than any other user. However, their crops require much more water (5 and 6 acre-ft / acre / yr to grow cotton and alfalfa, respectively). To put this in perspective, the native desert around Phoenix uses about 0.5 acre-ft / acre / yr. When the cost of water sufficiently reduces the farmer's profit, he is forced to stop farming and either abandons or sells his land to a developer who provides what many homeowners desire: artificial lakes, golf courses, pools, and green lawns. Conversion of water previously used for agriculture (5 or 6 times that used by a household), therefore, has the potential to sustain growth of municipalities and industry for some years into the future.

Barring conversion of saline water, additional importation of outside water, advancements in rainmaking, and rigorous conservation measures, regional residents must rely on the variable surface and diminishing groundwater supplies. In response to this situation, the initial direction of research in the Central Arizona Highlands focused on investigating the potentials for increasing water yields from forests, woodlands, and shrublands of the region through vegetative manipulations (Barr 1956). Numerous watersheds were instrumented with various climatic and hydrologic measuring equipment by the USDA Forest Service and its cooperators in the late 1950s and throughout the 1960s to study the effects of vegetative clearings, thinnings, and conversions on water yields under controlled, experimental conditions.

These watersheds formed a research network, called the *Arizona Watershed Program*, of public agencies and private groups interested in obtaining more water for future economic growth while maintaining the state's watersheds in good condition. This collaborative program was the focus of watershed research in the Central Arizona Highlands through the 1960s, 1970s, and into the early 1980s.

Multiple Use Considerations

Vegetative manipulations that were tested on the instrumented watersheds not only influenced the water yield, but also affected all of the other natural resource products and uses of the forests, woodlands, and shrublands in the region. Therefore, the USDA Forest Service and its cooperators enlarged the research program to evaluate the effects of vegetative manipulations on the array of multiple uses contained in the ecosystems studied. Results from this research showed that vegetation can often be managed to increase water yields while providing timber, forage, wildlife, and amenity values in some optimal combination. This finding was not surprising, as many of the vegetation management practices studied for their water-yield improvement possibilities are common in principle and application to management programs that are often implemented to benefit other natural resources.

Much of the research in the Central Arizona Highlands has centered on the Sierra Ancha Experimental Forest above Roosevelt Lake; the Three-Bar Wildlife Area west of Roosevelt Lake; the Whitespar, Mingus Mountain, and Battle Flat watersheds in the vicinity of Prescott; the Beaver Creek watersheds along the Mogollon Rim south of Flagstaff; and Castle Creek, Willow Creek, Thomas Creek, and Seven Springs watersheds in the White Mountains of eastern Arizona. Descriptions of research designs, characteristics of research sites, cooperators involved, results and implications, and the current status of research activities on these and associated sites are presented in the following chapters. The history of research efforts in the riparian ecosystems of the Central Arizona Highlands is also presented.

Chapter 2

Beginning of Water Studies in the Central Arizona Highlands

Gerald J. Gottfried, Leonard F. DeBano, and Malchus B. Baker, Jr.

Introduction

Water has been recognized as an important resource in central Arizona and has affected populations occupying the Salt River Valley for centuries. Water related activities have been documented since about 200 before the common era, when Hohokam Indians settled the Valley and constructed canals to irrigate their fields. Europeans began to settle in the Phoenix area in the late 1860s and depended on irrigation water from the Salt River for agriculture. However, water supplies fluctuated greatly because the river often flooded in winter and dried up in the summer. There were no impoundments to store water for the dry seasons. In 1904, the Salt River Water Users' Association signed an agreement with the United States government under the National Reclamation Act to build a dam on the Salt River below the confluence with Tonto Creek. The Roosevelt Dam, the first of 6 dams on the Salt and Verde Rivers, was completed in 1911.

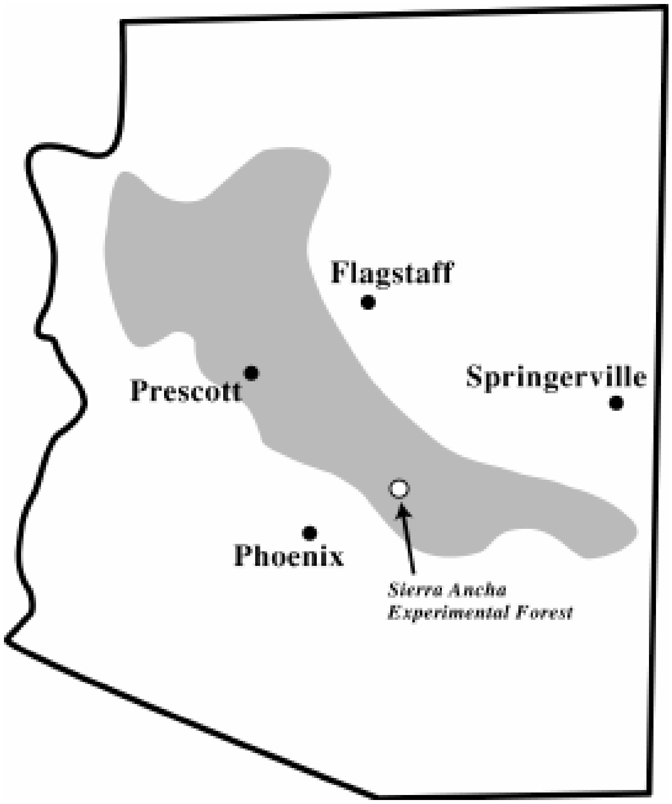

Figure 3. Sierra Ancha Experimental Forest in the Central Arizona Highlands.

In the early 20th century, watershed managers became concerned that erosion on the adjacent and headwater watersheds of the Salt River would move sediment into the newly constructed Roosevelt Reservoir and decrease its capacity. Measurements indicated that 101,000 acre-ft of coarse granitic sediments had accumulated behind Roosevelt Dam between 1909 and 1925. The Summit Plots, located between Globe, Arizona and Lake Roosevelt, were established in 1925 by the USDA Forest Service 15 mi upstream from Roosevelt Dam to study the effects of vegetation recovery, mechanical stabilization, and cover changes on stormflow and sediment yields from the lower chaparral zone (Rich 1961).

Shortly after establishing the Summit Plots, the USDA Forest Service dedicated a research area known as the Parker Creek Experimental Forest in May 1932 (USDA Forest Service 1932). This experimental forest was enlarged and renamed the Sierra Ancha Experimental Forest in April 1938 (figure 3). The hydrologic and ecological experiments that were conducted on the Sierra Ancha Experimental Forest are discussed below.

Other research studies began in the 1950s with establishment of the Three Bar watersheds in chaparral vegetation on the west side of the Tonto Basin (Hibbert et al. 1974, DeBano et al., Chapter 3 of this publication). The initial research objective of the Southwestern Forest and Range Experiment Station (currently the Rocky Mountain Research Station) was to develop a program to study the interrelated influences of climate and soils, topography and geology, and the nature, condition, and use of watershed vegetation on streamflow, soil erosion, floods, and sedimentation.

Sierra Ancha Experimental Forest

The research mission on the Sierra Ancha Experimental Forest was to study the effects of grazed and ungrazed vegetation on water yields and to learn more about water cycle relationships within the diverse vegetation zones extending from the higher elevation mixed conifer forests to the semi-desert grass type (USDA Forest Service 1938). The area of the enlarged experimental forest is about 13,500 acre (USDA Forest Service 1953, Pase and Johnson 1968). The experimental forest is within the Tonto National Forest and is located on the western slope of the Sierra Ancha Mountains about 10 miles from Roosevelt Dam. The hydrologic installations were constructed by the Civilian Conservation Corps during the 1930s.

The experimental forest lies along the crest of the Sierra Ancha Mountain range and includes areas between 3,550 to 7,725 ft in elevation. Geology of the range is complex with sedimentary, metamorphic, and igneous rocks uplifted in a dome-like structure (Pase and Johnson 1968). Thick formations of Dripping Springs quartzite, dissected by deep canyons or with intrusions of diabase and basalt plugs and sills, are common in much of the forest. Troy sandstone occurs at higher elevations (Rich et al. 1961, Pase and Johnson 1968).

Precipitation averages about 33 inches at the higher elevations at Workman Creek, 25 inches at the intermediate elevations (4,800 to 6,000 ft) surrounding the headquarters, and 16 inches at the lower elevations near the Base Rock lysimeters (Pase and Johnson 1968). Pase and Johnson (1968) identified 8 vegetation types including, from high to low elevations: mixed conifer, mountain park, ponderosa pine, chaparral, oak woodland, desert grassland, desert shrub, and riparian. Fifty-seven percent of the experimental forest is covered by chaparral shrubs. The habitat relations of the vertebrate fauna have been described by Reynolds and Johnson (1964).

The Sierra Ancha Experimental Forest provides a unique research environment for conducting short- and long-term studies about basic hydrologic and ecological relationships in vegetation types ranging from mixed conifer forests to lower elevation desert shrub-grassland communities.

Short-Term Studies

Short-term studies were used to investigate hydrological and ecological relationships of different plant communities on the Sierra Ancha Experimental Forest. The results of these studies provided the basis for establishing long-term watershed studies to fully evaluate water-yield responses to brush control in chaparral (Natural Drainages), and to timber harvesting in mixed conifer forests (Workman Creek). Studies were designed to test erosion control and revegetation techniques (Hendricks 1936, 1942, Hendricks and Grabe 1939). Cooperrider and Hendricks (1940) and Hendricks and Johnson (1944) studied the effects of grazing and wildfire on soil erosion. Sykes (1938) and Cooperrider et al. (1945) evaluated winter hydrographs for Parker Creek and the Salt River.

The effect of consumptive use of range vegetation on soil and water resources was determined by using small lysimeters. A lysimeter is an instrument for measuring the amount of water percolating through soils and for determining materials dissolved by the water. Evaporation from bare soil was compared to evapotranspiration from perennial *grasses* and shrubs (Rich 1951).

Fletcher and Rich (1955) developed a method of classifying Southwestern watersheds on the basis of precipitation, potential evapotranspiration, and potential water yields. Most water yields resulted from water stored in the soil during the winter when evapotranspiration is low. High-water yielding areas should be managed for water augmentation, while intermediate and low-water yielding areas should be managed to reduce erosion.

Early ecological studies were concerned with characteristics of the Arizona white and Emory oak trees (Bliss 1937, Pase 1969, Pond 1971). Little (1938, 1939) conducted several botanical studies. The forest floor was recognized as playing an important role providing soil protection, increasing water holding capacity and availability to vegetation, and enhancing plant germination (Hendricks 1941, Pase 1972, Garcia and Pase 1967, Pase and Glendening 1965).

Watershed assessments suggested that streamflow was related to the interaction of precipitation and to the different native vegetation types occupying the upland watersheds of the Salt River Basin (Cooperrider and Sykes 1938, Cooperrider and Hendricks 1940, and Cooperrider et al. 1945). This finding encouraged further research on techniques of vegetation manipulations and the hydrologic responses to these manipulations. Of particular interest was development of a method for controlling deep-rooted brush species, and replacing them with shallower-rooted grass plants.

Early studies tested herbicides for shrub control (Cable 1957, Lillie et al. 1964), while other studies evaluated the combined use of herbicide and prescribed burning for controlling vegetation (Lindenmuth and Glendening 1962, Lillie et al. 1964, Pase and Glendening 1965, Pase and Lindenmuth 1971).

Short-term studies were also conducted at Workman Creek to supplement information gained from watershed-level studies. Investigations were conducted on the control of New Mexico locust and Gambel oak (Gottfried 1980, Davis and Gottfried 1983). The above- and below-ground biomass of locust was also related to water yield (Gottfried and DeBano 1984). Another concern of managers was the potential impact of pocket gophers on ponderosa pine seedling survival (Gottfried and Patton 1984).

Long-Term Studies

Important study areas dedicated to long-term research were located at the Base Rock lysimeters, Natural Drainages watersheds, and the Workman Creek watersheds.

Base Rock Lysimeters

Hydrologic research in the 1930s used lysimetry to obtain quantitative information on the water balance for different vegetation types because it offered a degree of experimental control that was not attainable using experimental runoff plots or small and large watersheds (Martin and Rich 1948). However, limitations associated with the use of lysimeters were recognized. Typical limitations included difficulty making the lysimeters large enough to reduce border effects and the disruption or destruction of the natural soil profile. The lysimeters constructed on the experimental forest mitigated these limitations by using large, undisturbed soil blocks overlying bedrock and, therefore, were named the "Base Rock Lysimeters." Three lysimeters (18 ft wide and 50 ft long) with undisturbed soil profiles were established on an area supporting a deteriorated stand of perennial grasses, snakeweed (*Gutlerrezia sarothrae*), and yerba-santa (*Eriodictyon angustifloium*) (<2% total plant cover). Revegetation treatments including seeding, fertilizing, and watering the lysimeters were carried out during 1934 and 1935. By 1942, the cover had increased to about 8% and consisted of mainly sprangletop (*Leptochioa dubia*), sideoats (*Bouteloua curtipendula*), and hairy grama (*B. hirsuta*). Three grazing treatments applied between 1942 and 1948 were:

- Overgrazing with sheep at the rate of 2 mature ewes for 4 days annually, usually in October.
- More moderate grazing at half the above rate.
- Ungrazed.

Natural Drainages Watersheds

Four chaparral-covered watersheds, called the Natural Drainages, were established on the Sierra Ancha Experimental Forest in 1934. These watersheds ranged in size from 9 to 19 acres. Precipitation and runoff were measured. The upper slopes of the watersheds contain diabase soils, which cover between 28% and 54% of the watersheds. Soils on the lower slopes are derived from quartzite. The original vegetation on these watersheds was sparse, with low density chaparral stands on southerly exposures.

Before treatment, crown cover of the chaparral shrubs was 20% to 25% compared with covers 2-to-3 times this density on the Whitespar and Three Bar watersheds (DeBano et al., Chapters 3 and 4 of this publication). Shrub live oak was the most abundant shrub. Livestock grazing in the area started about 1880 and continued until 1934, when experimental watersheds were established on the Sierra Ancha Experimental Forest.

The Natural Drainages watersheds were one of the first watershed-level studies used in the Central Arizona Highlands to evaluate the effect of grazing on vegetative change and on production of streamflow and sediment. Two of the four watersheds were grazed by cattle and horses for short periods during the fall and spring beginning in 1939, and 2 watersheds were the controls (Rich and Reynolds 1963). Herbaceous vegetation was quantified using meter-square quadrants. Streamflow was determined using 90^o V-notch weirs and sediment was measured in weir basins at the bottom of each of the 4 watersheds. These studies were terminated in 1952 when it was determined that the intensities of grazing used in the studies had no effect on total water yield or sediment trapped in the weir ponds (Rich and Reynolds 1963).

A growing interest in augmenting streamflow in the Central Arizona Highlands by manipulating native vegetation developed among water users in central Arizona during the 1950s. As a result, many of the research efforts during this period were initiated to evaluate the feasibility of increasing streamflow. A second experiment designed to determine the effects of chaparral cover manipulations on streamflow was started on the Natural Drainages watersheds in 1954 (Ingebo and Hibbert 1974). Chaparral cover was suppressed on 2 watersheds by treating the shrubs with herbicides, while the other 2 watersheds were maintained as control areas.

Workman Creek Watersheds

A major project was conducted on the Workman Creek watersheds to evaluate the hydrology of higher elevation mixed conifer forests and to determine the changes in streamflow and sedimentation from manipulating the forest vegetation. The 3 watersheds on Workman Creek are *North Fork*, *Middle Fork*, and *South Fork*. The treatments evaluated were selected to cover the range of water yields possible through manipulation or removal of the forest vegetation (Rich and Gottfried 1976). These treatments were not intended to be examples or recommendations for actual management applications, but instead they were used to obtain basic hydrologic information on streamflow responses to vegetation manipulations.

North Fork.—Studies on the North Fork of Workman Creek were designed to evaluate streamflow responses to clearing the forest cover in stages, starting on the wettest and progressing to the driest sites. The first treatment was implemented in 1953.

Riparian trees, mainly Arizona alder (*Alnus oblongifolia*) and bigtooth maple (*Acer grandidentatum*), growing adjacent to streams, springs, and seeps, were cut and their stumps were treated with herbicides to prevent sprouting. The cut removed 0.6% of the total basal area.

The next treatment on North Fork converted the moist site forest vegetation, mostly Douglas-fir and white fir, to grass on about 80 acres. Larger trees were harvested, and smaller and unmerchantable material was windrowed and burned. The cleared areas were seeded with grass species.

The final treatment on North Fork removed the adjacent dry-site forest of ponderosa pine trees and converted the site to grass (figure 4).

South Fork.—Treatments on South Fork of Workman Creek were designed to test the current forest management prescriptions of 1953. The watershed was harvested according to a standard single-tree selection prescription starting in June 1953.

The objective of the second treatment on South Fork was to convert mixed conifers to a pure ponderosa pine stand by removing the other conifer species, and to maintain the stand at a density of 40 ft^2/acre. The hypothesis tested was that this forest density should optimize both timber and water production.

Middle Fork.—Middle Fork watershed was left untreated so it could be used as a control for quantifying changes in streamflow after treating North Fork and South Fork watersheds.

Cooperators

A number of organizations cooperated with the Rocky Mountain Station's research effort on the Sierra Ancha Experimental Forest. The Salt River Water Users' Association provided financial support for the treatments on Workman Creek. The Tonto National Forest assisted with implementation of these forest management treatments. Faculty and students from Arizona State University and the University of Arizona conducted collaborative experiments on Sierra Ancha. University-sponsored research has increased in recent years.

Results

A status-of-knowledge publication presented the results of the water yield improvement experiments and other research conducted on the watersheds through the early 1970s (Rich and Thompson 1974). This publication reported on the opportunities for increasing water yields and other multiple use values in mixed conifer forests. Many of these results were later refined, expanded upon, and subsequently reported on in other publications. A brief discussion of the results is presented below; details are in the cited literature.

Conclusions from the Base Rock Lysimeters showed that (Martin and Rich 1948):

- The major portion of annual water yield occurred during winter as sub-surface flow from long-duration, low-intensity storms.
- Most surface run-off and soil erosion occurred during summer storm events from short-duration, high-intensity thunderstorms.
- Overgrazing caused increases in summer surface runoff and erosion and decreases in areal infiltration capacities, while the amount of winter water

Figure 4. Overstory manipulations on the North Fork of Workman Creek Watershed.

percolation was independent of the grazing treatment. Soil losses during summer storms increased from 60 to 307 tons / mi^2 on heavily grazed plots compared to theungrazed controls. In contrast, winter soil losses only increased from 15 to 68 tons / mi^2 on moderately grazed plots.

- Results from late summer frontal-type storms were intermediate between those from summer and winter storm events.

Overall, major amounts of sediment-free water come from areas with good grass cover and soil erosion is greatest where vegetation densities have been decreased, as by overgrazing.

Results from herbicide studies on the Natural Drainages watersheds indicated:

- There was 3-times more grass, forb, and half-shrub production on the treated areas having quartzite soils than on similar soils on the control areas (Pond 1964). No differences in plant production were observed on the diabase soils.
- An increase of 22% in streamflow occurred on treated areas (Ingebo and Hibbert 1974). Pretreatment average annual streamflow was 1.65 inches.
- The treated areas showed a 30% increase in quickflows, a 32% increase in delayed flows (the rising and falling stages of a streamflow hydrograph), and a 26% increase in peak flows (Alberhasky 1983).
- A decline of 72% in annual sedimentation was attributed to the increase in grass cover on the treated areas.

Streamflow increases from vegetation manipulations were attributed to lower evapotranspiration demands by the replacement grass cover. The streamflow increases from the Natural Drainages watersheds were low compared to other chaparral areas (Hibbert et al. 1974); this was related to the initial low density of shrubs and to the southeastern exposure of the area that results in relatively high energy inputs for evapotranspiration.

Results from the 3-stage removal of the forest overstory on North Fork of Workman Creek indicated:

- Streamflow increased from both the moist- and dry-site treatments, but not from the riparian areas.
- Evaluation of the treatments in 1979, after 13 years of data collection, showed that the increases had remained stable (Hibbert and Gottfried 1987).
- Winter stormflows responded less to treatment than summer stormflows, although the actual volumes of winter runoff were larger (Hibbert and Gottfried 1987).
- Sediment yield increases were low (Rich et al. 1961). Most sediments moved during high-volume stormflows, and most material originated from the channels and main logging road (Rich and Gottfried 1976).

Results from thinning the forest overstory to 40 ft^2 / acre on South Fork of Workman Creek showed:

- Water yield increases, which remained constant for 13 years (Hibbert and Gottfried 1987). Severe forest overstory removal (to 40 ft^2 / acre) to encourage growth of the ponderosa pine forests is not recommended for present day management. An adverse reaction of the public would likely be created because of the esthetic of such a treatment and because of the perceived influence such a thinning would have on other components of the ecosystem.
- There was little effect on soil movement (Rich 1962, Rich and Gottfried 1976). A wildfire on the upper area of South Fork produced the greatest amount of soil disturbance.

Implications

Research on the Sierra Ancha Experimental Forest has contributed to the knowledge base of hydrology, watershed management, and basic ecology for over 65 years. These studies provided:

- Guidance for subsequent watershed research programs in chaparral and mixed conifer forested ecosystems.
- Information on water yield responses to vegetation manipulation that is useful to land managers and researchers.
- Research findings that continue to be implemented when designing multiple resource ecosystem management treatments.

Current Status

Most of the hydrologic measurements on the Sierra Ancha Experimental Forest were discontinued in the late 1970s and 1980s in response to a shift in USDA Forest Service research priorities. Currently, only the Upper Parker Creek weir, the Sierra Ancha weather station, and the USDA Natural Resources Conservation Service snow measuring station are active. Ecologically-oriented research continues to a limited extent.

Arizona State University entered into a lease agreement with the Forest Service in 1983 to use the Parker Creek Headquarters complex. The experimental forest and surrounding Tonto National Forest continues to be used for faculty and graduate student ecological research and summer field classes. The Parker Creek complex is used for Forest Service, university, and conservation group meetings. The Sierra Ancha Experimental Forest has a tradition of natural ecosystem ecology and management research and the potential for future contributions.

Chapter 3

Providing Water and Forage in the Salt-Verde River Basin

Leonard F. DeBano, Malchus B. Baker, Jr., and Gerald J. Gottfried

Introduction

The Salt-Verde River Basin, covering about 8.4 million acres of the Central Arizona Highlands, supplies most of the water for the Salt River Valley in addition to providing other multiple use values. Mixed conifer, ponderosa pine forests, and a portion of the pinyon-juniper woodlands predominantly occupy the higher-elevation watersheds. Chaparral shrublands occupy a wide range of elevations, experience varied annual precipitation amounts, and overlap major portions of the pinyon-juniper woodland and semidesert grassland types (figure 2). Management of these shrublands for increased forage and water production, and reduction in sediment production and its subsequent transport into Roosevelt Reservoir, has been of major interest to people in the Central Arizona Highlands and Salt-Verde River valley since the early 1900s.

Research And Management

The importance of the chaparral shrublands resulted in the establishment of research and management programs that used permanent study areas devoted to long-term demonstration and monitoring. Research watersheds were located on the Three-Bar Wildlife Area (figure 5) and the Natural Drainages watersheds on the Sierra Ancha Experimental Forest (see Gottfried et al. Chapter 2 of this publication). A demonstration management project was also established in the 1960s at Brushy Basin, located about 10 mi west of the Three-Bar experimental watersheds, to test the effectiveness of chaparral control methods.

Potential erosion and sedimentation problems were a major concern in the Salt-Verde River Basin because of the possibly that eroded materials from hillslopes would fill Roosevelt Reservoir (Rich 1961). Therefore, management of plant cover on upland watersheds was important. There was also interest in increasing forage production for livestock and wildlife, while maintaining wildlife habitat diversity.

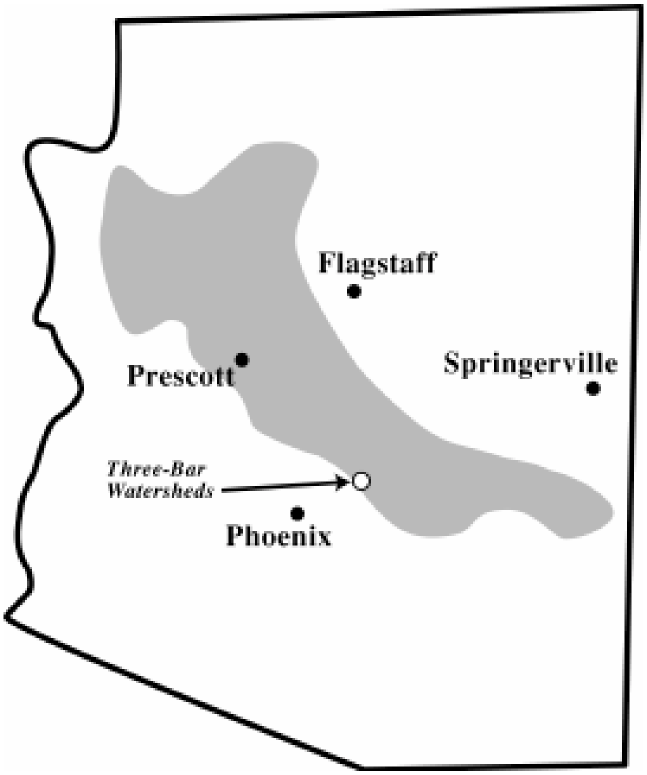

Figure 5. Three-Bar Watersheds in the Central Arizona Highlands.

Three-Bar Experimental Watersheds

The research program on the Three-Bar watersheds represented the first major experimental watershed program in Arizona chaparral shrublands. Four watersheds (A, B, C, and D) were established and instrumented in 1956 on the Three-Bar Wildlife Area west of Lake Roosevelt. This area supported dense chaparral stands and had not been grazed since 1947. All of the watersheds had been burned by a wildfire in June of 1959. After the burn, watershed A was abandoned and watershed F was instrumented in June 1963 to replace it. All 4 watersheds (B, C, D, and F) are north-facing, at elevations of 3,350 to 4,250 ft, on soils derived from granite, with the upper slopes exceeding 70%.

Previous studies on chaparral had been conducted at the Natural Drainages watersheds on the Sierra Ancha Experimental Forest (see Gottfried et al. Chapter 2 of this publication). However, the Three-Bar location, provided a better opportunity for evaluating the maximum water yields that might be expected from shrub-to-grass conversions because of its higher yearly precipitation and dense chaparral cover (>60% crown cover). The dense stands were highly productive areas. Experimental watersheds were subsequently established in medium density chaparral (40% to 60%) on the Whitespar watersheds and in low density cover (<40%) on the Mingus watersheds. These watersheds are in north-central Arizona (Yavapai County) in the Central Arizona Highlands (DeBano et al. Chapter 4 of this publication). The range of densities at Three-Bar, Whitespar, and Mingus were representative of most of Arizona's chaparral shrublands and allowed researchers and managers to better identify chaparral shrublands that could be economically treated to obtain increased streamflow.

Research Objectives

The Three-Bar Experimental Watersheds were established to determine the effects of chaparral shrub-to-grass conversions on increasing water yields (figure 6), on dissolved chemical constituents and sediment, and of fire and herbicide applications in controlling shrub re-growth.

While these research objectives provided a framework for treatment of Watersheds B, C, and F, other research agendas evolved as the understanding of chaparral response to treatment increased. Foliar sprays, initially used to control chaparral shrubs, inadequately eliminated all of the shrubs and required repeated application (Hibbert et al. 1974). Because of this inadequacy, soil-applied herbicides in subsequent treatments of Watersheds C, B, and F were tested. Above-normal nitrate levels were discovered in stream water as a result of earlier herbicide treatment on Watershed C. These high nitrate responses led to studies on water quality and nitrogen losses as a result of shrub treatments.

The treatment pattern changed from treating entire watershed areas (Watersheds C and F) to selectively controlling shrub plants in a mosaic pattern to provide protection from erosion on steep slopes, better habitat diversity for wildlife, and maintenance of increased streamflow (Watershed B). The mosaic treatment pattern of chaparral control was ultimately tested on the Whitespar watersheds (DeBano et al. Chapter 4 of this publication).

Brushy Basin Management Demonstration Area

Brushy Basin (8,100 acres) was the site of a chaparral management project initiated by the Tonto National forest on the west slope of Mazatal Divide, 2 mi northwest of Four Peaks (figure 7). The objective was to demonstrate how fire and herbicides could be used to control chaparral shrubs and to improve forage resources (Courtney and Baldwin 1964). The treatment consisted of a prescribed burn followed by a maintenance plan. The maintenance plan included continuous and complete herbicide treatment of the highest water-yielding sites with the exception of a hardwood-riparian area, occasional spraying

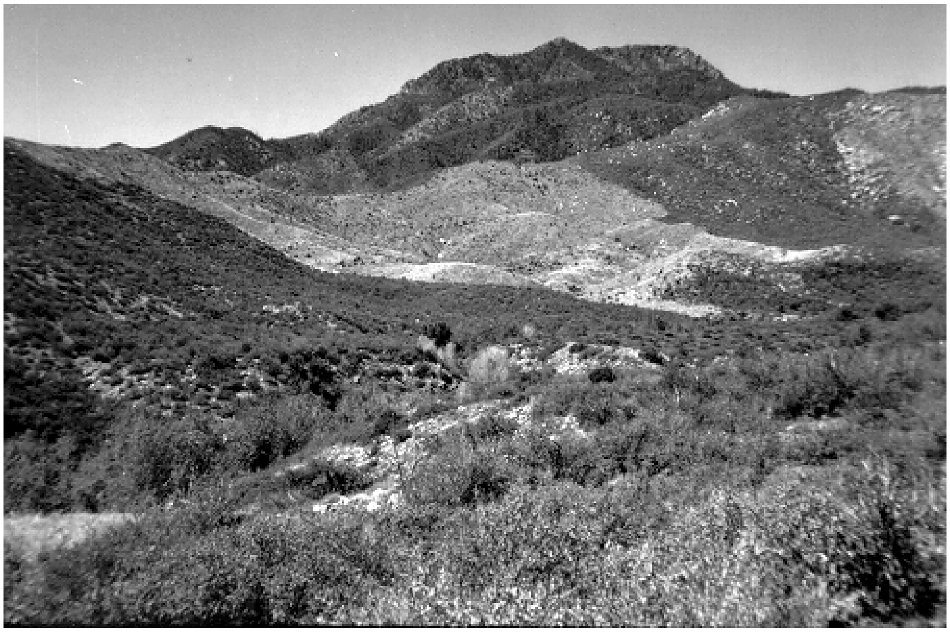

Figure 6. A shrub-to-grass conversion water yield improvement treatment on a Three-Bar Experimental Watershed.

with foliar herbicides to lower the density of brush on the moderate water-yielding sites, and retention of cover on steep and rocky sites (Suhr 1967).

Broadcast burning consumed about 80% of the canopy on about 5,000 acres over 3 yr. This burning program represented the first large-scale burning on national forest land (Moore and Warskow 1973). The burned areas were re-seeded with a mixture of grasses (Suhr 1967). Portions of Brushy Basin have been heavily grazed since this treatment, and erosion was particularly severe on some grazed areas during heavy rains in October 1972 (Ffolliott and Thorud 1974). Follow-up maintenance with herbicides was not implemented because of the environmental concerns associated with pesticide use, particularly foliar herbicides.

Cooperators

Interest in chaparral management evolved into a research and management program involving several agencies and organizations. The Tonto National Forest was responsible for managing much of the chaparral areas in the Central Arizona Highland. USDA Forest Service research was conducted by the Rocky Mountain Forest and Range Experiment Station and was assigned to the Forestry Science Laboratory at Tempe. Most of the Forest Service research addressed hydrologic and vegetative evaluations. Scientists with the Arizona Game and Fish Department provided wildlife evaluations on the Three-Bar Wildlife Area. Cooperative studies were also carried out with the University of Arizona, Arizona State University, and Colorado State University. Personnel from the Salt River Project and Arizona Water Resources Committee provided support and guidance in many of the watershed evaluations. Streamflow was gaged on some watersheds by the U.S. Geological Survey of the Department of Interior.

Results

Earlier status-of-knowledge publications presented the results of increasing water yields and other multiple use values in chaparral shrublands through the early 1970s (Brown, T. C. et al 1974, Hibbert et al. 1974). These results have been refined and, in some cases, expanded upon in subsequent publications. A brief discussion of the results is presented below; details are found in the cited literature.

Three-Bar Watersheds

After a wildfire in 1959, Watershed D recovered naturally to be used as a control and Watershed B, Watershed C, and Watershed F received chemical treatments. Results of the treatments (Hibbert et al. 1974) were:

- The effect of the wildfire on streamflow was short-lived. A sharp increase in overland flow occurred in the first few years after the wildfire, especially during the first summer rains.

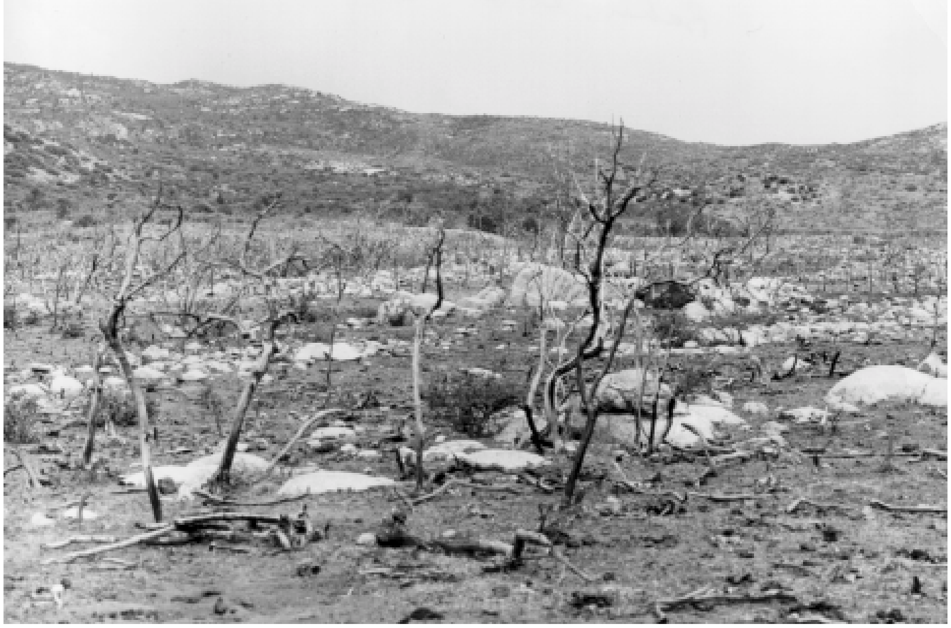

Figure 7. Overview of the Brushy Basin Management Demonstration Area.

- Stream flows increased on all the watersheds. However, after the third year, the crown cover on the control watershed (D) was dense enough to prevent any increased water production.

Following the treatment on Watershed C:

- Streamflow increased 4-fold (5.8 area-inches of water) over 11 yr when compared with flow from the control Watershed D.
- Foliar herbicides killed about 40% of the shrub live oak and 70% of the birchleaf mountainmahogany. Because of the poor rate of shrub control, the remaining shrubs were treated individually with soil-applied herbicides in 1965 and 1968. This treatment reduced the shrub crown cover to less than 3% by 1969.
- Annual forage production averaged 1,200 lb/acre and provided a ground cover that maintained high infiltration rates.
- The increase in streamflow, particularly yearlong streamflow, allowed riparian vegetation to become established below the gaging station (DeBano et al. 1984).
- Bird populations flourished in the newly created riparian areas, but were reduced in the areas converted to grass (Szaro 1981).

Results from Watershed B were:

- Nitrates in streamflow rose to relatively high concentrations (about 85 ppm) and were exported from the watershed in amounts up to 125 lb/acre/yr, in comparison to a control watershed value of about 1 lb/acre/yr. High concentrations of nitrates in the streamflow lasted longer from the 2-stage treatment on Watershed B than from the 1-stage treatment on Watershed F. High nitrate concentrations (44 to 373 ppm) were found in soil solutions from 5, 10, and 15 ft depths on the converted watershed compared to low nitrate concentrations (0.2 to 6.2 ppm) on an adjacent undisturbed area (Davis 1987a, Davis and DeBano 1986).
- Herbicide (picloram) concentrations in streamflow were higher (360 to 370 ppb) during the initial 3 months following treatment than thereafter. After 14 months and 40 inches of accumulated rainfall, picloram could not be detected in the streamflow (Davis 1973).
- Surviving chaparral shrubs were re-treated in 1968 and again in 1978 (Davis 1987a). These additional 2 treatments reduced the shrub cover to about 8%.
- Annual grass and forb production averaged 690 lb/acre on the treated areas as compared to 300 lb/acre on nearby untreated slopes.

Results from Watershed F were:

- Nitrate concentrations in streamflow from the control (Watershed D) remained less than 1 ppm, while nitrate from the treated watershed increased to a maximum concentration of 56 ppm during the first posttreatment year, with an annual average concentration of 16 ppm (Davis 1984, 1987b, 1989).
- Shrub crown cover was reduced from 55% to less than 5% the first year after treatment. Shrub kill increased to more than 95% after 2 years.
- Runoff efficiency (the ratio of streamflow-to-precipitation) was increased to 2.3 times the efficiency of the control watershed (D), an increase of 1.5 area-inches of streamflow.

Other Studies

Results of other studies near the Three-Bar experimental watersheds, and conducted elsewhere in the chaparral shrublands in the Salt-Verde River Basin, are summarized below. In addition to testing of the effectiveness of herbicides for shrub control, studies using prescribed fire and a biological control (goat browsing) were tested:

When using fire, more than half the chaparral canopy should be eliminated and prevented from becoming reestablished to obtain relatively high levels of seeded grass production (Pase 1971 and Pond 1961a). However, burning can also result in an increase in undesirable plant species (Pase 1965).

Goat browsing reduces total cover in chaparral stands, particularly when in conjunction with initial brush-crushing (Severson and DeBano 1991). Goat browsing to control chaparral shrubs can result in the consumption of the same plant species preferred by cattle, deer, and elk (Knipe 1983). Successful use of goats to control shrub cover requires an intensive level of animal management.

The root system of a shrub live oak (figure 8) was excavated to characterize its mass (Davis and Pase 1977). It was determined that:

- The root system included a taproot, many deep-penetrating roots, and profuse lateral roots.
- The shrub live oak root system effectively depletes both ephemeral surface and deeply stored soil moisture.

A study was conducted at El Oso west of Lake Roosevelt and north of the Three-Bar Wildlife area, to measure the temporal and spatial sediment delivery to and within a stream network following a wildfire in chaparral shrublands. This study indicated that:

- Severe erosion following a wildfire deposited large amounts of hillside soil and debris in the channel system (Heede 1988).
- As vegetation recovered after fire, sediment delivery from the watershed practically ceased.
- Relatively clear water, upon entering the channel, caused degradation of the sediment deposited in the tributaries and delivered this sediment into the main channel for years after active hillslope erosion had ceased.
- The delayed sediment delivery made it difficult to interpret the effect of current management activities on erosion responses.

Mule (*Odocoileus hemionus*) and white-tailed deer (*O. viginianus*) and black bear (*Ursus americanus*) were studied on the Three-Bar Wildlife Area by the Arizona Game and Fish Department. These studies indicated that:

- Mule and white-tailed deer select a variety of plants for food including forbs, dwarf and half-shrubs, mast and other fruits, and evergreen browse of both chaparral and desert shrub (McCulloch 1973, Urness 1973, Urness and McCulloch 1973).
- While conversion treatments increased forage production for cattle and deer, loss of cover adversely effected deer, particularly when conversions of large areas or entire watersheds were implemented (McCulloch 1972).
- Cover and food for black bear are enhanced in habitats composed of shrubs and low trees interspersed with a few forest species in the major drainages. This arrangement provides numerous mast- and fruit-producing species (LeCount 1980).
- Leaving areas of adequate size as escape cover and providing a number of seral stages of postburn vegetation should benefit both game and nongame wildlife species (Pase and Granfelt 1977). Less than half of any area should be converted (Reynolds 1972).

An inventory of 139 chaparral sites totaling almost 335,000 acres was accomplished in the early 1970s (Brown et al. 1974). The cost of converting portions of chaparral shrubland areas that met crown cover, slope, and managerial criteria for conversion to grass, and maintaining these conversions over 50 yr, was compared with the benefits to society of increased water yield and forage for livestock and reduced fire-fighting costs. It was shown that:

- Using fire as the main conversion tool, 96 of the inventoried sites (69%) had a benefit-cost ratio greater than 1. Using a soil-applied herbicide, 72 sites (52%) had a benefit-cost ration greater than 1.
- Proper management would favorably affect soil movement, wildlife habitat, an esthetics. Recreation use would be unaffected in most treated areas.

Implications

Information has been obtained on how chaparral shrubland ecosystems function for land management deci-

Figure 8. Root system of shrub live oak excavated to a depth of 21 feet.

sion making. Past research has contributed information on shrub control techniques, watershed and soil responses to shrub control, water quality, wildlife habitat changes, and economics. The most important management implication of this research is the ability to determine how to control chaparral shrubs to enhance the production of water and forage and to maintain wildlife habitat diversity.

If chaparral shrub suppression is desired, burning must be combined with other control methods such as applications of soil-applied herbicides or mechanical control methods. A problem associated with mechanical equipment is that it is limited to slopes with less than a 10% grade on rock free soils. One advantage of using prescribed fire is that the environmental changes created are similar to those occurring during the natural evolution of fire-adapted ecosystems (Axelrod 1989). A disadvantage of using prescribed fire is that shrub control is temporary (Hibbert et al. 1974). Therefore, a management objective is often the suppression of shrubs rather than their eradication.

Current Status

Hydrologic evaluations on the Three-Bar watersheds were discontinued in 1983. The Three-Bar Wildlife Area remains ungrazed and provides a study site for current wildlife studies and for monitoring by the Arizona Game and Fish Department.

Chapter 4

Managing Chaparral in Yavapai County

Leonard F. DeBano, Malchus B. Baker, Jr., and Steven T. Overby

Introduction

Yavapai County in central Arizona supports extensive stands of chaparral in the Bradshaw Mountains, Mingus Mountain, and the Santa Maria Range. Chaparral occupies about 400,300 acres of the Prescott National Forest (Anderson 1986). These chaparral communities provide a wide range of benefits including watershed protection, grazing for wildlife and domestic animals, recreational opportunities, and wildlife habitat. As in other chaparral areas in Arizona and California, these shrublands are subject to regular wildfires that can destroy the protective shrub canopy and leave the burned areas susceptible to runoff and erosion, normally for 3 to 4 following fire.

Mining and cattle ranching are important activities in these chaparral areas (Bolander 1986). Cattle grazing of chaparral stands began in central Arizona around 1874 and within a single decade the vegetation type was almost entirely stocked or overstocked (Croxen 1926). Almost every acre of Yavapai County was occupied by cattle or sheep by 1890. Because of these early extremely high stocking rates, by 1926 grasses in many chaparral stands had disappeared and the cover and density of shrubs had increased (Cable 1975).

The extensive stands of chaparral in Yavapai County provided the setting for further refinement of research evaluations and management techniques that started earlier in the Salt-Verde Basin (see DeBano et al., Chapter 4 of this publication). Consequently, experimental watersheds (Whitespar and Mingus), experimental grazing areas (Tonto Springs), and a pilot application area (Battle Flat) were established in Yavapai County. Satellite research studies were also implemented on fire effects and designing prescriptions for prescribed burning in chaparral.

Experimental Watersheds

Three experimental watersheds, the Whitespar, Mingus, and Battle Flat, were established in Yavapai County to study chaparral management (figure 9). The Whitespar watersheds played an important role in assessing the potential water yield increases that could be obtained by chaparral conversion practices in areas of moderately dense chaparral (40% to 60% cover density). This information extended the research results obtained from the Three-Bar watersheds, which were covered with a dense stand of chaparral (see DeBano et al., Chapter 3 of this publication). The Mingus watersheds contained a sparse cover of chaparral and were similar to the Natural Drainages watersheds on the Sierra Ancha Experimental Forest (see Gottfried et al., Chapter 2 of this publication).

Whitespar Watersheds

A pair of watersheds located about 8 mi southwest of Prescott, on the Prescott National Forest, were gaged in 1958. One watershed designated as Whitespar A was

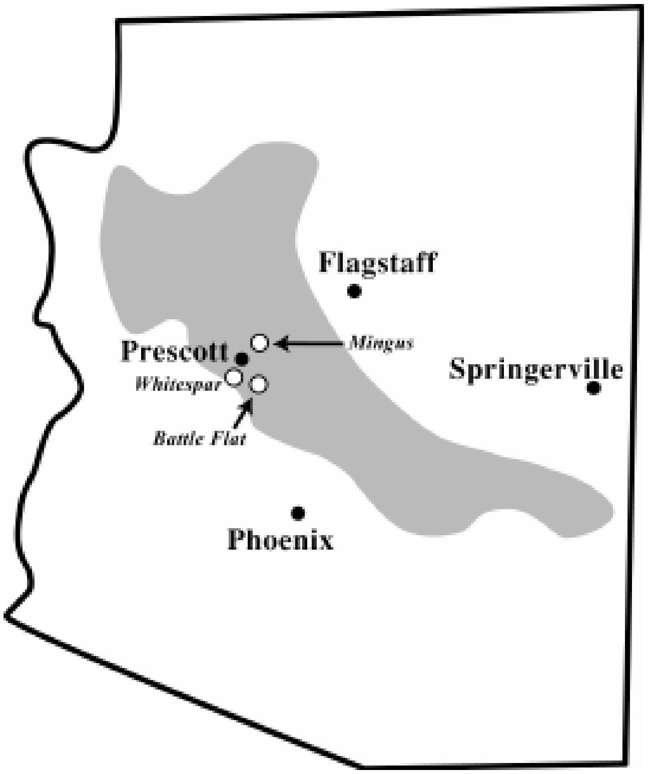

Figure 9. Watersheds in Yavapai County in the Central Arizona Highlands.

about 300 acres in size and an adjacent watershed designated as Whitespar B was 250 acres. The elevations of Whitespar A and B range from 5,900 to 7,200 ft (Davis 1993). The climate is semi-arid with 26 inches of annual precipitation over 30 yr. About 90% of the streamflow from the untreated watershed occurred between December and April. Medium-dense chaparral composed of shrub live oak/hairy mountainmahogany (*Quercus turbinella/Cercocarpus breviflorus*) habitat type provided a crown cover of about 50% (Hibbert and Davis 1986). Whitespar A was dominated by chaparral with isolated areas of Gambel oak and ponderosa pine along the upper ridges and north-facing slopes. Whitespar B was totally covered with chaparral.

The initial research emphasis on the Whitespar watersheds was on water yield responses, with sediment production as a secondary hydrological evaluation. The major input and output measurements were precipitation, stream discharge, and sediment production. There was also emphasis on developing methods for controlling chaparral and converting a shrub cover to grass. As the research program evolved, environmental and ecological issues became increasingly important. One of these issues was increased nitrate concentrations that had been detected earlier on the Three-Bar experimental watersheds (Davis 1984). The need to convert chaparral in a mosaic pattern to enhance wildlife, reduce fire danger and nitrate release resulting from brush control, and improve esthetics strongly influenced later treatments.

The Whitespar watersheds were treated in 3 phases reflecting the changing emphasis on chaparral management over time. Each treatment phase required a pretreatment stream discharge calibration period lasting several years to establish the annual runoff relationship between the control and the treated watershed. The 3 treatment phases on Whitespar A and B were experiments designed to address emerging questions.

The Phase 1 experiments were applied to Whitespar B in the 1960s to determine whether annual streamflow could be increased by killing the chaparral brush and trees in and along the main channel (essentially a riparian treatment). Previous studies in California indicated that clearing trees along channels would substantially decrease evapotranspiration and increase streamflow (Rowe 1963). The main emphasis in the 1950s and early 1960s was managing chaparral vegetation to produce water yield increases. The riparian areas throughout the Central Arizona Highlands were viewed as major consumers of available water, causing reduced streamflow. Conversion of these woody riparian species to grass or other species that use less water was promoted. A decade later, these riparian systems were recognized as important recreation sites and wildlife habitats that required preservation and enhancement to maintain their sustainability (see Baker et al., Chapter 7 of this publication).

Within the context of earlier research emphasis on riparian treatment, 37 acres (about 15% of the watershed) of the channel area were treated with soil-applied herbicides that was hand applied underneath shrubs and small junipers in March 1967 (Hibbert et al. 1974). Intershrub spaces were not treated to avoid killing grasses and forbs. Larger junipers were either cut or girdled. The single application of the soil-applied herbicide gave 80% to 90%

Figure 10. Vegetation treatment in the Phase 2 experiment on Whitespar B.

control of the shrubs and made a follow-up treatment unnecessary. The channel treatment effect was evaluated for 7 yr, after which the Phase 2 experiment was initiated.

The Phase 2 experiment began in 1973 with a second treatment on Whitespar B. This experiment was started after the effect of the channel treatment on streamflow had stabilized and been evaluated. The objective of the Phase 2 experiment was to determine whether ridgeline brush-control would affect annual streamflow volume. The treatment consisted of treating the boundary ridges and a main centrally-located ridge with soil-applied herbicides broadcast aerially (figure 10). A follow-up treatment was necessary in 1976 because of uneven chemical distribution and poor shrub control after the aerial application. The overall shrub reduction on the areas treated was about 85% (Hibbert et al. 1986). The combined area was about 20% of the watershed (49 acres). The evaluation was for 7 yr.

The Phase 3 experiment was the last applied on the Whitespar watersheds. In February 1981, soil-applied herbicides were applied by helicopter in a mosaic pattern on Whitespar A. The treatment was applied to about 55% of the watershed (168 acres). This treatment pattern was designed to incorporate what had been learned from previous experiments into a design that would increase water yield without degrading wildlife habitat or other watershed resource values. Hydrology, soil-plant water relations, and wildlife habitat improvement were considered in designing a mosaic conversion pattern on Whitespar A that was aesthetically pleasing and technically feasible to implement by applying herbicide with a helicopter (Hibbert and Davis 1986). Because of esthetics and wildlife values, all ponderosa pine and Gambel oak stands were excluded from treatment. The ponderosa pine sites were used extensively for roosting doves and pigeons and contained big game trails leading into the watershed. Gambel oak sites along stream channels are valuable javelina (*Tayassu tajacu*) and deer habitat.

Mingus Watersheds

Three Mingus experimental watersheds, located about 23 mi northeast of Prescott, Arizona, were established in 1958 and equipped with stream gaging stations in 1960 (Ffolliott and Thorud 1974, Hibbert 1986). Watershed A is about 96 acres, Watershed B is 67 acres, and Watershed C is 44 acres. The mid-area elevation ranges from 6,200 to 6,560 ft and the mean annual precipitation over 12 yr averages 17 to 19 inches. The chaparral cover consisted of a low density stand of shrub live oak-mountainmahogany brush. The density was less than 40% crown cover. The mean annual streamflow on the untreated watersheds was 0.04 to 0.19 inch and was ephemeral.

The treatment plan called for Watershed A to be burned and Watershed B to be treated with chemicals (figure 11). Watershed C was the control. Chemicals, fire, or a combination, were to be used to maintain the brush cover below 10% crown density (Ffolliott and Thorud 1974). The upper halves of Watersheds A and B were treated in 1974 and the lower halves in 1975 to minimize any treatment-induced erosion (Hibbert 1986).

Figure 11. Burning treatment applied on Mingus Mountain Watershed A.

Battle Flat Pilot Application Program

Following 20 yr of research on small experimental watersheds in the chaparral shrublands, planning began for a joint pilot application project in 1976 between the Southwestern Region of the USDA Forest Service and the Rocky Mountain Forest and Range Experiment Station (Bolander 1986, Hassel 1976, Krebill and Tackle 1978). The objective of this pilot application program was to test the state-of-the art technology on a larger, operational-scale chaparral watershed. Management techniques aimed at improving the production of water, maintaining water quality, increasing livestock and wildlife forage, enhancing wildlife habitat, reducing fire hazard and erosion, and determining the economic feasibility of chaparral management was to be evaluated and refined. This program also provided research opportunities to study fire effects on nutrients, erosion and sedimentation rates, plant productivity and growth, and fire history.

Study Area

A 3,780-acre watershed (Battle Flat) on the Prescott National Forest in central Arizona was designated as a pilot application area in chaparral shrublands in July 1977 (Hassell 1976). The Battle Flat Demonstration Area in the Bradshaw Mountains was chosen to test the current knowledge of managing chaparral shrublands on an operational-size watershed (Bolander 1986). The results of all information gained on experimental chaparral watersheds (both in Arizona and in California) were used to design treatments.

The demonstration area consists of 2 adjacent watersheds. The southern-most watershed (1,600 acres) is drained by the northeast trending Tuscumbia Creek; the northern-most watershed (2,174 acres) is drained by the east-southeast trending Battle Flat Creek. Elevation at the junction point of the 2 stream channels is 4,969 ft.

The topography is highly dissected and rugged. Most of the watershed faces southeast with slopes ranging from 8 to 30 degrees. Parent rock materials in the study area consist of granitics, volcanics, and alluvium. The Battle Flat watershed contains 11 different soil-map units (Humbert et al., 1981) whose texture range from sandy loams to very gravelly coarse loams. These soils are located on slopes from 0% to 60% and are all less than 16 inches deep. Runoff on these slopes is rapid, and erosion hazard is moderate to high.

Annual precipitation averaged 27 inches over 10 yr. The watersheds were dominated by shrub live oak (48%), birchleaf mountainmahogany (27%), and pointleaf manzanita (19%). The remaining 6% cover was a combination of several other species.

Project Planning, Inventories, and Research

Before treatment, several inventories were done on the control (Tuscumbia) and treated (Battle Flat) watersheds in addition to hydrologic instrumentation. These inventories included archaeologic, geologic, vegetation, soils, hydrologic, and wildlife habitat. The vegetation and wildlife inventory was done jointly by the Prescott National Forest, Southwestern Region of the Forest Service, and the Rocky Mountain Forest and Range Experiment Station in coordination with the Arizona Game and Fish Department.

Once the inventory data were obtained, it was possible to specify the mosaic treatment pattern. This effort included modeling chaparral conversion for water augmentation based on social, economic, and ecological parameters (Hodge et al. 1985). The purpose of the model was to maximize water yield, while constraining the anticipated effects of conversion within selected boundaries. Upper limit constraints were based on nitrate and herbicide contamination of water and soil erosion due to conversion. Lower limit constraints were based on economic benefits associated with increased water yield to ensure cost-effectiveness. This research was used to decide which soil-mapping units were appropriate for treatment based on the model. According to this model, about 50% to 55% of the watershed was to be treated in a mosaic pattern similar to that developed for Whitespar A, which was described earlier.

Several nutrient cycling studies on shrubs and soils were accomplished as part of the overall research program. One study was designed to gather prefire data over several years, focusing on plant available nitrogen and phosphorus, and comparing immediate pre- and post-burn levels of available nitrogen and phosphorus (Overby and Perry 1996). This study was coordinated with one on the effect of aspect and shrub species on the availability and accumulation of nitrogen and phosphorus in soils (Klemmedson and Wienhold 1991a, 1991b). Nutrient and biomass studies were completed on shrub live oak and birchleaf mountainmahogany before and after fire (Whysong 1991, Whysong and Carr 1987).

Hydrologic research evaluations consisted of analyzing stream flow data from several permanent gaging stations located on the major drainages and on some of the smaller subdrainages in the Battle Flat and Tuscumbia watersheds. In addition, stock water tanks were established in 2 of the smaller watersheds to obtain annual measurements of sediment production. One of these watersheds was prescribe-burned in 1985 (figure 12). Nutri-

Figure 12. Igniting prescribed fire on Battle Flat with heliotorch.

ent changes and losses associated with increased erosion resulting from this prescribed burn were also studied (Overby and Baker 1995, Overby and Perry 1996, Hook and Hibbert 1979).

Relatively little was known about the fire history in the chaparral shrublands at the time, although fire suppression records indicated that large fires had been common. The Battle Flat area provided an opportunity to establish the fire history in chaparral stands because vegetation along the drainages contained ponderosa pine trees that could be dated by tree ring methodologies based on interpreting fire scars on the trunk of ponderosa pine trees (Dieterich and Hibbert 1990). Shrubs do not lend themselves to this analysis because the whole plant is often consumed during a fire. In contrast, during ground fires the basal area of some ponderosa pine trees may be scarred without significantly damaging the trees. Therefore, the close association of ponderosa pine trees with surrounding hillslopes covered with chaparral allowed fire frequencies to be estimated for both the pine and chaparral areas.

Cooperators

In collaboration with the pilot application program, several research studies were initiated by Rocky Mountain Forest and Range Experiment Station scientists and other scientists from Arizona State University and the University of Arizona. These studies included establishing baseline information on streamflow, erosion and sedimentation, shrub biomass, scenic beauty, effects of fire on nutrient cycling, fire history, and the effect of fire on erosion.

Streamflow, precipitation, and sediment measurements were a joint effort between the Rocky Mountain Research Station and the Prescott National Forest. Overall program management was jointly shared by a project leader for the Rocky Mountain Research Station, the supervisor of the Prescott National Forest, and the lead hydrologist for the Southwestern Region of the Forest Service.

Results

As previously stated, 2 status-of-knowledge publications presented the results of water yield improvement experiments and other research conducted on the watersheds in chaparral shrublands (Brown, T. C. et al 1974, Hibbert et al. 1974). These results have been refined and, in some cases, expanded in subsequent publications. A brief discussion of the results is presented below; details are in the cited literature.

Whitespar Watersheds

The channel treatment of trees and shrubs at Whitespar B (Phase 1) resulted in an increase in amount and duration of streamflow. Although only 15% of the watershed was treated, it produced perennial flow in previously ephemeral stream channels that was beneficial to wildlife and livestock (Hibbert et al. 1986). When the increases were prorated to the area treated, there was an annual increase in streamflow of 4.2 inches. The increase in streamflow was short-lived as vegetation recovered after treatment and below normal precipitation occurred.

Ridgetop treatment of trees and shrubs at Whitespar B (Phase 2) resulted in no additional streamflow increases (Hibbert et al. 1986). It was concluded that any water saved by reducing the shrub cover along the ridgelines was used by the untreated downslope shrubs before it reached the channels.

The mosaic treatment of brush on Whitespar A (Phase 3) resulted in:

- Increased annual streamflow of 1.5 to 5.0 inches over a 7-year posttreatment evaluation period.
- A small, but statistically significant, increase in nitrate concentrations was attributed to the mosaic treatment (Davis 1993). Nitrate nitrogen released from converted areas was diluted by streamflow from untreated areas, which reduced nitrate concentrations in streamflow at the watershed outlet.

Mingus Watersheds

As expected, only small increases in streamflow occurred as a result of treatment on the Mingus Watersheds. Annual streamflow from Watershed A (prescribed burn) increased 0.30 inch and Watershed B (chemical treatment) increased 0.22 inch (Hibbert et al. 1986). The magnitude of response was similar to that measured on the low-precipitation watersheds of the Natural Drainages watersheds study area on the Sierra Ancha Experimental Forest (Gottfried et al,. Chapter 2 of this publication).

Battle Flat Watershed

Although extensive instrumentation, inventories, and baseline research studies were performed on the Battle Flat Demonstration Area, treatment of the entire watershed was delayed because of the political and legal constraints surrounding the widespread use of soil-applied herbicides for treating watersheds. However, one small area on the Battle Flat watershed was prescribe burned in 1985. Measurements associated with this prescribed fire, along with other inventories and studies, added to our basic understanding of chaparral shrublands.

Sediment accumulations in the 2 stock tanks before treatment with prescribed fire, showed that sediment production from chaparral is primarily the result of winter periods of heavy precipitation and runoff and generally not from summer rainstorms (Hook and Hibbert 1979). The sediments came mostly from erosion of channel alluvium in upstream tributaries where the sediments accumulated from downslope creep, dry ravel, and overland flow produced during the typical, smaller, convective rainstorm events. The study further concluded that:

- The long-term sediment rate from the unburned watersheds was about 0.6 lb / acre annually, but increased to almost 2.7 lb / acre (about 4 times) during winters of heavy precipitation.
- After the prescribed burn, sediment yields increased to over 7 lb / acre (about 12 times) annually for 3 years following the fire (Overby and Baker 1995).
- The increased erosion resulting from the prescribed fire removed substantial amounts of nitrogen, phosphorus, and cations from the burned watershed (Overby and Baker 1995). Both concentrations and amounts of these nutrients increased in the sediment material that was eroded from the burned areas.

A separate study on the small watersheds within the Battle Flat Watershed showed that interactions between species composition and aspect have an effect on nutrient responses to prescribed fire. Higher preburn nutrient concentrations were found under shrub live oak than under mountainmahogany (Klemmedson and Wienhold 1991a). Phosphorus was also a limiting nutrient before burning, particularly on south aspects (Klemmedson and Wienhold 1991b).

The results after the prescribed burn indicate that:

- Ammonia and phosphorus were translocated downward in the soil as a result of fire (Overby and Perry 1996).
- Residual ash and underlying soil contained increased concentrations of available nitrogen and phosphorus. This temporarily increased soil fertility on the burned sites.

Fire history for the Battle Flat watershed was established from the mid 1800s (Dieterich and Hibbert 1990). Reconstruction of the history showed that:

- Fires burned at an average 2-yr interval within the 200 acre ponderosa pine stand and surrounding chaparral, before intensive mining activities began in the 1860s.
- Ponderosa pine and associated oak and juniper trees were heavily cut during expansion of local mining from 1863 to 1885, after which fire protection, low fuel loading, and grazing eliminated large fires for many years. This resulted in the current overmature chaparral stands that lack a natural mosaic appearance and contain heavy accumulations of dead material.

- Large wildfires have swept through continuous stands of dense chaparral since the 1900s due to the large fuel accumulation.

Implications

Research and management efforts in Yavapai County consisted primarily of testing previous research findings on experimental watersheds and on an operational scale. Studies at Whitespar and Mingus experimental watersheds extended the information gained from the Three-Bar watersheds and Natural Drainages watersheds in the Salt River Valley (DeBano et al. Chapter 3 of this publication). It was concluded from the investigative studies that:

- The mosaic pattern (where about 50% of the brush was treated with soil-applied herbicides and fire) was beneficial for increasing water yield, maintaining water quality, improving wildlife habitat, and reducing fire hazard.
- The availability of soil nitrogen and phosphorus increased as a result of the burning and these fire-related responses were affected by plant species and aspect. The increased nutrient availability disappeared after 2 yr.
- Sediment production and nutrient loss increased even after low-intensity prescribed burns.
- Long-term productivity and sustainability of chaparral ecosystems were enhanced by prescribed fire (Overby and Perry 1996).

Current Status

Evaluations on the Mingus experimental watersheds were discontinued in 1983 and on the Whitespar watersheds in 1986 as part of the change in emphasis of watershed research in the Central Arizona Highlands. Streamflow and precipitation measurements were continued at Battle Flat through 1989, then all data collection was terminated.

Chapter 5

Interdisciplinary Land Use Along the Mogollon Rim

Malchus B. Baker, Jr. and Peter F. Ffolliott

Introduction

The amount of water stored in the Salt River Project reservoirs during the middle 1950s was low and, as a consequence, apprehension arose among some residents of the Salt River Valley that a serious water shortage would soon occur. Groundwater supplies in the Valley were also being rapidly depleted, and pumping costs were steadily rising. Long-term studies at Sierra Ancha Experimental Forest had shown some potential for increasing runoff by converting chaparral shrublands to grass (Gottfried et al., Chapter 2 of this publication). Therefore, a belief existed that the yield of water from the Salt and Verde Watersheds could be increased by drastic, but fairly simple, conversions of the various vegetation types. Suggestions for water yield improvement included widespread burning of chaparral, eradication of pinyon-juniper woodlands by burning and mechanical methods, and prescribed burning in ponderosa pine forests.

Several ranchers met with a USDA Forest Service representative and an official with the Salt River Project on the Beaver Creek watershed near Flagstaff to address this issue in the summer of 1955. People at this meeting were concerned that the flow of streams and the amount of livestock forage on watersheds in the Salt-Verde River Basins were being reduced by increasing densities of ponderosa pine saplings. As a result of this meeting, the University of Arizona was commissioned to investigate the potential for increasing water yields from the state's forests and rangelands. The findings of this study were contained in a publication entitled "Recovering Rainfall: More Water for Irrigation," commonly referred to as the Barr Report (Barr 1956). The study suggested that surface runoff from mountain watersheds might be increased by replacing high water-using plants, such as trees and shrubs, with low water-using grasses and forbs. This report resulted in a demand for an immediate action program to ascertain the feasibility of improving water yields through vegetative manipulations.

But many questions as to the effects of such vegetative manipulations on other natural resource products and uses of the watersheds remained unanswered, and the effectiveness of most of the practices proposed was largely untested. In response to the demand for increased water yields, the Arizona Water Program of the USDA Forest Service was initiated in the late 1950s to evaluate the feasibility of selected vegetative management programs to increase water yields and other multiple resource benefits in the Salt River Basin (Arizona State Land Department 1962). The Beaver Creek watershed became a significant component of this program.

Beaver Creek Watershed

The Beaver Creek watershed encompasses 275,000 acres on the Coconino National Forest, upstream from the junction of Beaver Creek and the Verde River (figure 13). This watershed is part of the Salt-Verde River Basin, which is a

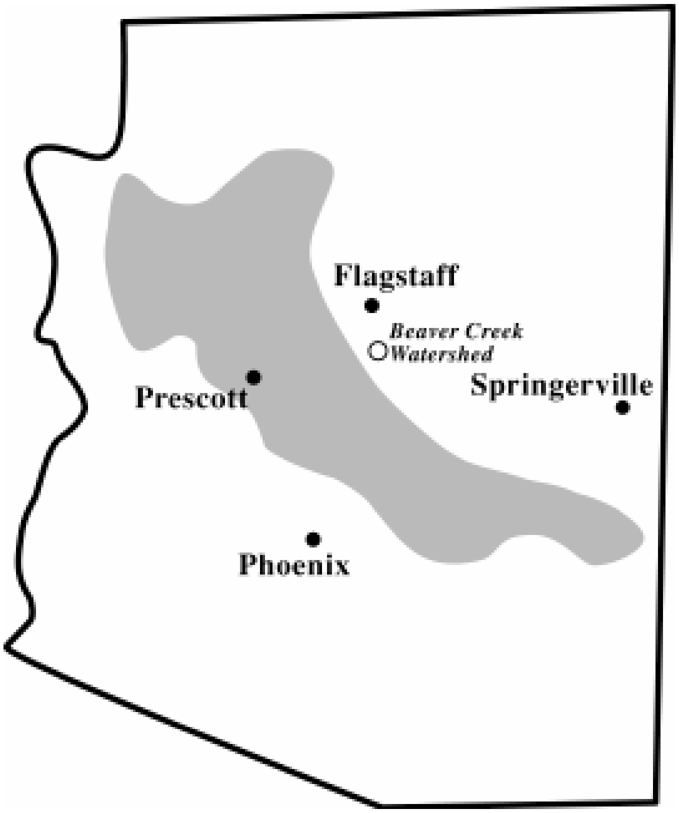

Figure 13. Beaver Creek watershed in the Central Arizona Highlands.

major river drainage in central Arizona. The Salt and Verde Rivers provide much of the water for Phoenix and other communities in the heavily populated Salt River Valley. The Beaver Creek watershed was selected for research because it contains extensive areas of ponderosa pine forests and pinyon-juniper woodlands, which are found in the Central Arizona Highlands and throughout the Southwest (Worley 1965).

Beaver Creek Project Design

The Beaver Creek Project was initiated by the USDA Forest Service as a pilot study in 1957 to test some of the Barr Report hypotheses. The original plan was to apply generally accepted management practices intensively to one large watershed, while retaining a similar watershed in an untreated condition to determine whether a change in runoff could be detected. Management practices contemplated were:

- Thinning and debris disposal in ponderosa pine forests to improve the growth of residual trees.
- Eradication of the pinyon-juniper woodlands to enhance livestock grazing conditions.

Isolation of the effects of certain land treatments was necessary to concentrate on treatments that were thought to be effective in improving water yields. A system of smaller pilot watersheds was established to study these effects.

Pilot Watersheds

Since the standard program of applying management practices to large areas of vegetation would take several years to perform, smaller watersheds were selected for treatment to obtain results earlier and to determine if local changes in runoff could be realized downstream. Twenty pilot watersheds were established between 1957 and 1962 to test the effects of vegetation management practices on water yield and other resources (Brown, et al. 1974). Of the 20 watersheds, 18 were from 66 to 2,036 acres in size; 3 in the Utah juniper type, 3 in the alligator juniper type, and 12 in the ponderosa pine type. The other 2 catchments, encompassing 12,100 and 16,500 acres of ponderosa pine forests, were set aside to demonstrate the effects of management practices on areas the size that managers work with operationally.

Stream gauges were built at the outlets of all watersheds, while sediment-measuring devices, in which suspended sediments and bedloads could be collected, were constructed on some. A network of precipitation gauges was installed throughout the study area (Baker 1982). Timber, herbage, and wildlife resources were inventoried (the latter by the Arizona Game and Fish Department) on a system of permanently-located primary sampling units established on each pilot watershed (Brown et al. 1974, Clary et al. 1974). Point sampling techniques were used to monitor stand structures, tree-stem form, and species composition over time. These sampling points were also center-points for plots of varying sizes on which regeneration success, herbaceous vegetation, wildlife populations and habitat preferences, and hydrologic conditions were sampled.

Yields of water, timber, forage, and other natural resource products from the pilot watersheds were determined before any treatments were applied to provide the needed pre-treatment calibration information. One watershed was then altered through vegetative manipulation and another held in its original condition as a control for evaluations of potential changes in these yields. If a resource change was detected after treatment, it was attributed to the treatment implemented.

To refine the findings from the studies on the pilot watersheds for use over a wide range of conditions, 24 smaller watersheds, 12 to 40 acres in size, with more uniform soil, plant life, and topography, were established in the early 1970s to sample the range of diverse ecological characteristics in the ponderosa pine forests (Brown et al. 1974). To compare the findings from watersheds with soils developed on basalt and cinders (55% of the Salt-Verde River Basin) to watersheds on soils formed from sedimentary rocks (45% of the Salt-Verde River Basin), 3 of these smaller watersheds were established on limestone soils (Campbell et al. 1977) and 4 were installed on sandstone soils (Ffolliott and Baker 1977).

Responsibilities

The Beaver Creek watershed, located on the Coconino National Forest, is administered for a full range of multiple use benefits. National forest personnel installed many of the measuring structures and devices, performed the land treatment prescriptions, and accomplished the normal protection and management functions.

Up dated evaluation techniques would be required if the Beaver Creek Project was to meet its objective. As a consequence, the assistance of Forest Service Research was necessary. A team of forest, range, and watershed *scientists, economists,* and *hydrologists* was assigned full-time to the project in 1960. This team of Rocky Mountain Forest and Range Experiment Station employees, in collaboration with their cooperators, developed the necessary research studies to support the project, and helped national forest personnel design the treatments that were applied to the pilot watersheds. This team was also responsible for collecting and analyzing much of the data obtained on the pilot watersheds before and after treatment.

Wild Bill Studies

Knowledge of the relationships between various land products and uses is required for effective multiple use planning. If managers modify an area in favor of one product, what will be the effect on other products? Since cattle production was an integral part of the Beaver Creek Project, an area of approximately 1,300 acres of ponderosa pine-bunchgrass range was established to develop relationships between beef and forage production under different overstory densities (Pearson 1972). The area, known as the Wild Bill Cattle Allotment, is northwest of Flagstaff on the Coconino National Forest. Specific objectives for this study were to:

- Determine the effects of various tree overstories on quantity, quality, and composition of forage.
- Establish the relationships between beef and timber production at various tree overstory densities.

Information obtained on Wild Bill was used to estimate changes in beef production following the various treatments applied to the Beaver Creek watershed. This aspect of the project resulted in a number of publications related to forage digestibility by cattle, plant phenology and forage production, and beef-forage-timber relationships (Clary et al. 1975, Pearson 1972, 1973, Pearson et al. 1972).

Biosphere Reserve

In 1976, the Beaver Creek watershed was designated a biosphere reserve, a component of a worldwide network of biosphere reserves in UNESCO's Man and the Biosphere (MAB) Program. Previously, the governors of Arizona and the State of Durango, Mexico, signed an agreement entitled "Comparative Studies of Dry Forests in Western North America" to improve the scientific knowledge and technology of Mexico and the United States. Two sites, the designated La Michilia Biosphere Reserve in Durango, Mexico and the designated-to-be Beaver Creek Biosphere Reserve, were selected as the primary study areas for this bi-national program.

Although the 2 biosphere reserves contained dry forests and woodlands, La Michilia and the Beaver Creek watershed were distinct from one another in some respects. Little information on multiple resource management had been gathered at La Michilia, an area partly used for timber production, livestock grazing, and hunting. Beaver Creek, however, had been managed actively for multiple resource benefits by the USDA Forest Service and, as mentioned, was the center of an intensive multiple-resource management, research, and testing program. While dissimilar with respect to past management and research activities, the 2 biosphere reserves shared similar climatic, topographic, and land use characteristics. Objectives of this bi-national program were to:

- Analyze the growth, yield, and quality of timber resource for primary wood products.
- Investigate the levels of forage production and associated cattle, other livestock, and wildlife production on the representative grazing lands.
- Determine the habitat requirements and the distribution of preferred habitats for indigenous wildlife species and cattle, with an emphasis on food habitats, population dynamics, carrying capacities, and potential competition.
- Develop a set of simulation techniques to predict the environmental and socioeconomic consequences of alternative land use practices and provide a basis to identify improved methods for sustainable multiple resource management and environmental preservation.
- Produce a computerized data management system to assist decision-makers and managers in achieving wise use and proper conservation of all natural resources.

From information obtained from the 2 biosphere reserves, alternative land management practices could be proposed to meet the local needs of forage for livestock and wildlife and timber for lumber and fuelwood supplies while attaining conservation through environmentally-sound management practices. Publications from this bi-national program are reported in a Department of State publication in which MAB-sponsored research in the temperate regions of the world was reviewed (Ffolliott and Bartlett 1991).

Cooperators

By the late 1960s, the major objective of the Beaver Creek Project had evolved into evaluations of the effects of vegetative treatments on all of the natural resources and uses of national forest lands, rather than on only water yields (Brown et al. 1974). Therefore, cooperation of many agencies, institutions, and organizations was enlisted. The help of the U.S. Geological Survey was secured to install and service specific stream gauges. The Arizona Game and Fish Department evaluated the effects of treatments on wildlife populations and habitat conditions. Research by universities in the state complemented the efforts of scientists from the Rocky Mountain Forest and Range Experiment Station. The advice and support of other groups, including the Salt River Project, Soil Conservation Districts, cattle-grower's associations, timber industries, and others, was solicited and made available.

One of the most important groups was the Arizona Water Resources Committee (AWRC); a committee comprised of civic-minded, thoughtful representatives of practically every citizens' group interested in public land management. The AWRC worked closely with the supervisor of the Coconino National Forest, supervisors of other national forests in the Central Highlands, the regional forester, and the director of the Rocky Mountain Forest and Range Experiment Station in an advisory and supporting capacity. The AWRC also played a critical role in securing the necessary financial support for much of the work accomplished by the Beaver Creek Project and the Arizona Watershed Program as a whole.

Results

Results from the experiments and studies conducted on the Beaver Creek watershed have been reported in nearly 700 publications including USDA Forest Service releases, journal articles, and special publications on specific topics (Baker and Ffolliott 1998). While the details of all of these results cannot be presented here, highlights of the major findings are presented.

Two status-of-knowledge publications presented the results of water yield improvement experiments and other research conducted on the pilot watersheds through the early 1970s. One of these publications reported on the opportunities for increasing water yields and other multiple use values in the ponderosa pine forests (Brown et al. 1974). The other publication described the effects of removing pinyon-juniper woodlands on natural resource products and uses (Clary et al. 1974). Many of these results have been refined and, in some cases, expanded upon in subsequent publications listed in an annotated bibliography of 40 yr of investigations on the Beaver Creek watershed (Baker and Ffolliott 1998). A brief discussion of the results is presented below; details are in the referenced bibliography and cited literature.

Natural resource responses to manipulation of ponderosa pine forests by total clearcutting (figure 14a), stripcutting in uniform or irregular strips (figure 14b), strip shelterwood cutting, thinning by group selection (figure 14c), a combined shelterwood-seed tree silvicultural treatment, patch cutting to improve wildlife habitats, and grazing on a watershed converted to herbaceous plants include:

- Annual water yield increases of 1 to 2 inches were realized in the initial (up to 10 yr) post-treatment periods as a result of various intensities and patterns of forest overstory reduction (Baker 1986). Considering multiple use objectives, an average annual increase of almost 0.6 inch is possible on the more productive sites (Brown et al. 1974). These increases in water yields diminished over time, approaching pretreatment levels after 10 or fewer yr.

- No meaningful changes in total sediment production or water quality occurred as a result of the treatments applied in ponderosa pine forests. However, relationships between the amount of sediment in suspension and streamflow discharge differed among the treated watersheds (Dong 1996). Highest sediment concentrations occurred after clearcutting, followed, in order of decreasing concentration, by stripcutting, thinning by group selection, and the combined shelterwood-seed tree silvicultural treatment.

- Repeated inventories of the timber resource indicate that volume production has been maintained in many cases, although at generally lower levels than those represented by pre-treatment conditions. Exceptions to this finding are on a watershed that was totally cleared in 1966 and 1967. Another watershed had also been converted from ponderosa pine forest to grass in 1958 and subsequently subjected to grazing in the spring and fall starting in 1968. While these 2 watersheds are currently stocked by stands of Gambel oak and alligator juniper, they have been withdrawn from pine production due to inadequate natural pine stocking (Ffolliott and Gottfried 1991a).

- Reductions in the density of ponderosa pine forest overstories have generally resulted in increases in the production of herbaceous plants (Bojorquez-Tapia et al. 1990) and vice versa. These increases can approach 500 lbs / acre after complete overstory removal including forage and non-forage plants. Average pretreatment forage production was 200 lbs / acre.

Figure 14a. Vegetation treatments in ponderosa pine forests on Beaver Creek Watershed including clearcutting (*top*), strip-cutting in uniform strips *(middle*), and thinning by group selection(*bottom*).

- Reducing densities of ponderosa pine forests has also increased food for deer and elk, while retaining protective cover (Larson et al. 1986). Residual dense stands, often referred to as dog hair thickets, have frequently provided bedding cover. Total clearcutting is detrimental to big game and Abert squirrel (*Sciurus abertii*), although cottontail habitat can be enhanced when slash and Gambel oak thickets are retained (Ffolliott 1990).
- Public responses to vegetative treatments applied to the Beaver Creek watersheds were variable. Through applications of Scenic Beauty Estimation (SBE), which provides quantitative measures of aesthetic preferences for alternative landscapes (Daniel and Boster 1976), natural-appearing watersheds were preferred by most publics. This conclusion substantiated the claim that naturalness is a desirable forest landscape characteristic (Boster and Daniel 1972). Also 2 of the treated sites studied, a conventional logging of Mahan Park near Beaver Creek and a uniform stripcut on Beaver Creek Watershed 9, were preferred by many publics over a nearly natural relict forest, despite the fact that these 2 sites were clearly distinguishable as treated. SBE is an efficient and relatively objective means of assessing the scenic beauty of forests and other wildlands and of predicting aesthetic consequences of alternative land management practices.
- Information obtained on resources in the ponderosa pine forests provided a framework for developing models to simulate the responses of natural resources to the treatments applied to the Beaver Creek watersheds. This aspect of the project resulted in a number of publications related to hydrology, vegetation, and wildlife responses (Baker 1975, Bojorquez-Tapia 1987, Brown and Daniel 1984, Ffolliott 1985, Ffolliott et al. 1988, Larson 1975, Larson et al. 1979, Li et al. 1976, O’Connell 1971, Rogers 1973, Rogers et al. 1982). A complete list of publications on modeling and simulation techniques is in Baker and Ffolliott (1998).
- Fire can be prescribed to consume portions of the forest floor, including the accumulation of dead organic material on mineral soil, and to impact the hydrologic behavior of the burned site (Ffolliott and Guertin 1990). Burning the L layer (unaltered organic material), the F layer (partly decomposed organic material), and the H layer (well-decomposed organic material) affects postfire infiltration rates and erosion potentials. Other effects of fire include thinning forest overstories from below, increasing seedling establishment and production of herbaceous plants, and temporarily reducing the fire hazard.
- Wildfire of moderate severity can have effects similar to prescribed fire. However, wildfire of high severity often results in burning the forest floor to the mineral soil and inducing a water-repellent layer in sandy soils (Campbell at el. 1977). The reduced infiltration rates can greatly increase surface runoff from the burned site, which causes soils to erode and removes nutrients that have been mineralized by the fire. All small trees and many large trees can be killed, which results in large increases in herbage production.

Conversion of pinyon-juniper woodlands to herbaceous covers by cabling, felling, and herbicide treatments (Clary et al., 1974) resulted in the following resource responses:

- Mechanical methods (cabling and felling) of pinyon-juniper removal cannot be expected to increase water yields (figure 15). However, a herbicide treatment (aerial application of picloram and 2,4-D) increased annual water yield by about 0.6 inch (Baker 1984). In this treatment, the pilot watershed was sprayed with the herbicide mixture to kill the overstory trees. These dead trees were removed after 8 yr of post-herbicide evaluation. Streamflow was reduced to near pretreatment levels after the dead trees were removed
- Cabling resulted in increased suspended sediment concentrations at specified streamflow discharges, while the herbicide treatment did not cause a change (Lopes et al. 1996). Soil disturbances during the uprooting of trees by cabling were believed responsible for the increased sediment concentration. Chemical water quality remained unchanged following conversion.
- Herbage production, generally lower in the pinyon-juniper woodlands than in the ponderosa pine forests, has increased as a result of the conversion treatments (Ffolliott and Clary 1986). The value of this increase for livestock or wildlife is temporary because it probably will decline as the pinyon-juniper overstory becomes reestablished.
- Big and small game species dependent on pinyon-juniper trees for forage and cover generally decline as a consequence of conversion treatments (Ffolliott and Clary 1986). However, cottontails can increase, provided a sufficient canopy cover remains. The numbers of overstory-dependent, non-game birds decrease after treatment and are replaced by ground-feeding species.

Figure 15. Felling treatment in pinyon-juniper vegetation type on Beaver Creek.

These results were obtained on watersheds located on volcanic soils along the Mogollon Rim. The literature suggests that similar results might be obtained on volcanic soils elsewhere in the Central Arizona Highlands. However, extrapolation of the results from Beaver Creek to sites on sedimentary soils requires prior validation (Ffolliott and Baker 1977).

Measurements continued on treated and control watersheds after the treatments were applied. Streamflow, sediment production, and water quality were monitored regularly through 1982. Other resources continue to be reinventoried periodically. Multiple-resource changes caused by management practices applied to pilot watersheds continue to be evaluated by comparing post-treatment values with pretreatment data, and with data from the untreated, control watersheds.

Implications

Similar projects included in the Arizona Watershed Program were undertaken by the USDA Forest Service in mixed conifer forests, chaparral shrublands, and streamside vegetation, as reported elsewhere in this publication. Results of studies conducted at Beaver Creek, and other research sites in the Central Arizona Highlands, have shown that:

- Changes in vegetative cover can produce short-term changes in streamflow from some vegetation types (Hibbert 1979, Baker 1984, 1986).
- Much of the additional streamflow accrues during above average precipitation years when reservoir capacity or operating strategy may not allow effective use or control of this additional runoff.
- Some vegetative modifications on upstream watersheds can be designed to increase water yields and still provide forage, wildlife, timber, and amenity values required by society in some optimal combination. This finding is not surprising as many of the management practices tested are common in principle and application to programs often used to benefit other natural resources in a ecosystem-based, multiple-use management framework.

Implications of the Beaver Creek Project and the Arizona Watershed Program as an entity are not confined to the Central Arizona Highlands or to the Southwest, but they are of national and international interest (Ffolliott and Brooks 1990, 1996). The Beaver Creek watershed continues to be frequently visited by scientists, administrators, and students from other states and countries. The results from Beaver Creek are being applied in many arid and semi-arid regions of the world.

Current Status

Most of the published and unpublished results of research conducted on the Beaver Creek Watershed between 1957 and 1982, and from more recent monitoring activities, re-inventories of resources on the watershed, and additional analyses of the original data is in the annotated bibliography by Baker and Ffolliott (1998). The 24 subject areas contained in the bibliography and nearly 700 references cited provide insight into the breadth and diversity of research developed during the Beaver Creek Project.

Because of the unique nature and length of the data sets obtained on Beaver Creek, particularly the hydrologic data, scientists continue to analyze these data sets to meet current objectives. The Beaver Creek watershed has provided the study site and, in many instances, the Beaver Creek Project has furnished financial assistance for 49 theses and 18 dissertations on a diversity of topics. Included are 2 dissertations from Colorado State University; one dissertation from the Massachusetts Institute of Technology; one dissertation from Michigan State University; 9 theses and one dissertation from Northern Arizona University; 39 theses and 12 dissertations from the University of Arizona; and one thesis and one dissertation from Utah State University.

Because of the length of time since much of the original data were obtained (20 to 35 yr in many cases), additional, up-dated information on plant responses to the treatments is being collected by re-inventorying the original, permanently-located sampling units on the watersheds (Ffolliott and Gottfried 1991a, 1991b; Sheppard and Edminster 1997). Repeated measurement of these inventory locations provides a method of evaluating long-term changes in managed and unmanaged ponderosa pine forests and pinyon-juniper woodlands. The information obtained allows investigations of long-term ecosystem responses to disturbances including climatic change, habitat fragmentation, and invasion of exotic species.

The Beaver Creek Watershed remains a biosphere reserve and continues to function as an outdoor laboratory, providing study areas for various research cooperators. Those interested in exploring these opportunities should contact the Rocky Mountain Research Station, USDA Forest Service, Flagstaff, Arizona.

Most of the references in the annotated bibliography of publications based on the Beaver Creek Project (Baker and Ffolliott 1998) are found in the Northern Arizona University Library, Special Collections (Beaver Creek Watershed Project), other university libraries, or the Rocky Mountain Research Station field unit in Flagstaff, Arizona. Included are copies of administrative reports, hand written notes from respective scientists, maps showing location of study plots, and original records of research data. This information is invaluable for continuing long-term evaluations of climate, flora, and fauna of the ponderosa pine forests and pinyon-juniper woodlands in the Southwest.

Chapter 6

Creating a Basis for Watershed Management in High Elevation Forests

Gerald J. Gottfried, Leonard F. DeBano, and Peter F. Ffolliott

Introduction

Higher mountains and plateaus in the Central Arizona Highlands generally support southwestern mixed conifer forests, associated aspen and spruce-fir forests, and a small acreage of grasslands interspersed among the forested areas. Most of the major rivers in the region originate on headwater watersheds that support mixed conifer forests where annual precipitation, particularly snow, is high and evapotranspiration demands are lower than other vegetation types in the Central Arizona Highlands. Rich and Thompson (1974) reported that 6% of Arizona's surface water originates from the portion of the state occupied by mixed conifer watersheds (less than 0.5%).

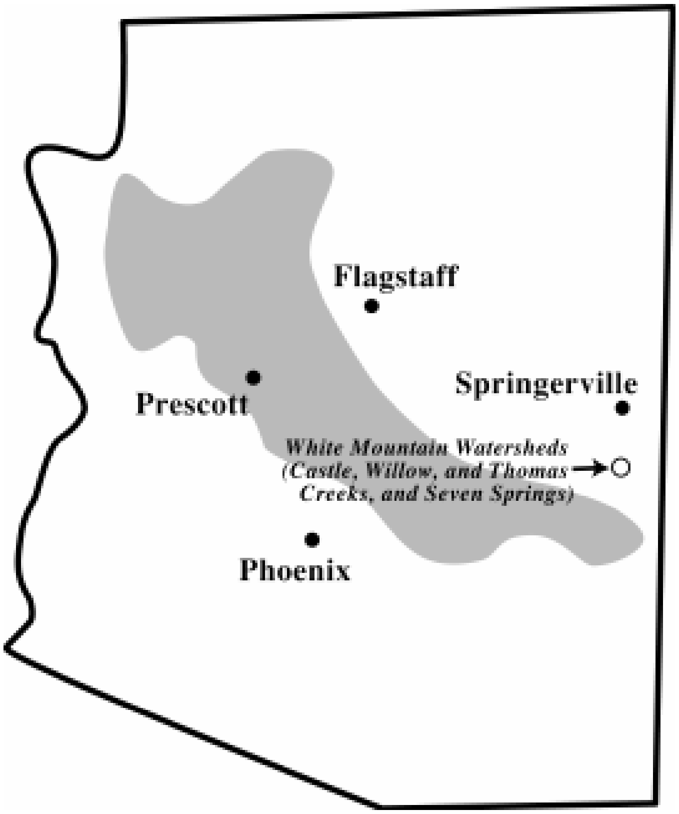

Figure 16. High elevation watersheds in mixed conifer forsets and grasslands of the Central Arizona Highlands.

Studies on the mixed-conifer-dominated watersheds at Workman Creek on the Sierra Ancha Experimental Forest (Rich et al. 1961, Rich and Gottfried 1976, Gottfried et al., Chapter 2 of this publication) demonstrated that large and significant increases in streamflow could be obtained by replacing the forest with a grass cover on large or strategically located parts of a watershed or by greatly reducing the forest overstory density. However, most of the experimental treatments at Workman Creek were relatively drastic and compromised other resource sustainability.

The USDA Forest Service's Rocky Mountain Forest and Range Experiment Station expanded its watershed research program in mixed conifer and high elevation ponderosa pine forests to the White Mountains of eastern Arizona during the late 1950s and early 1960s (figure 16). The initial research objective was to determine if results from Workman Creek experiments could be confirmed, and if they were transferable to other mixed conifer areas in Arizona. Information from the Workman Creek studies provided the basis for designing forest overstory treatments that were beneficial for timber production and wildlife habitat values and that would produce significant increases in streamflow. The major experiments in the White Mountains were designed to test multiple-use forest watershed treatments.

Experimental Watersheds

The White Mountains are a transition area that contains many features of the northern Colorado Plateau and southern Basin and Range Province vegetation types (Chronic 1983). The surface geology is attributed to tertiary and quaternary basaltic eruptions that produced extensive flows (Wilson 1962). Soils are from basalt and, except in alluvial areas, have been classified into the suborder boralf, indicating cool temperatures (Gottfried and DeBano 1990, Gottfried 1991). Most of the surface soils are sandy loams, and soil depths vary from 20 to over 40 inches.

Four pairs of experimental watersheds were established in the White Mountains of Arizona. The East and West Fork Watersheds of Castle Creek are located 12 miles south of Alpine, Arizona. The North and South Fork Watersheds of Thomas Creek are situated south of Castle

Creek, about 14 miles south of Alpine, and the East and West Forks of Willow Creek are located further south near Hannagan Meadows. A fourth set of experimental watersheds, the East and West Forks of Seven Springs, were established in the high mountain grasslands located north and east of Mt. Baldy and 11 miles south of Springerville, Arizona. All watersheds are administered by the Apache-Sitgreaves National Forests.

Castle Creek

The vegetation on Castle Creek is predominately ponderosa pine with an understory of Gambel oak. Mixed conifer species occur on moist north-facing slopes and along drainages. West Fork (900 acres) and East Fork (1,163 acres) range between 7,835 and 8,583 ft in elevation (figure 2). Annual precipitation averaged 27 inches, and annual runoff during the calibration period averaged 2 inches on West Fork and 3 inches on East Fork.

Willow Creek

The East Fork (489 acres) watershed and the West Fork (290 acres) control watershed on Willow Creek range between 8,800 and 9,300 ft in elevation (figure 2). The watersheds received an average annual precipitation of 34 inches (Gottfried et al. 1997). The watersheds supported an old-growth, uneven-aged southwestern mixed conifer forest consisting of Rocky Mountain Douglas-fir, Rocky Mountain white fir, ponderosa pine, southwestern white pine, Engelmann spruce, blue spruce, corkbark fir, and quaking aspen.

Thomas Creek

The South Fork (562 acres) and North Fork (467 acres) of Thomas Creek range from 8,400 to 9,300 ft in elevation (figure 2). The watersheds support dense mixed conifer stands that are similar in composition and structure to those on Willow Creek. Vegetation on most of the watersheds was classified as *Picea engelmannii/Senecio cardamine* habitat type (USDA Forest Service 1986). Annual precipitation averaged 30 inches. Annual runoff from South Fork averaged 3 inches from both South Fork and North Fork.

Seven Springs

A fourth set of experimental watersheds, the East and West Forks of Seven Springs, were established in the high mountain grasslands. The grasslands cover about 80,000 acres at elevations above 9,000 ft, and are surrounded by or interspersed with mixed conifer forests. The predominant grass species is Arizona fescue with associated mountain muhly, pine dropseed, and longtongue mutton bluegrass (*Poa longiliguia*) (Thompson et al. 1976). Elevations on the watersheds range from 9,200 to 9,765 ft. East Fork covers 748 acres and West Fork 482 acres.

Research Design

Castle Creek

The results from the moist-site cut on North Fork and the single-tree selection harvest on South Fork of Workman Creek indicated that even-aged management could maintain long-term timber production and improve water yields (Rich 1972). The 2 Castle Creek Watersheds, East Fork and West Fork, were used to test this hypothesis.

In 1965, one -sixth of the area of the West Fork was harvested in irregular blocks fitted to stand conditions. The remaining area was placed into optimum growing condition by thinning and sanitation operations (figure 17). The idea was to duplicate commercial forest management using a 120-yr rotation and a 20-yr cutting cycle. The harvest reduced watershed basal area from 135 to 63 ft^2/acre. Harvest blocks were planted with ponderosa pine for adequate regeneration.

A debate concerning the impacts of aggressive fire suppression on forest health and the potential dangers of stand-replacing wildfires began in the middle 1970s. Forest history studies indicate that before fire suppression, most wildfires were surface fires that reduced fuel loadings, improved seedbeds, thinned advance regeneration, and retarded the establishment of shade-tolerant species (Dieterich 1983). Managers attempting to reintroduce fire into the region's forests, often found it difficult because of heavy fuel buildups. Therefore, in 1981 a second watershed treatment was initiated at Castle Creek to test the effects of preharvest prescribed burning on water parameters.

The burning treatment was applied to the East Fork, which had previously served as the control watershed. Analyses of the data indicated that this approach was valid because the streamflow annual volume relationship between West Fork and East Fork had remained constant since 1967. The fire was ignited in November 1981 and burned about 503 acres or 43% of the watershed (Gottfried and DeBano 1990). Surface fuels were consumed, while the middle forest floor layer was only slightly charred and few downed logs were totally consumed. Changes in the residual stand were minimal and tree mortality was 1% of the basal area.

Willow Creek

The second test of the effects of timber management was conducted in the mixed conifer stands on the East Fork of Willow Creek in late 1971 and 1972. The objectives of this treatment were to measure the effects of overstory removal and timber selection harvest on the quality and quantity of water yield and on other multiple use products such as timber, forage, wildlife, and recreation (figure 18). The proposed treatment was similar to that applied to the West Fork of Castle Creek. The treatment was designed to bring the basal area level to optimum stocking primarily by removing mature, over-mature, defective, damaged, and high risk trees.

Figure 17. Thinning treatment on the West Fork of Castle Creek.

Figure 18. Patch clearcut treatment on the East Fork of Willow Creek.

Thomas Creek

Research emphasis in the mid 1970s shifted to the South and North Forks of Thomas Creek. The objective was to demonstrate and evaluate the knowledge of integrated resource management for southwestern mixed conifer forests (Gottfried 1991, Gottfried and Ffolliott 1992).

A primary objective of the harvesting treatment on Thomas Creek was to develop an operational resource allocation plan and use a procedure to establish a management plan over a 120-yr period. Brown (1976) developed the basic allocation model. Based on inputs from managers and researchers in natural resource disciplines, a prescription using patch clearcutting with other single-tree and group selection methods was selected. They decided that this prescription would produce the highest return for a mix of timber, watershed, range, and wildlife resources. Harvesting that created small openings had been advocated by Hibbert (1979) and Rich and Thompson (1974) as a method of increasing water yields from moist, mixed conifer forests. The Thomas Creek prescription was also consistent with the silvicultural recommendations for southwestern mixed conifer forests proposed by Alexander (1974) and Jones (1974).

Seven Springs

The original treatment plan on the Seven Springs Watersheds was to install rows of large snow fences on one watershed to reduce the movement of snow due to wind and consequent losses of water through sublimation. Estimates based on a model developed by Schmidt (1972) predicted that this treatment could increase water yields by 1.5 to 2 inches if snow could be collected in drifts and protected from sublimation behind the snow fences. However, this plan was eliminated because of high construction expenses and concerns about the visual impact of the fences on recreationists traveling to the popular Big Lake area. The alternate plan was to create natural windbreaks by planting trees. Test plantings were conducted and initial results showed satisfactory survival but growth was very slow because of temperature-related bud damage.

A 120° V-notch weir was used on all of the experimental watersheds in the White Mountains. Hydrologic records began at the Castle Creek Watersheds in 1955, at the Willow Creek and the South Fork of Thomas Creek in October 1962, at the North Fork of Thomas Creek in October 1965, and at Seven Springs in October 1964. A weather station, including a recording precipitation gage and hygrothermograph, was established within each watershed pair; additional standard precipitation gages were also located within most watersheds. Sediment was measured in stilling basins that were constructed upstream from the weirs on all watersheds.

Snow Studies

Snow falling at the higher elevation forests is an important source of water for much of the Central Arizona Highlands (Ffolliott et al. 1989). However, less than 10% of this water is recovered as streamflow. Snowpacks in the Central Arizona Highlands differ from those at more northern latitudes, since extremely wet or dry winters are common and most snowpacks, except those at the highest elevations, experience some melting throughout the winter. Forest management affects snowpack accumulation and melt dynamics and can be used to increase and concentrate accumulation and to speed or retard spring snowmelt. Snowpack dynamics have been an important consideration in all of the forest watershed studies in the Central Arizona Highlands. Watershed-level snow studies have been augmented by a large amount of research on experimental plots and sites.

Snow research efforts in the Central Arizona Highlands have focused on developing snow management guidelines for increasing the amount of recoverable water from snowpacks on forested watersheds (Ffolliott et al. 1989). Process studies in the White Mountains included the use of snow lysimeters to characterize snowmelt rates, timing of melt, and site differences in snowpack behavior under different forest canopies. Snowpack changes were linked to energy budget indices. Melt from lysimeters at Thomas Creek was related to streamflow (Gottfried and Ffolliott 1980). Lysimeter data in the mixed conifer forests showed that sites with low and medium stand densities had greater snowpacks, melt rates, and more runoff than denser sites.

Theoretical studies focused on the relationships between components of the solar radiation energy budget and snowmelt runoff. A number of predictive techniques and simulation models were developed from studies in the White Mountains. The SNOWMELT model, originally developed for use in the Rocky Mountains, has been adapted to conditions in the Central Arizona Highlands (Solomon et al. 1976). Another model, YIELD, can be used to predict the effects of forest management on water yields (Ffolliott et al. 1989). The accuracy of several snowmelt-streamflow models has been compared during this effort (Ffolliott and Gottfried 1995).

The measurements on Thomas Creek by Plasencia (1988) and Gottfried (1991) are examples of studies about the effects of forest management on snowpack dynamics. Similar studies have been conducted in the ponderosa pine forests at Beaver Creek (Ffolliott et al. 1989).

Cooperators

The Apache-Sitgreaves National Forest was the main cooperator on the various studies in these high elevation forests. They were responsible for maintaining the hydrological and meteorological installations and assisted with several of the snow and ecological studies. In addition, the University of Arizona cooperated with most of the studies. The Salt River Valley Users Association contributed partial financial support of the first Castle Creek treatment.

Results

Earlier statue-of-knowledge publications reported the results from experimental watersheds and studies conducted in the mixed conifer forest ecosystems (Rich and Thompson 1974). Highlights of the major findings are presented below.

Castle Creek

Results from the irregular, block, harvesting treatment in predominately ponderosa pine on Castle Creek, West Fork were:

- An annual average water yield increase of about 30%, or 0.5 inch, was attributed to reduced evapotranspiration and increased snow accumulations in the openings (Rich 1972).
- Evapotranspiration was lowered by 4 inches (19 to 15 inches) (Thompson 1974).
- Increased water yield remained stable for 21 yr (1967 to 1987), probably because new tree roots had not fully occupied the soil mantle, and the height differences between the residual trees surrounding the openings and the regeneration continued to provide aerodynamics that favored increased snow accumulations in the openings (Gottfried and DeBano 1990).
- Effects on wildlife were important. The mixture of forest and interspaced clearcut blocks provided excellent conditions for deer and elk; day-use was increased (Patton 1974).

Results of prescribed fire on Castle Creek, East Fork included:

- No increase in average annual water yields (Gottfried and DeBano 1990), which was understandable because the fire did not affect forest overstory conditions or consume much of the forest floor.
- Concentrations of NH_4-N and NO_3-N, PO_4, and K increased during the first 2 post-fire snowmelt periods (Gottfried and DeBano 1990). The changes in nutrient concentrations, while statistically significant, were small and of little consequence in terms of site productivity and downstream water quality.

Willow Creek

Results of the diameter-limit harvest in mixed conifers on Willow Creek, East Fork were:

- Logging and wind damage caused a 68% reduction in tree density and a 82% reduction in basal area (Gottfried 1983).
- Aspen became the dominant overstory after the harvest.
- Initial logging damage to advance regeneration was severe in the diameter-limit area; there was a 71% decline in density (Gottfried 1983). Regeneration numbers and stocking were recovering 6 yr after harvest because of vigorous aspen suckering.

The heavy logging removals and wind damage compromised the original research objectives on Willow Creek, East Fork. The diameter-limit area, before aspen dominance, was similar to a large clearcut rather than the intended stand of young sawtimber trees. The proposed openings could not be distinguished from adjacent thinned areas. Approximately 62% of the watershed was in openings (Gottfried 1991).

Evaluations of changes in runoff on Willow Creek, East Fork indicated:

- A 54%, or 3.8 inches, increase in water yields.
- Snow water-equivalent data from a USDA Natural Resources Conservation Service (NRCS) snow course could be used to predict snowmelt runoff from a headwater drainage (Gottfried et al. 1997).

The diameter-limit treatment was beneficial because:

- Deer and elk use increased in the diverse cover that provided food while retaining sufficient timber for bedding and hiding cover (Patton 1976).
- Some species, such as the yellow-bellied sap sucker, were more common in the openings than in the uncut stands, although total bird densities were reduced (Franzblau 1977).

Thomas Creek

Streamflow responses to patch cutting on Thomas Creek, South Fork were:

- Annual water yield increased about 2 inches or 45% (Gottfried 1991). The yearly streamflow increases were generated by winter snowmelt or rain storms.
- Increases in peak flows occurred. Annual increases were about 3 $ft^3/s/mi^2$ or 65%.
- Water yield increases are usually attributed to increased snowpack accumulations and reduced evapotranspiration in the forest openings (Gottfried 1991). Snow surveys did not measure any significant changes in snow water equivalents following the harvest, although more snow was measured in the small openings than in the adjacent partially-harvested stand (Plasencia 1988).
- During high and average precipitation years, increases in water yield can occur without heavy reductions in stand density or the creation of large openings because the residual stand is unable to use all of the available water.

There was a concern that the timber harvest on South Fork would cause accelerated soil erosion. Heede and King (1990) determined:

- Overland flow and sediment delivery from severely disturbed and undisturbed sites were low and inconsequential. This was true even though measured sediment deliveries from severely disturbed areas (37 lbs / acre / yr) were higher than from undisturbed areas (5 lbs / ac / yr).
- Increased streamflow after treatment caused the natural channel adjustment process to accelerate, but the impacts on downstream areas were unknown.
- Mule deer, elk, and livestock benefitted from the harvested openings because of increased production of herbaceous species (Ffolliott and Gottfried 1989).
- Only minor, short-term changes in bird populations were reported (Scott and Gottfried 1983).
- Habitat requirements of red squirrels (*Tamisciurus hundsonicus*) were evaluated and used in the preparation of a marking guide to minimize detrimental affects from timber cutting (Patton and Vahle 1986, Vahle and Patton 1983).

Ecologically-oriented studies were also conducted on the Thomas Creek areas before treatment. A study by Dieterich (1983), described the fire history in this mixed conifer stand. Dieterich found that before 1900, fires burned through South Fork at intervals of 22 yr and that small, localized fires occurred frequently throughout the area. Fire suppression resulted in changes in stand structure and composition, a greater number of smaller trees, and more shade-tolerant species that normally would have been reduced by periodic ground fires. Other studies conducted on Thomas Creek and Willow Creek were used to characterize dwarf mistletoe infections by host, site, and stand characteristics (Gottfried and Embry 1977) and to describe species and stand growth of an old-growth mixed conifer forest (Gottfried 1978).

Studies were also initiated during preparation of or immediately after the harvest. Determination of the effects of treatment on forest productivity and sustainability was based on common stand parameters such as species composition, stand structure and stocking, regeneration success, and growth of residual trees and stands (Gottfried and Ffolliott 1992). The Thomas Creek treatment produced a wide range of benefits while retaining many desired old-growth stand characteristics.

Seven Springs

Climatic data from Seven Springs (grassland) and the nearby station at Burro Mountain, within a mixed conifer stand, were compared to determine feasibility of using windbreaks in these grassland sites. Soils analyses indicated that the main difference between forest and grassland soils was the lack of mycorrhizae in the grassland soils (Thompson et al. 1976). Temperature data from Seven Springs and Burro Mountain Station were similar. Annual precipitation at Seven Springs averaged 22 inches while Burro Mountain averaged 32 inches, but high winds on the grasslands may have resulted in inaccurate gage readings. Thompson and his associates (1976) believed that lower available soil water, related to snowpack sublimation, was one reason that trees had not moved into the grasslands. Trees are found at the edges of the grasslands where topography shelters them and the snowpack from wind; moderating the microclimate.

Implications

Research results from the experimental watersheds in the White Mountains of Arizona have increased the knowledge about hydrology and watershed management of mixed conifer and high elevation ponderosa pine forests in the Central Arizona Highlands, and to some extent, of the high elevation grasslands. Watershed treatments were directed towards practical options that would be useful to forest managers. This is demonstrated by:

- The shift in opening size, from large openings dominated with seeded grasses on the North Fork of Workman Creek (Rich and Gottfried 1976), to smaller 20 acre openings on Castle Creek where tree regeneration was the goal. The small 1 to 2 acre openings on the South Fork of Thomas Creek were the next step in achieving forest regeneration while increasing runoff by increasing snow accumulations and lowering evapotranspiration demands. The shift in size also reflects concerns about forest esthetics. The change from even-aged to uneven-aged silviculture in the residual stands also reflects this change.
- The initial emphasis of the watershed management research program was to determine how to increase runoff into the Salt River System. Management for other forest resources, especially timber and wildlife, was of secondary importance in the 1950s. However, management for water at the expense of the forest was unacceptable.
- Water-yield augmentation is no longer a primary management goal in the Central Arizona Highlands. Even timber production has declined as other forest value, such as recreation and concerns about rare and endangered species, have increased.

Current Status

Most of the watershed experiments were terminated between 1983 and 1986. However, the Apache-Sitgreaves National Forest continues to collect streamflow and precipitation measurements from the Castle, Willow, and Thomas Creek Watersheds as part of its hydrological monitoring program. Vegetation transects and points continue to be visited by USDA forest pathologists to determine changes in dwarf mistletoe infections over time. Additional inventories are being considered by scientists at the Rocky Mountain Research Station. Data from the watersheds have also been used by graduate students at the University of Arizona.

Chapter 7

Changing Values of Riparian Ecosystems

Malchus B. Baker, Jr., Leonard F. DeBano, and Peter F. Ffolliott

Introduction

Riparian ecosystems in the Central Arizona Highlands, and throughout the Southwest in general, provided the necessary water for humans, livestock, and agricultural crops during settlement by Europeans in the late 1800s. Other resources available in these moist environments included wildlife and fish, livestock and wildlife forage, and shade. Trees were often used for fuel, poles, and building materials. As human population increased in the early 1950s, demands for increased water supplies often dominated management of riparian ecosystems, which resulted in the destruction of many riparian areas (Horton and Campbell 1974). Within the last 25 yr people have become more aware of the diversity and multiple benefits provided by healthy riparian ecosystems.

This chapter describes changes in research emphasis that reflect changing attitudes of the public about the importance of riparian ecosystems. No one site has been the focus of this research. Instead, investigations were, and continue to be, conducted in response to a wide range of issues. Some important concerns are:

- Flow of water into and through these ecosystems.
- Maintenance of wildlife and fish habitats.
- Vegetative structure, classification, and patterns of plant succession.
- Impacts of grazing by livestock and wildlife.

Riparian Ecosystems

The nature of riparian ecosystems and the linkages between them and the upland watershed areas are described to place subsequent discussions into a watershed perspective. Riparian areas are at the interface between terrestrial and aquatic ecosystems. The abruptness and extent of the transitions across these interfaces are generally site-specific. Riparian ecosystems are delineated by soil characteristics and vegetative communities that require free or unbound water (DeBano and Schmidt 1989). These vegetative communities consist of herbaceous riparian plants (generally species of *Carex*, *Eleocharis*, *Juncus*, and *Scirpus*), which typically produce the characteristic dark-green edge on the sides of stream, and woody species (alder, ash, cottonwood, saltcedar, and willows) that usually reside on the higher alluvial terraces. Riparian systems are ecological sites where soil moisture exceeds the requirement of species present because of water flowing into and through the ecosystems.

Riparian ecosystems in the Central Arizona Highlands furnish habitats for a variety of wildlife species, are grazed by livestock and wildlife, and provide areas for fishing, hiking, bird watching, picnicking, and camping. Maintaining the integrity of these ecosystems requires careful management and, in some cases, protection from overgrazing, excessive tree cutting and recreational use, and other disturbances.

Riparian-Watershed Linkages

Erosion and surface runoff are important to the stability of riparian ecosystems and its surrounding hillslopes. A response to a disturbance, such as a vegetative conversion treatment or fire, must be considered within this context (DeBano and Schmidt 1989, DeBano et al. 1996a, Baker et al. 1998). Water flow and sediment movement through a riparian ecosystem is controlled by vegetation, topography, hydrology, and geologic formations within this linked system.

Riparian ecosystems are considered healthy if channel deposition (aggradation by sedimentation) and downcutting (degradation by erosion) is at equilibrium (figure 19). A healthy riparian area maintains a dynamic equilibrium between the streamflow forces producing change and the forces of resistance to change of its vegetative, geomorphic, and structural features (DeBano and Schmidt 1989). This dynamic equilibrium is sufficiently stable so that external disturbances on surrounding hillslopes can often occur without altering the equilibrium. This resistance to change results largely from adjustments among several factors, such as vegetation,

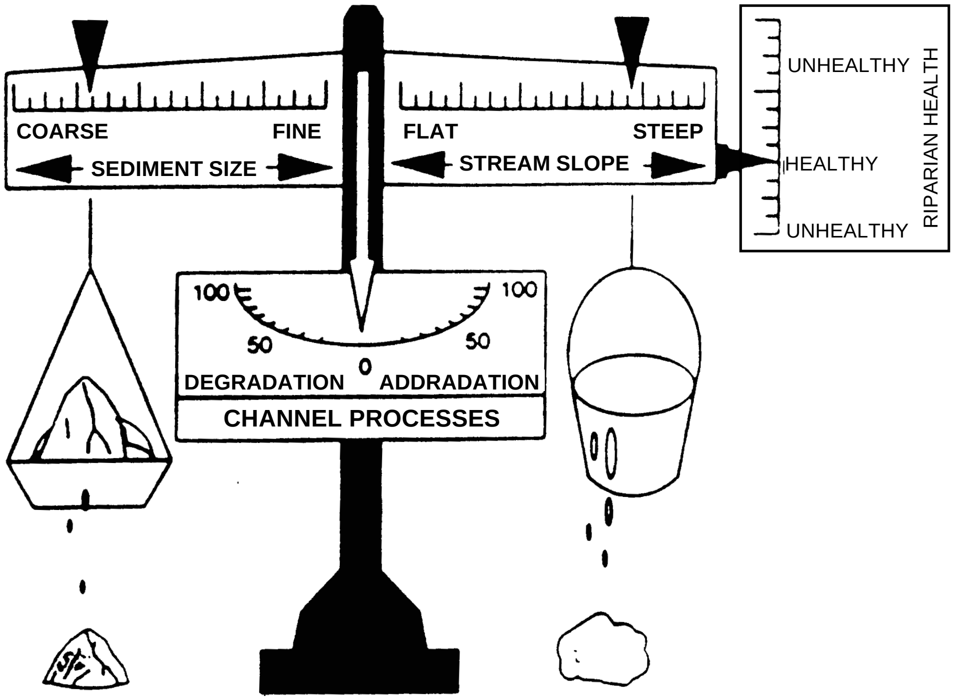

Figure 19. Relationships of a stable stream channel balance (adapted from Rosgen 1980, based on Lane 1955).

channel depth, and stream morphology, which react simultaneously within the riparian system to increases or decreases in flow or sediment from the uplands.

Short-term increases in surface runoff from disturbances on upland areas can increase streamflow volume and velocity, which causes changes in channel erosion and deposition downstream (figure 19). In a healthy riparian area, oscillations in the system produce little change in its dynamic equilibrium. Equilibrium can easily be reestablished when the resiliency of the system is not severely stressed by the disturbance. When degradational or aggradational forces overwhelm this dynamic equilibrium, riparian health can be adversely affected. Usually degradation processes (causing channel downcutting) result in unhealthy riparian conditions more rapidly than do aggradational processes (causing sediment deposition). The sensitivity of the equilibrium to aggradation and degradation processes are indicated by the riparian health scale in figure 19.

Fire is a common disturbance in riparian ecosystems and the surrounding hillslopes. Fire can burn either the upland watershed or both the riparian and upland areas. Fire rarely occurs only in a riparian ecosystem unless a controlled burn is prescribed to do so. When only the upland watershed area is burned, the riparian ecosystem acts as a buffer between the burned hillslopes and stream. However, when both the upland and riparian areas are severely burned, devastating results can occur. Of most significance, the buffering effect of the riparian ecosystem is lost, leading to a disruption of the dynamic equilibrium (DeBano and Neary 1996).

Changing Research Emphasis

A major goal of flood plain management through the mid 1960s was control or elimination of riparian vegetation for water salvage and flood control. By the late 1960s, pressure by environmental groups and the general public to preserve and develop riparian ecosystems for wildlife habitats, recreation, and aesthetic values largely halted these water salvage programs. As a consequence, holistic, ecosystem-based riparian management has prevailed throughout the Central Arizona Highlands since the mid 1970s.

Early Emphasis

Removal of riparian trees and shrubs (phreatophytes) in stream channels, floodplains, and terraces to reduce transpiration characterized riparian management from the early 1950s through the mid 1970s. A phreatophyte is a plants with a root system that obtains water either directly from groundwater or from the capillary fringe above the water table. The potential for water-yield improvement by converting phreatophytes to low water-using plants was considered for a number of reasons. The high transpiration rate of plants in arid or semi-arid environments with roots extended into the groundwater or capillary fringe above the water table was a major reason for conversion. The rapid invasion of the introduced saltcedar, a high water-using phreatophyte that forms dense, impenetrable thickets, created further interest. Managers believed that phreatophytes were low in economic value and, more importantly, were water-wasters (Horton 1960). Therefore, their eradication was stressed as a major management goal.

Water-Yield Improvement

To determine the potential for water-yield improvement by manipulating riparian vegetation, early experiments were conducted on Sycamore Creek, the Whitespar Watersheds, and the North Fork of Workman Creek. These experiments involved water-budget analyses and paired-watershed studies.

Thomsen and Schumann (1968) conducted a water-budget study on the lower 10 miles of Sycamore Creek where riparian vegetation covered about 1,400 acres of stream channel and floodplain. The study was designed to estimate possible changes in the water yield through removal of riparian vegetation. Water losses were estimated to average 81,500 acre-ft annually or about 1.1 acre-ft per acre. Since transpiration by vegetation was thought responsible for much of this loss, it was determined that a large percentage of water would be saved by eradication of the riparian vegetation (Horton and Campbell 1974).

A primary reason for gaging the Whitespar watersheds near Prescott was to determine the streamflow response when channel-side chaparral shrubs were converted to a grass-forb cover (Ingebo 1972, Hibbert et al. 1974, DeBano et al. this publication). For the 4 years following the herbicide treatment, annual streamflow increased an average of 0.61 inch or about 30% when compared to the untreated control watershed. This increase of streamflow averaged 4 inches from the treated area (15% of the watershed). Over 75% of the increase came during the December through April major flow period.

All of the Arizona alder and bigtooth maple adjacent to springs, seeps, and streams on the North Fork of Workman Creek were cut in 1952, and their stumps were poisoned with an herbicide to prevent resprouting. The effect of removing these broad-leaved trees on subsequent streamflow was insignificant, even during the growing season when the greatest rate of transpiration would occur. It was hypothesized that the number of trees removed and the area affected by this treatment were too small to cause a significant change (Rich and Thompson 1974, Gottfried et al., Chapter 2 of this publication).

While the results from these and similar experiments on effect of riparian vegetation removal on water regimes were inconclusive, relatively large-scale operational eradication programs continued into the 1970s (Horton and Campbell 1974). Riparian plants, particularly woody phreatophytes, were removed from within stream channels, on floodplains, and terraces by mechanical, chemical, or a combination of mechanical-chemical means. Following initial conversion, the treated areas were usually subjected to mechanical or chemical maintenance programs to suppress invasion by high water-using plants.

Current Research Emphasis

Continual pressure by environmental groups and the general public to preserve and develop riparian ecosystems for wildlife habitats, recreation, and aesthetic values resulted in altering the riparian management emphasis in the Central Arizona Highlands and throughout the Southwest by the mid 1970s. Interest in the condition, role, and sustainability of riparian ecosystems had increased greatly. Because water-yield improvement was not the primary focus of management, eradication of riparian vegetation ceased. Environmental groups and the general public had become increasingly concerned about maintaining the integrity of riparian ecosystems for multiple values.

Concern for the declining health of riparian ecosystems, initially expressed by the scientific community, had expanded to a broad spectrum of interest groups including land and water resource managers, educators, recreation managers, legislators, and environmentalists (Shaw and Finch 1996). These groups were seeking information and a better understanding of the dynamics, functions, uses, and the restoration of riparian ecosystems. A series of symposia has reflected this growing interest and the often conflicting uses and desired future conditions of riparian ecosystems (Johnson and Jones 1977, Johnson and McCormick 1979, Johnson et al. 1985, Tellman et al. 1993, and Shaw and Finch 1996).

Current Research Program

The sustainability of riparian ecological systems in Southwestern forests and woodlands is being investigated by scientists with the USDA Forest Service, Rocky Mountain Research Station, Flagstaff, Arizona. The purpose of this project is to create, develop, and apply knowledge on fluvial, geomorphological, and ecological system functions, processes, and dynamics needed to sustain diverse and healthy riparian ecosystems in the Central Arizona highlands and elsewhere in the arid Southwest.

Goals

Goals of this research program include:

- Determination of specific interrelationships among hydrologic, geomorphic, and biotic processes that affect fish habitat, riparian vegetation, channel dynamics, and instream flow regimes.
- Development of predictive models to determine the effect of watershed-scale activities, such as prescribed fire, grazing, and vegetation management, on the functioning and quality of riparian ecological systems.
- Determination of factors that influence populations and habitats of threatened, endangered, and sensitive fish, and other fish, plants, and biota inhabitating Southwestern riparian ecosystems.

Results

Results from earlier studies conducted on riparian ecosystems have been previously reported in a status-of-knowledge paper (Horton and Campbell 1974). Results of the current research program show that:

- Although there is a public perception that riparian areas are fragile, current information indicates that riparian systems are often resilient. Today, many riparian areas are at risk because of various stresses, such as overgrazing by livestock and wildlife, drought, and flooding, which have caused the system to lose its dynamic equilibrium. However, once these stresses are relieved, many riparian systems can regain their equilibrium within a few years because of resilient, native, herbaceous, riparian plants such as *Carex*, *Eleocharis*, *Juncus*, and *Scirpus* (Medina 1996; Medina et al 1996).
- Instream structures, channelization, bank modification, and rip-rap can be used to provide flood control, irrigation development, and wetland conversion. Many restoration projects using these methodologies, however, have resulted in further site degradation and reduction in the functioning condition of the affected streams (Baker and Medina 1997).
- The importance of the interactions between the riparian vegetation and channel systems must be recognized as integral factors in maintaining ecosystem productivity (Medina et al. 1997). Channel systems are continually adjusting to varying flows and sediment loads, a process that is incompatible with placement of fixed structures. Riparian vegetation on flood plains allows the stream to function properly and helps provides resiliency to withstand a variety of environmental conditions.
- Often, restoration of a degrading channel system only requires exclusion of grazing (ideally, both domestic animals and wildlife) for a few years and occasionally reestablishment of riffle bars (Medina 1996). Removal of the grazing stress allows the riparian plants to regain vigor and restores their functioning ability to detain flood flows, reduce water energy and bank erosion, and to trap sediments and nutrients in the water (figure 20). The riffle bars slow down the water velocities, reduce or terminate downcutting of the channel, and provide fish spawning habitat.

Implications

Research efforts in the riparian ecosystems and changing attitudes of the general public have had major effects on how riparian areas are currently viewed and managed. Riparian ecosystems are now considered important habitats for wildlife species and important grazing areas for livestock and wildlife, while providing opportunities for fishing, hiking, bird watching, picnicking, and camping. Maintaining the integrity of these fragile systems requires careful management and, in some cases, protecting them from overgrazing, excessive tree cutting, recreational use, and other disturbances.

Currently, research emphasis is on assessment of the condition of our riparian resources and on restoration of areas that are not functioning properly. Although millions of dollars have been spent during the last century for riparian restoration and fish habitat improvement, riparian areas have been and are still disappearing, while others remain in a degraded condition (Baker and Medina 1996). Current research, however, provides hope that with little effort and money, many degraded but resilient systems can be restored using inexpensive materials and equipment and changes in grazing strategies.

Figure 20. Section of Boggy Creek in eastern Arizona,immediately following exclosure with an elk proof fence in 1992 (*above*), and some location in October 1996 (*below*).

Chapter 8

The Future

Peter F. Ffolliott

Introduction

Research in the vegetation types of the Central Arizona Highlands has evolved, for the most part, from single resource evaluations (increased water yield) to evaluations that consider the multiple benefits of vegetation management treatments. The papers presented in this publication have demonstrated that vegetation can be managed to increase water yields, while providing timber, forage, recreation, wildlife, and other amenities. One question that should be asked is to what extent can the established research framework and available databases be used to meet future management-oriented informational needs in the Central Arizona Highlands and elsewhere in the Southwest?

Long-Term Monitoring and Evaluation

Long-term monitoring and evaluations, based on reinventories of the permanently-located sampling units on the study sites in the Central Arizona Highlands, represent a valuable use of the cumulative research efforts. A better framework for conservation and the sustainable use of natural resources in the region should evolve from the evaluations obtained.

Repeated measurements of permanent inventory locations provide a basis for the long-term monitoring and evaluations that are central to almost every important ecological concept and environmental issue (Franklin 1989). Information from these measurements allows a look at the “big picture” of how ecosystems might respond to disturbances resulting from climatic change, habitat fragmentation, or invasions of exotic species. Information of this kind is becoming increasingly important in developing a holistic, coherent viewpoint of how ecosystems function (Baskin 1997, Shepperd and Edminster 1997).

Sampling variability is generally reduced when the same transects, plots, or points can be repeatedly visited in a series of inventories. Analysis of such data sets can result in accurate, precise, meaningful conclusions and predictions for long-term management purposes. To illustrate this point, analysis of data obtained from repeated inventories of ponderosa pine stands on a Beaver Creek watershed shows the changes in volume of trees 7.0-inches diameter breast height (dbh) and larger before (1963 to 1969) and after (1970 to 1995) a heavy thinning treatment was applied on the watershed in 1970 (figure 22). Knowledge of this progression can be helpful in prescribing future management actions on the watershed. Even this relatively long post-treatment record (1970 to 1995) might be insufficient for full appreciation of the changes from implementation of the thinning treatment. Therefore, continued monitoring and evaluation of the thinning treatment is anticipate.

Other Uses of Databases

The diverse databases developed from the research programs in the Central Arizona Highlands describe the dynamics of the ecosystems studied and are unique in their multiresource character. These databases are available today because efforts were made to protect the original maps and airphotos, inventory forms, and file copies of summaries. Many of these databases have been computerized, making them easier to preserve, retrieve, and update. Computerization of the databases facilitates incorporation of future resource inventories into the databases. This allows continuing evaluations of ecosystem properties after implementation of alternative land management activities.

These databases were developed originally at a considerable expense of time and money. By computerizing this information, the stored information can be easily retrieved and analyzed, using new techniques and methodologies to help meet current needs. The databases can be used as stored in the system or modified in structure to analyze the changing trends in specific resource values through time. This information is available to managers, researchers, and decisionmakers to better understand the ecologies of ecosystems in the highlands region.

Initiation of New Studies

Managers, researchers, and decisionmakers continue to analyze these databases to meet current objectives and answer questions that are asked about the impacts of alternative land management activities on these resources and ecosystem properties. However, analyses of existing information can sometime only partially answer these questions. When additional knowledge is needed, the research framework on the Sierra Ancha Experimental Forest, the Beaver Creek watersheds, Castle Creek, Willow Creek, and Thomas Creek watersheds, and other research sites in the Central Arizona Highlands can provide the basis for implementing new studies to complement what is known.

These research sites continue to serve society's needs for outdoor laboratories to study how vegetative manipulations, or its absence, affect forage, wildlife, wood, and water resources, and amenity values such as scenic beauty. As the mixture of these benefits and values changes, the emphasis placed on the newly-formulated studies should also change.

Implications

Implications of the overall research efforts in the Central Arizona Highlands are not confined to Arizona or the Southwest, but instead they are of national and, in some instances, international interest. The research sites continue to be visited frequently by out-of-state and foreign scientists, land managers, administrators, and students. As a consequence, results of the research programs in the highlands are being applied throughout the world today.

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