

Forest Watershed Management in the Southwestern United States

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Abstract: Ponderosa pine and mixed conifer forested watersheds are the source of much of the surface water for the major river systems that support the cities, industries and farms of the arid southwestern United States. The need for sound watershed management was recognized during the early years of the 20th century. Research was initiated to determine the hydrology of forested watersheds and to provide land managers with information that could be used to design and implement treatments that benefited water augmentation and the production of other natural resources. A variety of experimental and current or potential silvicultural prescriptions were evaluated at locations throughout Arizona. While runoff augmentation is no longer the primary objective of forest management, research results provide guidance for forest watershed managers who are responsible for developing and implementing multi-resource prescriptions. The current emphasis for watershed management is to maintain and improve forest health and hydrologic function of watersheds. Well-designed and implemented silvicultural operations have a minor impact on the physical, chemical, and biological characteristics of stream water. Natural fire regimes have changed in the southwestern United States because of livestock grazing and aggressive fire suppression activities. The result has been an increase in fuels and stagnant stands, and an increase in large, severe, stand-replacing wildfires. Scientists are studying the role and impacts of fire as they attempt to restore more natural fire regimes in the forested ecosystems of the region.

Key words: Forest watershed management, historical research, water quality, fire effects, ponderosa pine, mixed conifer forests, southwestern United States.

A common impression of the southwestern United States, primarily the states of Arizona and New Mexico, is of vast deserts covered with cacti and low shrub species. While several major desert ecosystems are important components of the region's landscape, the topography and vegetation of the Southwest are diverse, including high plateaus and mountains that extend over 3,600 m in elevation.

The higher elevations receive relatively large amounts of precipitation, often in the form of snow, and support forests of

ponderosa pine (*Pinus ponderosa*) and mixed conifers. Forested watersheds are the sources for much of the surface water for the major river systems within the region, including the Colorado, Salt and Verde in the Gila River Basin, and Rio Grande. The waters from the Salt and Verde Rivers in Arizona and Rio Grande in New Mexico are one of the reasons for the pre-historic American Indian and later European-American settlements and subsequent rapid growth of the Phoenix and Albuquerque metropolitan areas. However, the amounts of precipitation vary from year to year,

with extreme dry or wet years being more common than the "average" year. Major dams and other diversions have been constructed throughout the area to assure a continuous flow of water for municipal, agricultural, and industrial uses. The need for watershed protection was recognized early, and some national forests initially were established from public lands for this purpose. The Tonto National Forest in central Arizona, for example, was established in 1905 to protect the Salt River watershed and the Theodore Roosevelt Dam, the first reclamation project in the United States, which was under construction at the time.

Sound watershed management must be based on research. Watershed management research was initiated in Arizona in the 1920s when concerns developed that accumulation of sediment behind Roosevelt Dam would compromise the reclamation project. Research subsequently expanded to answer managers' questions about the hydrology of upland watersheds and efforts to manage forests and woodlands for augmented streamflows in the context of multiple-resource management. Forest managers incorporated research results into management activities and into multiple-use planning. Current watershed management efforts are aimed at maintaining or improving watershed conditions and water quality and at assessing the impacts of recent disastrous wildfires on hydrology and watershed condition. This paper reviews past forest watershed management research in the Southwest, management to reduce erosion and improve water quality from forested areas, and the impacts of fire on forest watershed values.

The Setting

Topography

The topography of the Southwest is diverse. Elevations in Arizona vary from less than 42 m near the border with California and Mexico, to more than 3,800 m on top of the San Francisco Peaks near Flagstaff. The state is divided into the Colorado Plateau, the intermediate Central Highlands, and the Basin and Range geological provinces that are located from the north to the south. Each of the provinces contains mountains, canyons and valleys, cliffs and plains that were formed and influenced by geological events (Chronic, 1983). The Basin and Range Province, which extends from the northwest to southeast across the state is characterized by mountain islands, some extending more than 2,700 m in elevation, surrounded by valleys supporting desert grasslands or desert-shrub vegetation.

New Mexico is divided into three topographic zones (Chilton *et al.*, 1984). These include a Rocky Mountain zone that extends through the north central part of the state, the plains zone that occurs from the chain of central mountain ranges to the eastern border with Texas and Oklahoma, and the intermountain plateau and valley zone. New Mexico has 23 mountain ranges, with the highest mountain at an elevation of 4,012 m.

Climate

The climate is characterized by variable frontal precipitation in winter from the Pacific Ocean, an arid pre-summer, and summer rains that are predictable in timing

and amount at a given station, but vary from site to site (Gottfried *et al.*, 1995). The summer moisture comes primarily from the Gulf of Mexico in response to a high-pressure cell that builds across the United States during the season. The proportion of winter to summer moisture varies throughout the region with southern and eastern areas being more dependent on summer precipitation than more northern and western sites. The eastern section of Arizona receives more than 60% of the precipitation between May and October while central and western areas receive about 50% during this period (Sellers and Hill, 1974). The summer season is characterized by convective storms that are often associated with high intensity rainfall events. Occasional tropical storms enter the region from the Pacific Ocean in late summer producing large precipitation events.

Approximately half of Arizona averages less than 25 mm of annual precipitation (Sellers and Hill, 1974); however, mountainous regions may average between 760 and 1,015 mm as rain and snow. Elevation is a key factor influencing the amounts of precipitation recorded in the Southwest. The highest mountains receive the largest amounts of moisture, primarily as snow. The higher precipitation and lower temperatures provide the necessary environment for forests to occur. However, some of the plateaus, which are more than 1,800 m in elevation but are in the rain shadows of surrounding mountains, are quite arid. Temperatures are variable as would be expected from the topographic differences. Sellers and Hill (1974) report that Flagstaff at an elevation of 2,135 m

has a mean annual temperature of 7.4°C while Phoenix at 340 m has a mean of 21.4°C.

Vegetation

The Southwest contains six life zones from deserts to alpine tundra based on vegetation types and varying by elevation and aspect (Lowe, 1964). Ponderosa pine and mixed conifer forests are of prime interest because of their importance to watershed and natural resource management. Ponderosa pine forests occupy about 1.21 million ha in Arizona (O'Brien, 2002) and 1.17 million ha in New Mexico (Van Hooser *et al.*, 1993). Ponderosa pine forms almost pure stands in association with a variety of grasses and other herbaceous species. The species is found from about 1,670 to 2,600 m in elevation and is often associated with pinyon (*Pinus edulis*), alligator juniper (*Juniperus deppeana*), and Gambel oak (*Quercus gambelii*) at its lower extreme and with Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) at higher elevations. The southwestern mixed conifer forests occupy about 809,000 ha in Arizona and New Mexico between 2,440 and 3,350 m in elevation. These forests are a combination and intermixture of forest species and types that grow in close proximity with each other. The dominant tree species are Douglas-fir, ponderosa pine, white fir (*Abies concolor* var. *concolor*), Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), corkbark fir (*A. bifolia*), southwestern white pine (*P. strobiformis*), and quaking aspen (*Populus tremuloides*). Limber pine (*P. flexilis*) stands are only found in northern New Mexico.

These forests are noted historically for their production of timber, and accessible stands have been harvested since the 1870s when the railroads entered the region. The value of forested watersheds was recognized in the 19th century. Most of the non-reserved forests are in public ownership and administered by the US Department of Agriculture, Forest Service, by the Department of the Interior, Bureau of Land Management, or by the state forestry departments. Much of the private forestland is administered by or for American Indian tribes. Current management on non-reserved lands is aimed at multiple-use of the forest resources. The forests are important for wildlife habitat, both game and non-game species, and for a number of threatened, endangered, and sensitive species. Livestock, primarily cattle, graze many forestlands, although herbaceous production is low in some of the denser stands. The importance of recreation has increased as the Southwest's population has increased. These forests and their lakes are especially important for the desert urban populations as they attempt to escape the summer heat.

Watershed Management Research

The history of watershed research

Initial watershed research efforts sought methods of controlling erosion from lower elevation chaparral sites surrounding Roosevelt Reservoir. Chaparral is a vegetation type dominated by evergreen, sclerophyllous shrubs. Soil erosion was seen as a threat to the longevity of the dam and the general reclamation project along the Salt River. The Summit Watersheds were established in 1925 to address the problem (Rich, 1961). The Forest Service's

Southwestern Forest and Range Experiment Station (now the Rocky Mountain Research Station) established the Parker Creek Experimental Forest in 1932 in the Sierra Ancha Mountains northeast of Roosevelt Reservoir and enlarged and renamed the forest in 1938 as the Sierra Ancha Experimental Forest (Fig. 1). The 5,190 ha Experimental Forest, because of its broad elevational range (1,080 to 2,355 m) includes seven vegetation types from desert-shrub to mixed conifer forests (Pase and Johnson, 1968). The research mission here was to study the effects of grazed and ungrazed vegetation on water yields and to learn more about the water cycle relationships within the diverse vegetation zones of the Southwest (Gottfried *et al.*, 1999a).

Both plot and watershed research was initiated at Sierra Ancha. Much of the early work concentrated on grazing effects, primarily in the chaparral shrublands that cover about 57% of the Experimental Forest. However, major watershed studies were begun in the 1930s at the Workman Creek watersheds in the mixed conifer-ponderosa pine forests and on the Parker Creek and Pocket Creek Watersheds that support a mixture of chaparral stands and conifer forests, depending on aspect. The initial effort at Sierra Ancha was designed to determine the basic hydrologic relationships for forested watersheds in the Southwest.

An effort was launched in 1955, during an extended drought, to determine the feasibility of increasing streamflow by manipulating the plant cover in the different vegetation types within the Salt and Verde River Basins (Baker and Ffolliott, 1999; Fox *et al.*, 2000). Although watershed

treatments were in progress at the time in the mixed conifer stands at Workman Creek, additional research was initiated to evaluate the chaparral, pinyon-juniper, and ponderosa pine forests of central Arizona and other mixed conifer watersheds in eastern Arizona. The goal was to determine the effects of vegetation manipulations on the other natural resource products and uses, as well as on runoff. A review of research results determined that augmented streamflow was possible where annual precipitation exceeded 460 mm (Hibbert, 1979). Research at a number of chaparral sites in Arizona demonstrated that runoff could be increased when the vegetation was growing on deep soils or porous parent materials (DeBano *et al.*, 1999). However, research in coniferous woodlands dominated by pinyon and junipers (*Juniperus* spp.) generally did not show increased water yields, even when the entire tree cover was removed (Baker, 1984; Clary *et al.*, 1974; Collings and Myrick, 1966). There is some contrary anecdotal evidence about increases occurring after severe land treatments, but these have not been confirmed scientifically. The best opportunities for increasing water production in the context of multiple resource management were in the ponderosa pine and mixed conifer forests.

Forest Watershed Management Research for Multiple Benefits

Southwestern mixed conifer and upper ponderosa pine forests

The Workman Creek studies: The initial research in these forests was conducted on the three Workman Creek watersheds

in the Sierra Ancha Experimental Forest (Fig. 1) to evaluate the hydrology of higher elevation mixed conifer forests and to determine the changes in streamflow and sedimentation from manipulating the forest cover (Gottfried *et al.*, 1999a). The treatments were selected to cover the range of water yields possible through manipulating or removing the forest vegetation. Some treatments were designed to obtain basic hydrological information, and others were designed to test common or potential silvicultural prescriptions.

The basic experimental design was to treat the North Fork and South Fork and hold Middle Fork as the hydrologic control. Studies on North Fork were designed to evaluate streamflow responses to clearing the forest cover in stages, starting on the wettest and progressing to the driest sites (Rich and Gottfried, 1976; Gottfried *et al.*, 1999a). The first treatment in 1953 removed the riparian vegetation along the stream channel and around springs. In 1958, the mixed conifer stands nearest the channels were commercially harvested and small trees and unmerchantable material were pushed and burned. Cleared areas were seeded with grasses; however, Gambel oak and New Mexican locust (*Robinia neomexicana*) invaded the site. The final treatment in 1966 was the harvesting of drier site ponderosa pine stands. Streamflow increased significantly ($\alpha = 0.05$) after both the moist- and dry-site treatments, but not from the riparian treatment. Average annual streamflow increases from the combined moist- and dry-site treatments were 84% or 69 mm. The increases remained stable for at least 13 years following treatment (Hibbert and Gottfried, 1987).

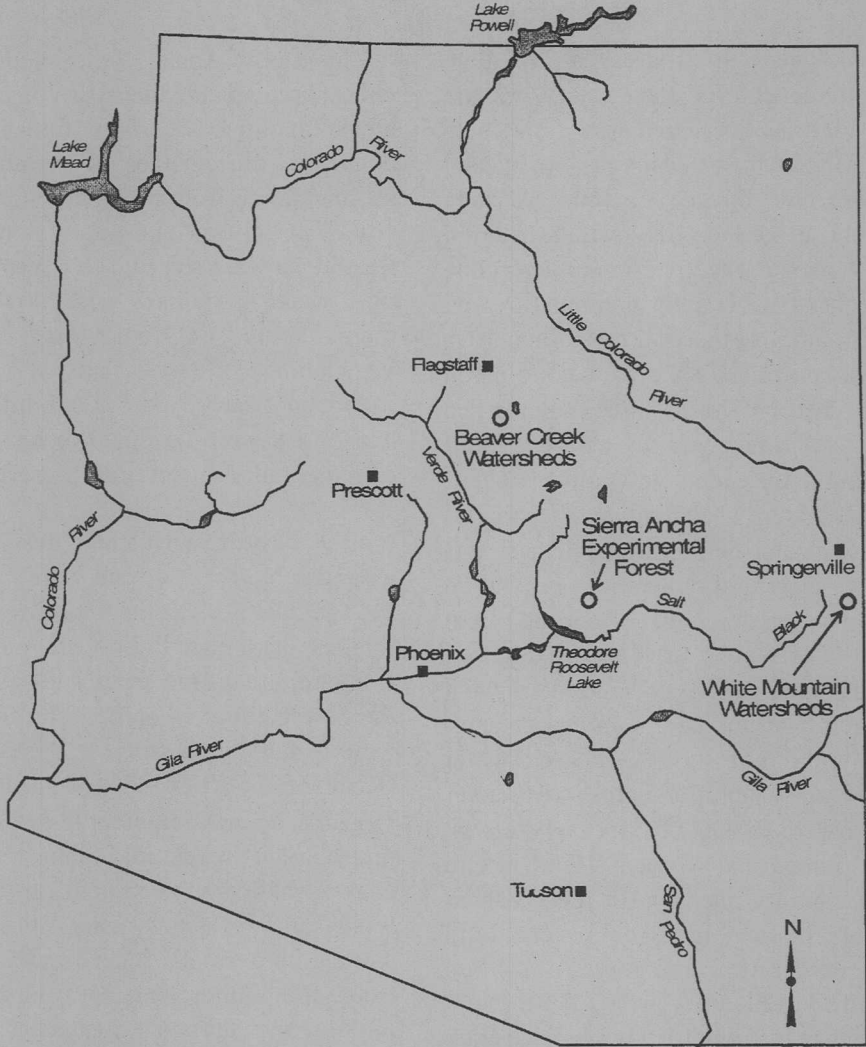


Fig. 1. Forest watershed management research in Arizona was conducted in the Sierra Ancha Experimental Forest, on the Beaver Creek Watersheds, and in the White Mountains. These sites represent forest conditions in the headwaters of the major river systems throughout the southwestern United States.

The initial treatment on South Fork in 1953 was to evaluate the common single-tree selection prescription. A wildfire burned through part of the watershed in 1957, and the two events resulted in the removal of 45% of the initial stand basal

area. The second treatment in 1966 was designed to convert the mixed conifer forest into a pure ponderosa pine forest by harvesting the Douglas-fir and white fir and planting pine seedlings. The eventual goal was to thin the resulting stand to

9.2 m² ha⁻¹ of basal area to determine if this density would optimize both tree and water production. Basal area per hectare is the sum of the cross-sectional measurements of all trees at 1.37 m above the ground level. Residual pine stands were thinned to this level. The single-tree selection produced a small but statistically significant increase in streamflow of 7% or 5.8 mm. The results of the conversion treatment produced streamflow increases of 111%, or 93.2 mm, that were similar to the results from North Fork. Increases were constant for the initial 13 years following the final treatment. South Fork currently contains a mixture of ponderosa pine small sawtimber, poles, and seedlings, and locust and oak trees. The two treated watersheds and the control watershed were burned in the year 2000. Current research is evaluating the impacts of the severe wildfire on mixed conifer hydrology and erosion and sedimentation.

The White Mountain experiments: Watershed management research moved into the White Mountains of eastern Arizona (Fig. 1) soon after initial results from Workman Creek were reviewed. The initial objective was to determine if results from Workman Creek could be confirmed and if they were transferable to other mixed conifer areas (Gottfried *et al.*, 1999b). One concern was that the relatively large openings of more than 32 ha would be unacceptable for multiple-use forest management, and compromise prescriptions that benefited water and timber production and wildlife habitat were necessary. Three sets of paired experimental watersheds were established on Castle Creek, which

supported high elevation stands of ponderosa pine and mixed conifers, and on Willow and Thomas Creeks, which supported dense mixed conifer stands.

The results from Workman Creek indicated that even-aged management could maintain long-term timber production and improve water yields (Rich, 1972). The experiments on Castle Creek, where the West Fork (364 ha) was harvested and East Fork (471 ha) served as the hydrologic control, were designed to test this hypothesis. The watersheds are located between 2,388 and 2,616 m in elevation. In 1965, one-sixth of the stand was harvested in irregular blocks fitted to stand conditions, and the remaining stand was put into optimum growing condition by thinning and sanitation operations. The idea was to create conditions where trees would achieve a desired size within 120 years and where one-sixth of the stand would be harvested every 20 years. The harvest reduced the stand basal area from 31.0 to 14.5 m² ha⁻¹. Harvested blocks were planted with ponderosa pine seedlings to ensure adequate regeneration.

Water yields from the Castle Creek harvesting treatment resulted in an average annual increase of about 29% or 12.7 mm that was attributed to reduced evapotranspiration and increased snow accumulations in the openings (Rich, 1972). The increases in streamflow remained stable for the 21 years from 1967 through 1987. This stability was related to the fact that new tree roots had not fully occupied the soil mantle and the height difference between the residual trees and the regeneration continued to provide aerodynamic conditions that

avored increased snow accumulations in the openings (Gottfried *et al.*, 1999b). The mixture of openings and forest provided excellent habitat for deer (*Odocoileus* spp.) and elk (*Cervus elaphus*) (Patton, 1974).

A second treatment was initiated in 1981 to test the impacts of pre-harvest prescribed fire as a method of reducing heavy natural fuel loadings. Aggressive fire suppression has been partially responsible for the accumulations of heavy fuel loadings within many southwestern ecosystems that have increased the potential of severe, stand-replacing wildfires. The stable increases in streamflow since 1967 allowed the fire treatment to be applied to East Fork, and the West Fork to become the control watershed (Gottfried and DeBano, 1990). The fire reduced surface fuels on approximately 43% of the watershed but caused little mortality to the overstory. Average annual water yield increases of 8.1 mm or 8% for the entire watershed were not statistically significant because of the minimal impacts to the stand. Concentrations of nutrient in runoff water increased significantly but were small and of little consequence in terms of site productivity and downstream water quality.

The second test of the effects of timber management on water augmentation was conducted on the East and West Fork watersheds of Willow Creek, a relatively short distance from Castle Creek. West Fork has an area of 117 ha and East Fork contains 198 ha; elevations on the experimental area range from 2,682 to 2,835 m. The silvicultural prescription on East Fork was similar to the one used on the West Fork of Castle Creek, but the Willow

Creek watersheds are at a higher elevation site that is dominated by mixed conifer stands containing an important spruce-fir component. Heavy logging removals, which contributed to excessive wind damage, compromised the original research objectives. The designated openings were often indistinguishable from the areas that had been marked as residual thinned stands; 62% of the watershed was in openings (Gottfried, 1983). Regeneration numbers and stocking recovered because of vigorous quaking aspen suckering. The treatment resulted in a 54% or 96.5 mm average increase in water yields.

The third watershed management experiment in the White Mountains was conducted on the two Thomas Creek watersheds that supported an undisturbed, old-growth mixed conifer forest. The South Fork (227 ha) and the North Fork (189 ha) range from 2,560 to 2,835 m in elevation. The objective was to demonstrate and evaluate the knowledge of integrated resource management for southwestern mixed conifer forests (Gottfried, 1991). The prescription called for the creation of small openings by patch clearcutting and harvesting of the surroundings stand by single-tree or group selection methods to maintain uneven-aged conditions. Openings with an average area of about 0.5 ha were created on 13% of the total watershed area; part of the watershed was not harvested because of steep slope conditions. The harvest resulted in a 34% reduction in total basal area to 30.2 m² ha⁻¹ on the treated portion of Thomas Creek South Fork. The treatment resulted in a 45% or 50.8 mm increase in annual streamflow, much of

it attributed to winter precipitation. Peak flows also increased by 65% ($28 \text{ L s}^{-1} \text{ km}^{-2}$) following treatment. The increases were attributed to reduced evapotranspiration and to increased snow accumulations in the patch clearcuts and group selection openings, although overall snow accumulations on the watershed were unchanged relative to the control watershed. The study also determined that the partially harvested stands contributed to water yield increases during years with average or above average precipitation because the residual stands are unable to utilize all of the available water. Although the harvest had a minimal effect on overland flow and erosion, increased streamflow volumes and peak flows have accelerated natural channel erosion processes within the study area (Heede and King, 1990). The treatment benefited residual tree growth for most species (Gottfried, 1992) and was beneficial to deer, elk, and livestock because of increased production of herbaceous species in the openings and only resulted in minor changes to the bird population (Gottfried and Ffolliott, 1992). The Thomas Creek study demonstrated that water yield increases could be achieved with less severe treatments that did not result in large clearcut openings or in the removal of large numbers of trees. The Thomas Creek treatment produced a wide range of benefits while retaining desired old-growth stand characteristics.

Lower ponderosa pine forests

The southwestern United States experienced a drought during the 1950s, and land owners and managers were concerned that the increases in stand

densities in Arizona's ponderosa pine and pinyon-juniper woodlands contributed to reduced surface runoff and amounts of forage for livestock (Baker and Ffolliott, 1999). A review of existing information determined that replacing high water-using trees and shrubs with low water-using grasses and forbs would increase water yields. However, there were concerns about the effects of vegetative manipulations on other natural resource products. The Beaver Creek watershed study became a significant component of the effort to evaluate the feasibility of manipulating vegetation by silvicultural treatments to increase water yields and other multiple resource benefits (Fig. 1). The Beaver Creek complex encompasses 111,289 ha, south of Flagstaff in the Verde River Basin. Average elevations ranged from 2,054 to 2,225 m. Average winter precipitation ranges from about 360 to 510 mm at Beaver Creek with 60% occurring mostly as snow during the winter (Baker, 1986). A multidisciplinary team, including forest, wildlife, and range scientists, hydrologists, and economists was constituted in 1960 for the project. A large number of researchers and managers from the Forest Service, other federal and Arizona State agencies and universities cooperated with the Beaver Creek Project throughout the research effort. Twenty pilot experimental watersheds were instrumented to determine the effects of a variety of land management treatments on streamflow and erosion and on the other natural resources. The 12 watersheds that supported ponderosa pine stands and range from 66 to 730 ha in size are the focus of this discussion. Sub-drainages were also instrumented within the pilot watersheds

to refine the findings from the larger watersheds. The remaining eight watersheds included six that were covered by pinyon-juniper woodlands and two large, untreated ponderosa pine watersheds of more than 4,856 ha. Since basalt is the main parent material at Beaver Creek, additional watersheds were established on limestone and sandstone sites in eastern Arizona to determine the hydrology of these areas but these were not treated.

Results from the Beaver Creek experiments have been reported in nearly 700 publications, including USDA Forest Service publications, journal articles, and special publications on specific topics, and dissertations and theses (Baker and Ffolliott, 1998). The ponderosa pine studies evaluated natural resource responses to a number of silvicultural treatments, including clear-cutting, strip cutting in uniform and irregular strips, strip shelterwood cutting, thinning by group selection, a combined shelterwood-seed tree silvicultural treatment, patch cutting to improve wildlife habitat, and grazing treatments on a watershed converted to herbaceous plants (Baker and Ffolliott, 1999).

Annual water yield increases of between 25 to 51 mm were measured in the initial post-treatment periods as a result of the various intensities and patterns of forest overstory reductions in the ponderosa pine studies (Baker and Ffolliott, 1999). Increases from a completely cleared watershed were statistically significant for the initial 7 years after treatment, with the greatest response occurring during the first year when an increase of 99 mm or 63% above the expected flow was measured (Baker, 1986). Water yield increases

declined and lost statistical significance as vegetation became reestablished. The period of increased flows ranged from 3 years on a strip-cut watershed to 10 years on a watershed where 75% of the stand had been harvested in groups. In general, Baker (1986) determined that water yields in the Southwest were greatly influenced by the amount and distribution of precipitation, basin physiography, and soil type. Water responses lasted longer on watersheds with northern exposures, and they were achieved with smaller reductions in basal area on these cooler sites than on watersheds with southern exposures. Precipitation timing and amount were more important factors influencing increased water yields than the proportion of the overstory removed. However, runoff increases of between 15 and 45% are realistic from ponderosa pine forests on shallow, basalt-derived soils when stand basal area is reduced between 30 and 100%. Researchers concluded that average annual water yield increases of almost 15.2 mm are possible on productive ponderosa pine sites even when multiple resource objectives are considered.

No meaningful changes in total sediment production or water quality occurred as a result of the forest treatments on the basalt-derived soils (Baker and Ffolliott, 1999). However, the relationships between the concentrations of suspended sediment and streamflow discharge differed among treated watersheds. Highest sediment concentrations occurred after clearcutting followed by strip cutting, thinning by group selection, and the combined shelterwood-seed tree treatment.

The Beaver Creek experiments demonstrated that manipulating the forest

vegetation can produce short-term increases in streamflow, and that increases generally occur during years with above average precipitation (Baker and Ffolliott, 1999). However, these increases also occur when the reservoirs are near capacity, and it is difficult to effectively control the additional runoff. Vegetation manipulations for runoff augmentation can benefit wildlife, forage production, timber, and amenity values. Results from Beaver Creek have not been limited in applicability to the Southwest but are of national and international interest.

Implications

Forest watershed management research has increased the understanding of forest hydrology and implications for management of the forests in the region. The initial experiments at Workman Creek and Beaver Creek bracketed the water yields possible through a range of vegetation treatments (Baker, 1986; Gottfried *et al.*, 1999a). Increases were achieved by replacing deep-rooted trees with shallower-rooted grasses, shrubs, and tree seedlings that utilize less water. While many of these treatments would not necessarily be considered for present day management, they did establish a foundation for subsequent research that evaluated potential multi-resource prescriptions that removed fewer trees and produced smaller openings (Baker, 1986; Gottfried *et al.*, 1999a,b). Comparisons among sites demonstrated the importance of soil characteristics on the longevity of water yield increases. For example, increases at Castle Creek were not diminished after more than 20 years, while increases on the shallower soils at Beaver Creek generally were not sustained for more than 10 years. The Beaver Creek results

also showed the importance of aspect on sustaining increased streamflows (Baker, 1986). Research on the impacts of watershed treatments on sedimentation rates provided a foundation for evaluating the need to manage for sustained water quality and site condition. While recognizing that harvesting and wildfires have many different impacts on the land, managers are currently using research information from the studies to evaluate the impacts of large wildfires on streamflow quantities and peak flows.

While water yield augmentation is no longer a prime objective of forest management, the results from the experiments at Workman Creek, the White Mountains, and Beaver Creek have provided guidance for forest watershed managers who are responsible for developing and implementing multi-resource prescriptions on federal, state, and private lands throughout the Southwest. The managers are better able to assess the implications of standard silvicultural treatments, such as thinning or regeneration methods, and treatments designed to improve wildlife habitats on watershed resources. However, the current drought in much of the western United States recently has renewed some interest and public discussion about harvesting forests for water yield augmentation (Morrison, 2002). The current emphasis is to maintain and improve forest health and to maintain or, where necessary, to restore proper hydrologic functioning of watersheds (Ffolliott *et al.*, 2002a).

Water Quality and Silviculture

The physical, chemical, and biological characteristics of surface water combine and interact to determine the quality of

stream water. While silvicultural treatments can impact these characteristics in some instances, the effects of these treatments are relatively minor in the southwestern United States. Exceptions occur when poorly planned silvicultural treatments are improperly implemented on sensitive watershed areas (Brooks *et al.*, 2003). Silvicultural treatments have little immediate effect on groundwater resources.

Physical characteristics

Among the more important physical characteristics of surface water are sediment concentrations, thermal pollution, and the level of dissolved oxygen. Sediments consisting largely of silts and colloids of various materials affect domestic and industrial uses of water and can adversely affect aquatic organisms and their environments. Thermal pollution has many impacts on aquatic organisms and water quality. Dissolved oxygen is important determinant of chemical and biological processes in water.

Sediment: The total sediment load transported in streamflow includes suspended sediment and bedload materials. However, the largely episodic transport

of suspended sediment in the southwestern United States has a greater effect on water quality than bedload movement (Baker *et al.*, 1999; Lopes *et al.*, 2001). Suspended sediment restricts sunlight from reaching photosynthetic plants, can smother benthic communities in aquatic ecosystems, and cover spawning gravels used by fish. Suspended sediment also represents the largest portion of the total sediment loads that move through the stream systems in the region (DeBano *et al.*, 1996; Lopes *et al.*, 2001). Up to 90% of the total sediment transport in streams flowing at high discharges can be comprised of suspended soil particles (Table 1), and similar percentages are also observed on an annual basis.

The largest amounts of total sediment that are transported in a single hydrologic event are associated with the high-intensity, short-duration, and mostly convectional rainfall events of relatively limited extent that occur at all elevations in the late summer to early autumn (Baker and Ffolliott, 1999, 2000; Gottfried *et al.*, 1999a; Lopes *et al.*, 2001). There is a rapid response time to peak streamflow discharge as a result of these rainfall events, and the streamflow

Table 1. Total sediment (suspended sediments and bedload) transport following a 100-year storm in the Southwestern United States for different vegetation types and management practices

Vegetation	Sediment transport		
	Total (kg ha ⁻¹)	Suspended sediment (%)	Bedload (%)
Ponderosa pine forests			
Thinning	2,017	60	40
Clearing	19,726	90	10
Partial clearing and thinning	2,690	90	10
Pinyon-juniper woodlands			
Herbicidal conversion	129	80	20
Mechanical conversion	2,466	73	27

Source: Baker *et al.* (1971); Thorud and Ffolliott (1973).

duration is normally limited to hours or a few days. Intermediate amounts of sediment are moved with the low-intensity, relatively long duration frontal rainfall events in late autumn and winter months when there are insignificant amounts of snow on the ground. Snowmelt-runoff events generate most of the streamflow in the region. These events also contribute most of the annual sediment load, although sediment concentrations in the streamflow are low.

Effects of silvicultural treatments: Surface water flowing from undisturbed watersheds in the mixed conifer and ponderosa pine forests of the southwestern United States typically has low suspended-sediment concentrations of 10 to 20 mg L⁻¹. Much of this sediment comes from the stream channel itself, although limited amounts of sediment are contributed from overland flow in large storm events. Higher concentrations of suspended sediment are the result of accelerated erosion caused by disturbances on upland drainage areas such as livestock overgrazing, logging operations, or road construction (DeBano *et al.*, 1996; Lopes *et al.*, 2001; Brooks *et al.*, 2003). Natural catastrophes such as flooding or the occurrence of wildfire also result in higher concentrations of suspended sediment.

No meaningful changes in total sediment production occur as a result of the application of carefully implemented silvicultural treatments. However, the relationships between the amount of suspended sediment and streamflow discharge differ among treated watersheds. Highest suspended sediment concentrations occur after clearcutting, followed by partial

clearcutting, shelterwood-seed tree cutting, and thinning (Baker and Ffolliott, 1999; Lopes *et al.*, 2001). These increases in suspended sediment concentrations parallel the level of disturbance to the herbaceous ground covers by the silvicultural treatments and the slash treatments such as piling only or piling and then burning. Clearcutting causes the most extensive and wide spread disturbances on a watershed, while the disturbances attributed to shelterwood-seed tree cutting and thinning are less extensive and more localized.

Roads built to carry out silvicultural treatments and other management activities on the watersheds often produce levels of sediment that exceed those caused by all other land-management activities combined. These problems are compounded when disturbances take place on steep terrain and near stream channels (Heede, 1980; Lopes *et al.*, 2001). Therefore, proper road design and maintenance are critical to minimizing sediment problems. Continual maintenance is also crucial to mitigating the adverse impacts of roads on sedimentation and water quality.

Nutrient and heavy-metal transport capacities of sediment: A potential source of nutrient and heavy-metal loss from a watershed is material transported through the sedimentation process. These losses occur as a result of the weathering forces acting on the physical and biological environment, the latter represented by the vegetation type on the watershed (Gosz *et al.*, 1980; Brooks *et al.*, 2003). Sediment transported from drainages composed of different bedrock and vegetation combinations carry differing levels of nutrients and heavy metals. Sediment from

limestone parent materials is high in calcium and potassium, while that from basalt parent materials is high in sodium (Gosz *et al.*, 1980). Magnesium is highest in the sand fraction of basalt geologies and the clay-silt fraction of limestone. Sandstone has the lowest concentration of these elements, and granite is intermediate. Vegetation on a watershed of a specific geology affects the organic matter content, total phosphorus, and levels of extractable nutrients of the sediments. It also follows that silvicultural treatments have little effect on the losses in nutrients and heavy metals adsorbed by sediment because there are little changes in sediment transport attributed to such treatments.

Thermal pollution: The temperature of stream water controls the survival of certain flora and fauna residing in a riparian corridor. An increase in water temperature also causes an increase in the biological activity, which places a greater demand on the dissolved oxygen in a stream. That the solubility of oxygen in water is related inversely to temperature has compounded this effect. Changes in water temperature can result in the replacement of existing species, such as cold-water species being replaced by warm-water species (Rinne, 2002; Brooks *et al.*, 2003).

Loss of riparian vegetation is one way by which stream water temperature is increased. The removal of trees and other vegetation along a streambank by a silvicultural treatment increases the exposure of stream water to solar radiation, and the resultant rise in water temperature can be predicted if one considers an energy budget for the water in the stream. If trees

are removed from the streambanks, the only change in the energy budget is an increase in solar energy entering the system, which in turn will cause a rise in stream water temperature because there are no new outlets of energy from the system. Increases in stream water temperature can range from fractions of a degree for small openings in a forest overstory to more than 10°C for a complete removal of trees along the streambanks (DeBano *et al.*, 1996; Baker *et al.*, 1999; Brooks *et al.*, 2003).

Dissolved oxygen: Dissolved oxygen is a transient property that fluctuates rapidly in time and space. From a biological perspective, it is one of the most important water quality characteristics in the aquatic environment. However, the dissolved oxygen concentration only represents the status of the water system at a particular point and time of sampling. There is little information on the effects of silvicultural treatments on dissolved oxygen concentrations in the region. Nevertheless, these effects are presumed minimal when the treatments are kept away from stream systems.

Prevention and control: Maintaining a vegetative cover is the best way to reduce soil erosion and consequent sedimentation. Avoiding silvicultural treatments and other land-management practices that reduce infiltration capacity and soil permeability are also necessary. The more water that goes into the soil, the better are the chances of sustaining plant growth and reducing the erosive effects of overland flow. Limiting silvicultural treatments on steep soils is also important. Establishing and maintaining a vegetative cover to protect

critical areas of exposed mineral soil help to control excessive soil erosion and sedimentation. Roads that are located to minimize the amount of exposed mineral and disturbed areas on a watershed are a necessity (Baker *et al.*, 1999; Brooks *et al.*, 2003).

Dissolved chemical constituents

Water is an effective solvent, and its chemical characteristics adjust accordingly as it comes into contact with each part of the watershed system. Chemical reactions and physical processes take place as the water contacts the atmosphere, soil, and biota. These reactions and processes and the condition of each compartment of the ecosystem determine the kind and amount of chemical constituents in solution. Streams that flow from undisturbed forested watersheds generally exhibit low concentrations of dissolved nutrients (Baker *et al.*, 1999). Because of this, the biological productivity in most of these streams in the southwestern United States is also low, and the water is generally of sufficient quality to be used for many purposes.

Sources of dissolved chemical constituents: Sources of dissolved chemical constituents in water flowing from a watershed are the constituents in the precipitation falling on the watershed, geologic weathering of parent rock, and biological inputs. The cohesive properties of the bipolar water molecule allow it to wet mineral surfaces and to penetrate into the smallest of openings. Chemical and physical weathering then convert rock minerals into soluble or transportable forms that can be introduced into stream water. Sources of nitrogen are the fixation of

nitrogen gas by certain bacteria and plants, additions of organic matter to water bodies, and small amounts from the weathering of rocks. Nitrogen occurs in several forms, including ammonia, gaseous N, nitrite-N, and nitrate-N. Organic N breaks down into ammonia, which eventually becomes oxidized to nitrate-N, a form available to plants. Denitrification can convert nitrate back to ammonia and nitrogen gas in the absence of oxygen. Nitrate-N is the ion of primary interest to watershed managers in the southwestern United States. Calcium, magnesium, sodium, and sulfur and other ions normally remain at concentrations far below water quality standards in most instances (Ffolliott, 1989). High concentrations of nitrate-N in water can stimulate growth of algae and other aquatic plants. If phosphorus is present, only about 0.30 mg L⁻¹ of nitrate-N is needed for algal blooms.

Effects of silvicultural treatments: No meaningful or consistent changes in the concentrations of dissolved chemical constituents in stream water occur as a result of the silvicultural treatments applied to watersheds in mixed conifer or ponderosa pine forests of the southwestern United States (Baker and Ffolliott, 2000). A comparison between the dissolved chemical constituents in the water flowing from these watersheds and water quality criteria proposed by the US Environmental Protection Agency suggests that the levels of acceptability for aquatic life, irrigation, and public water supplies are not normally exceeded (Ffolliott, 1989). However, the levels of acceptability for a constituent have not been listed or prescribed in many instances.

Prevention and control: The Federal Water Pollution Act, commonly called the Clean Water Act, passed in 1977 indicates that implementing Best Management Practices (BMP) is the most practical and, therefore, preferred approach to preventing or controlling the transport of excessive amounts of sediments, dissolved chemical constituents, and other pollutants to stream waters in the United States (Brown *et al.*, 1993; Gelt, 2000). While the initial emphasis was placed on mitigating point-source pollution, amendments to the act addressed nonpoint-source pollution and designated silvicultural treatments such as timber harvesting, improving thinning practices, and road construction. BMP are applied before, during, and after pollution-producing activities to, hopefully, reduce or eliminate the introduction of pollutants into receiving watersheds. Many BMPs are known for silvicultural treatments and other forestry activities, livestock grazing, and road construction (Ffolliott *et al.*, 2002b). However, BMPs for the control of some types of chemical pollutants found in the stream waters of the southwestern United States remain unknown. Maintaining a protective cover of vegetation on a watershed is the basis of many BMPs.

Biological characteristics

Watershed managers are often concerned that surface waters from upland watersheds can become contaminated by health-impairing bacteria and pose hazards to the welfare of humans and animals. *Escherichia coli* is a ubiquitous bacterium that is found in the gut of all warm-blooded animals. Long considered to be benign, several pathogenic strains of *E. coli* have developed

in recent years and gained attention due to the health risk that they pose. *E. coli* is often used as an indicator species in bacteriological testing to determine if water is suitable for drinking or other forms of human contact. Waterborne protozoan parasites can also cause gastrointestinal illnesses in people, their livestock, and wildlife species. *Giardia* and *Cryptosporidium* have drawn considerable attention recently. Both parasites can be carried by a variety of warm-blooded animals including rodents, deer and elk, and livestock. Cattle are often perceived to be a leading source of *C. parvum* in surface water.

Silvicultural treatments have not significantly affected the biological characteristics of stream water. However, livestock grazing adjacent to streams can cause bacterial and protozoan densities to increase when rainfall events result in high overland flows (Brooks *et al.*, 2003). Intensive grazing by livestock on sensitive areas in riparian corridors is avoided to minimize this impact.

Cumulative effects

Silvicultural treatments that increase erosion can also increase the transport of sediment, nutrients, and other chemicals from upland watersheds, and the productivity of these watersheds can be reduced if these erosive processes continue. Water transports heat by changes in temperature from one site to another, and, therefore, the effects of a reduction in riparian vegetation on water temperature can impact downstream water uses that are dependent on temperature. Increased nutrient loads deplete dissolved oxygen by

stimulating algal blooms. Detrital organic materials consume oxygen as they decay. The cumulative effects of all such factors on the oxygen and temperature regime of streams and rivers must be recognized throughout a watershed. Silvicultural treatments that alter the volumes or timing of streamflow also affect the rates of chemical and nutrient transport. Silvicultural treatments often cause a short-term increase in nitrogen concentrations in streams (Brooks *et al.*, 2003). The increases in nitrogen concentrations can result from reduced nutrient uptake, increased subsurface flow, increased alteration of nitrogen to leachable forms, or increased volumes of decaying organisms. Vegetative conversions can also alter the spatial distribution of the resulting nitrogen mineralization because the plants lend different mineralization potentials to the soil. Other land-management activities that contribute to these mechanisms such as herbicide application and controlled burning can have similar effects.

Fire in Forests of the Southwestern United States

Fire has been an integral part of the forest environment in the southwestern United States where it has played a major role in the ecology and management of ponderosa pine forests (Cooper, 1961; Weaver, 1951; Wright, 1978). Fire also occurs in mixed conifer (Dieterich, 1983) and aspen forests (Jones and DeByle, 1985) and pinyon-juniper woodlands (Wright *et al.*, 1979), but to a lesser extent. The effects of fire on ecosystem dynamics and sustainability of ponderosa pine forests have been studied the most extensively.

Role of fire in southwestern forest ecosystems

Prior to Euro-American settlement of the Southwest, fire was common in forests throughout the region. As a result, ponderosa pine stands have adapted to a regime of an arid environment that has frequent, low-intensity fires (DeBano *et al.*, 1998). Naturally-occurring fires in ponderosa pine stands prior to Euro-American settlement mainly consumed light surface fuels consisting of grass and accumulations of pine needle cast (Sackett *et al.*, 1994). They burned on an average of every 10 years or less and often every 2 years (Dieterich, 1983). The frequent fire interval was sustained by the warm, dry weather during the early summer and the continuity of light surface fuels that are made up of grass and pine needles. This combination of climate and surface fuels provided ideal conditions for a high incidence of fires started by lightning. Under these natural conditions, light surface fires burned at frequent intervals through ponderosa pine stands. Large woody material consisting of branches or tree boles fell infrequently and, when consumed by it, they provided soil seedbeds that favored ponderosa pine seedling establishment. By comparison, fire in mixed conifer forest was less frequent, averaging once every 22 years (Dieterich, 1983).

The natural fire regime in ponderosa pine and other forest types was changed as a result of extensive livestock grazing during the later part of the 19th century (Sackett *et al.*, 1994). Overgrazing reduced the fine, surface grass fuels that were needed to carry the naturally occurring low-severity wildfires. As a result, regeneration of

ponderosa pine forests increased because there was less understory competition. The lack of fire also resulted in increased fuel accumulations and in stagnated, overcrowded stands. These stagnated sapling "dog-hair" stands were not only unproductive but led to a severe wildfire hazard by creating ladders that moved ground ignitions quickly into the tree canopy. In addition, a policy of fire suppression during the past 100 years led to further accumulations of stagnant sapling growth and the accumulation of thick forest litter layers. Fuel accumulations ranging from 49 to 76 t ha⁻¹ have been measured in southwestern ponderosa pine stands (Sackett, 1979; Harrington, 1982). Likewise, forest floor fuels accumulated to 20 t ha⁻¹ in sapling thickets and to more than 112 t ha⁻¹ on old-growth stands because of the extremely slow decomposition rates of ponderosa pine litter (Sackett *et al.*, 1994). The accumulation of fuels has also occurred in most forest ecosystems in the United States and Canada because of aggressive fire suppression programs that limited naturally occurring fires since the early 1930s (Keane *et al.*, 2002).

The combination of fuel accumulations, dense sapling thickets, lightning-caused and human-caused ignitions, and drought conditions in the Southwest has led to an increase in severe wildfires during recent decades (Sackett *et al.*, 1994). Since 1915, about 70% of the wildfires in Arizona and New Mexico that consumed more than 40,470 ha of forest vegetation have occurred between 1970 and 1990. Since 1990 the scenario has been even worse. For example, the Dude Fire in 1990 consumed 9,783 ha in Arizona, the Cerro Grande Fire near

Los Alamos in New Mexico consumed 19,283 ha in May 2000, and in July 2002, the Rodeo-Chediski Fire in Arizona consumed 189,652 ha and caused the evacuation of several towns in the fire area.

Fire effects on forest ecosystems

Fire affects the vegetation, litter, soils, and hydrology of forests. The magnitude of change produced by fire depends on the severity of the fire, which can range from minor resource damage under cool-burning prescribed fires to major responses that occur during stand-replacing wildfires in the forest (DeBano *et al.*, 1998; Neary *et al.*, 1999, 2000). Ideally, prescribed burning is done under conditions of lower temperature and higher humidity burning conditions where the fuel loading is low and fuel moisture is high. Low severity fires under these conditions have minor impacts on ecosystem resources. In contrast, during wildfires the temperatures, wind speeds, and fuel loadings are high, and humidity and fuel moisture are low. Consequently, the resulting high-severity crown fires have a major impact on many of the ecosystem processes and lead to increased sensitivity of burned sites to vegetation loss, increased erosional forces and reduced land stability (DeBano *et al.*, 1998).

The effects of wildfires on vegetation are most obvious, particularly when high-severity crown fires consume all the standing vegetation, including trees. This type of fire not only changes the present vegetative structure but also frequently changes the successional patterns of vegetation following the fire (DeBano *et al.*, 1998). The combustion of protective

canopy and litter cover exposes the bare soil surface to raindrop impact, followed by surface runoff and erosion. In contrast, prescribed fires are designed to burn coolly and only consume part of the surface litter and small "dog-hair" saplings, producing little change to the canopy of the older trees. The effect of different fire severities was documented following a wildfire in central Arizona (Campbell *et al.*, 1977). Annual stormflow discharge increased 3.5-fold on severely burned watersheds and 2.3-fold on watersheds burned moderately compared to a nearly unburned watershed. The average runoff efficiencies increased from 0.8% on the unburned watershed to 3.6 and 2.8% on the severely burned and moderately burned watersheds, respectively. In contrast, a cool-burning prescribed fire in a ponderosa pine forest in the White Mountains in Arizona had little effect on water quality or winter streamflow (Gottfried and DeBano, 1990).

Fire has less obvious but significant effects on soil and litter where the combustion of organic matter produces changes in the physical, chemical, and biological properties of the surface and subsurface soil horizons (DeBano *et al.*, 1998; Neary *et al.*, 1999). The magnitude of change in physical, chemical, and biological soil properties caused by fire depends on fire severity and extent of soil heating. High-severity wildfires frequently consume much of the above- and below-ground organic matter. In contrast, cool-burning prescribed fires may burn only a small part of the standing trees, leaving large areas of uncombusted organic matter on the soil surface and producing little change in the upper mineral soil layers.

The loss of organic matter is roughly proportional to the severity of the fire.

The most important soil property changes during fires are the loss of organic matter, nitrogen, and phosphorus. Nitrogen begins volatilizing between 200 and 300°C and is completely lost at 500°C. Organic matter is lost at similar temperatures and phosphorus at higher temperatures. The loss of organic humus materials in the soil destroys soil structure near the soil surface and reduces the porosity of the soil leading to decreased infiltration and surface runoff. The nitrogen contained in the organic matter in the litter and underlying soil can be easily volatilized and lost. For example, a slash-burning study in a dense ponderosa pine forest reported that 79% of the carbon and 87% of the nitrogen was lost from the slash and forest floor during burning (Klemmedson, 1976). However, not all the nitrogen is lost, and some highly available forms remain in the soil following fires. Prescribed burning of understory and surface litter in a ponderosa forest in central Arizona produced an immediate post-fire increase in available ammonium nitrogen followed by an increase in nitrate nitrogen as nitrification proceeded following the burn (Covington and Sackett, 1992). This available nitrogen is readily available to post-fire plants and stimulates their growth. The combustion of organic matter also affects soil microorganisms because it provides energy for microbial growth and functioning, and soil microorganisms are sensitive to soil heating and can be killed at temperatures as low as 60°C (DeBano *et al.*, 1998).

Fire also has an effect on soil and litter dynamics of ponderosa pine stands that

results from altering inhibitory substances and the wettability of the soil. Available nitrogen is often limited in unburned ponderosa pine forests because nitrogen cycling processes (mineralization and nitrification) decrease as litter thickness increases. One hypothesis describes these nitrogen processes as being inhibited by monoterpenes that accumulate in the absence of fire (White, 1991). Regular combustion of the litter layer by fire both destroys the inhibitory effect of these monoterpenes and directly releases available nitrogen. Another process affected by fire is the wettability of the soil. The volatilization of organic matter during a fire produces a water repellent soil layer in forests and other vegetation types that can decrease infiltration and accentuate runoff and erosion (DeBano, 2000). The creation of a water repellent soil condition is more likely to develop during wildfires because of the extensive soil heating that occurs.

The role of fire in ecosystem health

The damaging effects of wildfires in the Southwest during the past two decades has renewed and increased the interest in restoration ecology that in its simplest terms involves the ecological restoration of natural ecosystem structures and processes (Covington, 2000). Within a general framework, treatment strategy is based on reference conditions, cover evolution and conservation biology, and ecosystem ecology principles. An important criterion of these proposed restoration treatments is being able to emulate presettlement structure, function, and composition of the stands to be treated within a broad intellectual and scientific framework (Moore *et al.*, 1999; Mast *et al.*, 1999).

On-the-ground treatments utilizing this approach often consist of thinning younger trees followed by prescribed burning (Fulé *et al.*, 2001). This type of treatment applied in ponderosa stands in northwestern Arizona significantly lowered stand density and crown fuel loading, while it increased crown base heights compared to untreated stands. This restoration approach, however, is still under debate for two reasons. First, there are some limitations on using historical ecology because of incomplete knowledge concerning past variation produced by humans and climate (Swetnam *et al.*, 1999). Second, sole use of repeated prescribed fires to maintain presettlement restoration goals may be based on incompletely described and poorly understood seral stages occurring on individual sites (Tiedemann *et al.*, 2000).

Future Perspectives of Watershed Management

Future watershed management in the Southwest and throughout the nation will probably be based on a more holistic approach to the management of the biological, physical, and social elements of watersheds (Ffolliott *et al.*, 2002a). Increasing populations will put greater pressures on the forests and their resources and amenities. Watershed management practices must be designed to provide goods and services to society without adversely affecting basic soil and water resources. However, the public also must recognize the need to balance the economic and environmental values of watershed resources and that maintaining the balance could limit resource availability. The future emphasis of watershed management will be on continuing watershed improvement

practices, sustaining the integrity of riparian ecosystems, meeting the increasing demands for watershed resources, and developing technologies for the efficient use of limited watershed resources (Ffolliott *et al.*, 2002a).

Summary

Forest watershed management has been important in the southwestern United States since the early 20th century. The initial emphasis was the stabilization of watersheds that were the source of the region's water supplies so as to protect and sustain the longevity of downstream dams and diversion structures. A watershed research program was initiated in the 1930s to gather fundamental information about the hydrology of forested watersheds. The research efforts by the USDA Forest Service and cooperating universities expanded during the 1950s droughts to determine the potential for increasing streamflows by manipulating the forest cover. Experiments conducted throughout Arizona demonstrated that treatments that created large openings or significantly reduced stand densities would produce increased streamflow. This information then was used to develop and test silvicultural treatments that would increase water yields but benefit the other multiple resources that are associated with forested ecosystems. While water yields are no longer a primary objective, managers use the information from the experimental program in planning and evaluating multiple-use land treatments. The results currently are being used to evaluate the potential impacts of wildfires on streamflow parameters and to plan suitable restoration projects.

The current and a future emphasis on watershed management will be to ensure the delivery of high quality water from the region's forested watersheds. Silvicultural treatments have little effect on water quality except where poorly planned and improperly implemented treatments occur on sensitive sites. Roads have a greater impact on water quality than all other land management activities combined. Many water quality problems in forested areas are related to activities in riparian corridors such as removal of the tree cover, poorly designed roads and stream crossings, and intensive livestock grazing. Best Management Practices for forestlands are achieved by the maintenance of a protective vegetative cover. Silvicultural treatments that increase streamflow may result in relatively short-term increases in sediment and nutrient transport.

Fire regimes in the southwestern forests have changed since Euro-American settlement. The forest ecosystems are adapted to frequent low intensity fires that generally consumed fuels on the forest floor; however, overgrazing and aggressive fire suppression have reduced fire frequencies resulting in high fuel accumulations and high intensity, high severity wildfires. The effects of fire depend on severity; wildfires that occur during dry periods result in vegetation losses, increased erosion, and reduction in land stability, while the impacts of prescribed fires that occur under more moderate climatic and fuels conditions are less severe. The reintroduction of fire coupled with treatments to reduce forest stand densities are important parts of

restoration ecology that attempts to restore natural ecosystem structures and processes.

Watershed management in the future will emphasize watershed improvement practices, sustaining riparian ecosystems, and managing watersheds to meet society's growing demands for limited watershed resources. Sound land stewardship, now and in the future, requires partnerships among the general public, land users, and watershed managers.

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