Contributions of Watershed Management Research to Ecosystem-Based Management in the Colorado River Basin

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Abstract.—The Rocky Mountains and Southwestern United States, essentially the Colorado River Basin, have been the focus of a wide range of research efforts to learn more about the effects of natural and human induced disturbances on the functioning, processes, and components of the regions's ecosystems. Watershed research, spearheaded by the USDA Forest Service and its cooperators, leads to a better understanding of the regions's ecology, and to the formulation of management guidelines to meet the increasing needs of people living in these regions and throughout the Western United States. This paper presents pertinent details of watershed research that has been accomplished in the Colorado River Basin two regions and to provides highlights of the research results.

Introduction

People's behavior throughout the West, particularly the Southwestern United States, was conditioned and circumscribed by the perennial shortage of water. The expected, but variable, supplies of surface water were quickly 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 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 hectares that formerly supported agriculture have been abandoned, converted to housing developments, or switched to an alternate water source such as the Central Arizona Project, which became available in the late 1980s. However, the water situation, especially in heavily populated areas, has had little affect on people's water consumption, except for the farmer. As the cost of water increases, the farmer's income decreases. Eventually, the farmer is forced to stop farming, and either abandons or sells the land. The profit margin for the urban home owner is much higher. Consequently, Arizona has many human-made lakes, golf courses, and green lawns, and residents continue to demand more. Conversion of water previously used for agriculture, however, has the potential to sustain the growth of municipalities and industry into the future.

The combined surface and ground water supplies in the Colorado River Basin are generally adequate for current needs. However, growing demands and uses of water in this basin could soon result in a widespread water shortage. Local shortages already exist (Hibbert 1979). Barring conversion of saline water, additional importation of outside water, advancements in rainmaking, and rigorous conservation measures, residents must rely on the variable surface and diminishing groundwater supplies. In response, the initial direction of the research in the Colorado River Basin focused on investigating the potentials for increasing water yields from the region's forests, woodlands, and shrublands through vegetative manipulations (Baker 1999, Gary 1975, Leaf 1975, Martinelli 1975, and Sturges 1975). Numerous watersheds were instrumented with climatic and hydrologic measuring devices 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 conversion of vegetation on water yields under controlled, experimental conditions.

Theoretically, the surface water supply in the Colorado River Basin could be increased by as much as 1/3 (0.7 million ha-m annually) if vegetation and snow on 16% (10.5 million ha) of the basin were manipulated solely to increase water yield (Hibbert 1979). However, other forest resources, economics, and social and environmental concerns would greatly reduce the treatment area and effectiveness of the increasing water yield.

Water-yield increases are greatest where large reductions can be made in water transpired by plants and evaporated from snow. Clearcutting and conversion of vegetation usually increase water yield significantly. These practices can be appropriate in several vegetation types, such as chaparral and mountain brush, where the commercial value of the vegetation is low. However, where clearcuts and type conversions are unacceptable management practices, the potential for increasing the water yield is less, although it can still be substantial.

Hibbert (1979) reports that water yield in the Upper Colorado River Basin could be increased by 61,650 ha-m per year, or 3.5%, by treating up to 22% of each vegetation type, except aspen (*Populus tremuloides*) where 40% would

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be treated. About half of the increase would come from subalpine forests including Douglas fir (*Pseudotsuga menziesii*). More extensive treatments in the Lower Colorado River Basin would be necessary to obtain an additional 30,825 ha-m annually, an 8% increase in water yield. About 92% of the total increase would be generated by treating about 20% of the chaparral and 33% of the ponderosa pine (*Pinus ponderosa*).

While information on the cost of producing extra water is incomplete, it is believed that the cheapest water (based on cost to produce the additional water) would come from commercial forests, where timber yields would pay for part of the treatment costs (Hibbert 1979). Water would be more expensive from vegetation conversion treatments, because most of the treatment costs would be levied against water production. Regardless, most of the water is expected to cost less than imported water, and some of the water from commercial forests would supplement and be in the price range of water produced by weather modification.

Colorado River Basin

The Colorado River drains nearly 650,000 km^2 (65 million ha) in 7 Western states before entering the Gulf of California in Mexico (Hibbert 1979). The basin includes virtually all of Arizona and portions of New Mexico, Colorado, Wyoming, Utah, Nevada, and California. The drainage area is divided into Upper and Lower Basins at Lee Ferry, about 16 km south of the Utah-Arizona border. The Upper Basin contains 28.3 million ha and the Lower Basin contains 36.4 million ha.

Upper Basin

Precipitation averages 400 mm annually in the Upper Basin, where it is concentrated in the mountains (Hibbert 1979). The proportion of precipitation yielded as streamflow is nearly 6 times greater in the Upper Basin (16% or 64 mm) than in the Lower Basin (3% or 10 mm). Precipitation and streamflow vary greatly from year to year. Annual yields from the Upper Basin at Lee Ferry have varied from 37% to 163% of the 83-year mean flow of 1.8 million ha-m (Hibbert 1997). Seasonally, flow is concentrated in a few months of each year when the snow melts.

Conifer forests, including spruce fir (*Picea-Abies*), lodgepole pine (*Pinus contorta*), Douglas fir, mixed conifer, and ponderosa pine, cover nearly 6 million ha of the Colorado River Basin (Hibbert 1979). Subalpine forests of spruce fir, lodgepole pine, and Douglas fir occupy some 2.8 million ha in the Upper Basin. The elevations of these forests varies from 2,100 to 3,500 m, just below the alpine zone. The climate is cool and moist; mean temperature is near freezing. Precipitation is about 2/3 snow and averages from 500 to 1,400 mm/year. Water yield, largely from snowmelt, varies from 130 to 1,000 mm/year. Basin-wide, average precipitation in the subalpine forest is estimated at 700 to 760 mm and streamflow at 300 to 380 mm.

Ponderosa pine occupies about 0.6 million ha in the Upper Basin. The elevation range for ponderosa pine is between 1,850 and 2,750 ft, where the type grows best on sites that are warmer and drier than those occupied by mixed conifer and subalpine forests. Gambel oak and chaparral species are common understory plants in the lower fringe area of the pine. Annual precipitation is about half snow and averages from 380 to 635 mm. Water yield is mostly from snowmelt and averages 50 to 150 mm annually, depending on precipitation, elevation, and soils.

Quaking aspen occupies approximately 1.3 million ha in the Colorado River Basin, nearly all of it in the Colorado and Utah portions of the Upper Basin (Hibbert 1979). The aspen type is recognized for its multiple values of wood, livestock forage, wildlife habitat, watershed protection, recreation, and esthetics. Aspen is commonly found between 2,100 and 3,000 m in elevation in clumps to extensive stands interspersed among conifers of the subalpine, mixed conifer, and cooler portions of the ponderosa pine type. Precipitation averages 500 to 1,000 mm, half or more of it is snow. Water yield averages 70 to 130 mm in the Lower Basin but can reach 500 mm in the Upper Basin.

Mountain brush lands are extensive only in the Upper Basin, where they are found on about 1.3 million ha (Hibbert 1979). Gambel oak (*Quercus gambelii*), mostly in brush form, growing 0.6 to 3.7 m high in clumps or thickets, is the predominant species. Associated shrubs that sometimes dominate the site are chokecherry (*Prunus* spp.), serviceberry (*Amelanchier* spp.), snowberry (*Symphoricarpos* spp.), big sagebrush (*Artemisia tridentata*), mountainmahogany (*Cercocarpus* spp.), and other woody species. Though sometimes classified as chaparral, and similar in appearance, the mountain brush type differs in that most of the species are deciduous and, therefore, are active only in the summer. Mountain brush is commonly found at 1,500 to 3,000 m in elevation on relatively warm, dry exposures. Average annual precipitation ranges from 400 to 600 mm, less than half of it falling as snow. Water yield of 25 to 150 mm is expected.

Big sagebrush, found on some 10.5 million ha in the Colorado River drainage area (Hibbert 1979, Sturgis 1975) thrives over a broad range in elevation and climate. Big sagebrush is found at elevations up to 3,000 m and is well adapted to warm, dry growing seasons at lower elevations. Precipitation varies from 200 to 500 mm. Water yield is less than 25 mm on most sagebrush lands. However, where precipitation exceeds 350 mm, yield can reach 75 to 100 mm on the wettest sites. The relocation of snow by winter winds and the resulting water loss by sublimation are important features of this type.

The pinyon-juniper ecosystem occupies some 13 million ha in the Colorado River Basin (Hibbert 1979). Principal species are Utah (*Juniperus osteosperma*), Rocky Mountain (*J. scopulorum*), one seed (*J. monosperma*), and alligator juniper (*J. deppeana*) , and Colorado and single leaf pinyon pine (*P. edulis* and *P. monophylla*) The type is most commonly found in the foothills, low mountains, and low plateaus between 1,200 and 2,300 m in elevation. Though normally considered low in commercial value, the pinyon-juniper type is an important source of forage for livestock, food and cover for wildlife, and for various products such as fence posts, firewood, pinyon nuts, and Christmas trees. Extensive pinyon-juniper control programs have been conducted in the Lower Basin.

Pinyon juniper occupies 5.1 million ha in the Upper Basin. Precipitation averages 300 to 460 mm, with local areas receiving up to 500 mm. Winter rains and snow provide the bulk of the moisture. Water yield is generally less than 25 mm, although some of the better watered sites can approach 75 mm.

Lower Basin

The Lower Basin receives an average of 330 mm of annual precipitation; the Upper Basin receives 400 mm annually (Hibbert 1979). The proportion of precipitation yielded as streamflow is 3% or 10 mm, nearly 6 times less than streamflow in the Upper Basin.

The Lower Basin is characterized by a cyclic climatic regime of winter precipitation, spring drought, summer precipitation, and fall drought (Baker 1999). 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 tends to be widespread and relatively low in intensity.

The major source of moisture for summer rains is the Gulf of Mexico. This moisture moves into the region from the southeast and passes over highly heated and mountainous terrain, where it rises rapidly, cools, and condenses. Summer storms, therefore, are primarily convectional, often intense, and usually 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.

Mixed conifer forests in the Lower Basin occupy sites that are wetter and cooler than those usually occupied by pure stands of ponderosa pine. These sites are warmer, but not necessarily drier, than subalpine forest sites to the north. The most common overstory species are Douglas fir, ponderosa pine, white fir (*Abies concolor*), Engelmann spruce (*Picea engelmannii*), aspen, southwestern white pine (*P. strobiformis*), blue spruce (*P. pungens*), and corkbark fir (*A. lasiocarpa var. arizonica*). Most of the mixed conifer stands are found between 2,100 and 3,000 m elevation. These mixed conifer forest occupy nearly 160,000 ha. Precipitation averages 630 to more than 760 mm / year and is usually in excess of potential evapotranspiration; half or more of the precipitation falls as snow (Hibbert 1979). Streams originating in this area above 2,900 m in elevation are often perennial, while those originating in low elevation mixed conifer forests (2,400 to 2,900 m) are mostly intermittent. Water yield averages 75 to 130 mm, sometimes more on the wettest sites; 3/4 or more of it is from snowmelt.

Ponderosa pine occupies 2.4 million ha in the Lower Basin (Hibbert 1979). Elevation range for ponderosa pine forests is between 1,800 and 2,700 m, where the type grows best on sites that are warmer and drier than those occupied by mixed conifer and subalpine forests. Gambel oak and chaparral species are common understory plants in the lower fringe areas of the pine. Annual precipitation is about half snow and averages from 500 to 630 mm in the Lower Basin. Water yield is mostly from snowmelt and averages 50 to 150 mm annually, depending on precipitation, elevation, and soils. The overall average water yield from ponderosa pine in the Colorado River Basin is 75 to 100 mm.

Pinyon-juniper vegetation occupies 8.1 million ha in the Lower Basin. Summer rains account for half or more of the precipitation. Evapotranspiration rates are relatively high in the growing season and only during the coldest months of December through February is precipitation greater than evapotranspiration. Water yield is generally less than 25 mm, although on some of the wetter sites it can approach 75 mm.

The chaparral type is restricted almost entirely to the Lower Basin, where it covers about 1.4 million ha, nearly all in Arizona (Hibbert 1979). Unlike the mountain brush in Colorado and Utah, chaparral species tend to be low-growing shrubs with thick, evergreen leaves well adapted to heat and drought. The type is common on rugged terrain from 900 to 2,000 m in elevation. Shrub live oak (*Q. turbinella*) is most abundant, followed by mountainmahogany. Other common shrubs are manzanita (*Arctostaphylos* spp.), Emory oak (*Q. emoryi*), silktassel (*Garrya wrightii*), desert ceanothus (*Ceanothus greggii*), and sugar sumac (*Rhus ovata*). Most species sprout prolifically from root crowns after burning or cutting and are difficult to eradicate.

Chaparral shrublands occur on rough, discontinuous, mountainous, terrain south of the Mogollon Rim in central Arizona. Average annual precipitation varies from about

380 mm at the lower limits to over 630 mm at the higher elevations (Hibbert 1979). 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 evaporation rates can approach 900 mm. Water yield varies greatly depending on precipitation, elevation, and soils. The overall average is 25 mm or more; the lower, drier sites produce little, while the wettest sites can yield 75 or 100 mm.

The desert shrub zone in Arizona, an area of about 14.5 million ha, includes the northern and southern desert shrub type (Ffolliott and Thorud 1975). The delineation between desert shrub and the adjacent grassland vegetation is indistinct on many sites due to the invasion of the grasslands by the desert shrubs. The northern desert shrub type (see the sagebrush type description in the Upper Basin section) is largely confined to elevations between 750 and 1,500 m north of the Colorado and Little Colorado Rivers. The southern desert shrub type occurs mainly in southwestern third of Arizona, at elevations from about 50 to 900 m. This type extends upward into the desert grassland type, often invading these grassland ranges, possibly as the result of the exclusion of fire and depletion of grass stands.

Overstory species of the desert shrub type include numerous shrubs and cacti. The composition and density of these overstories are dependent upon climatic patterns, edaphic factors, and imposed land management practices. Pure stands of big sagebrush are common throughout the northern desert shrub type (Ffolliott and Thorud 1975). Another characteristic shrub of this type is blackbrush (*Coleogyne ramosissima),* fourwing saltbrush (*Atriplex canescens*), and winterfat (*Eurotia lanata*). The most common dominant shrubs in the southern shrub type include creosote (*Larrea tridentata)*, paloverde (*Cereidium* spp), and cacti (*Carnegiea gigantea* and *Opuntia* spp). The occurrence of these shrubs and cacti is often controlled by soil texture, permeability, presence of alkali, caliche, and other influences. Other shrubs found within this type are catclaw acacias (*Acacia greggii*), bur-sage (*Franseria deltoidea*), mesquite (*Prosopis juliflora*), tarbrush (*Flourensia cernue*), and ocotillo (*Fouquieria spendens*).

Average precipitation in the northern desert shrub type is about 250 mm annually, with a general range of 125 to 350 mm (Ffolliott and Thorud 1975). Depending upon the exact location, precipitation between June and September can approach, or slightly exceed, 50% of the annual amount. Annual precipitation in the southern desert shrub type varies from 75 to 300 mm, but averages about 150 mm. On the Santa Rita Experimental Range in south central Arizona, about 60% of the annual precipitation amount commonly comes between July and the end of September, with no effective precipitation expected in April, May, and June.

Upstream riparian areas consist of vegetation along streams that drain to the Colorado River, and its major tributaries. Total area occupied by these bands of vegetation exceeds 40,500 ha in the Lower Basin (Hibbert 1979). No acreage figure is available for the Upper Basin. Common riparian trees and shrubs are cottonwood (*P. fremontii*), willow (*Salix* spp.), sycamore (*Platanus wrightii*), and alders (*Alnus tenuifolia*). Native herbaceous species include sedges (*Carex* spp.), spike rushes (*Eleocharis* spp.), rushes (*Juncus* spp.), and bulrushes (*Scirpus* spp.) (Medina 1996). Elevations range from about 300 to over 3,000 m. Estimates of potential evapotranspiration for the lowest elevations are as high as 1.8 m / year. These upstream riparian areas are of special interest because they are areas of heavy water consumption, conveyance systems for water yield generated on upstream watersheds, areas of high scenic value, and high value areas for wildlife and recreation.

Multiple Use Research

Water has historically affected populations occupying this region. Water related activities have been documented since about 200 B.C., when Hohokam Indians settled the Salt River Valley in central Arizona and constructed canals to irrigate their fields (Baker 1999). European settlers in the Phoenix, AZ area in the late 1860s depended on irrigation water from the Salt River for agriculture. However, water supplies fluctuated greatly because the river often flooded in the winter and dried up during the summer. There were no impoundments to store water for the dry seasons. Therefore, the Salt River Water Users' Association, the largest irrigation district in Arizona, signed an agreement in 1904 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. Watershed managers in the early 20th century became concerned that erosion on the adjacent and headwater watersheds of the Salt River would move sediment into the newly constructed Roosevelt Reservoir, which would decrease its capacity. Measurements indicated that 12,450 ha-m of coarse granitic sediments accumulated behind Roosevelt Dam between 1909 and 1925 (Baker 1999). Because of the concern about these sediment accumulation, the Summit Plots were established in 1925 by the USDA Forest Service 24 km upstream from Roosevelt Dam to study the effects of vegetation recovery from livestock grazing (the dominate land use at the time), mechanical stabilization of disturbed soil, and reseeding on stormflow and sediment yields from the lower chaparral zone (Rich 1961).

The early research on the Summit Plots was expanded to consider the effects of watershed management practices on all the region's natural resource products and uses of the forests, woodlands, and shrublands. The USDA Forest Service and its cooperators began to thoroughly evaluate the effects of vegetative manipulations on the array of multiple uses from the ecosystems studied. Results from this research show that vegetation can often be managed to increase water yields, while still providing timber, forage, wildlife, and amenity values required by society in some optimal combination. This finding was not surprising, as many of the vegetation management practices studied to improve water yield were common in principle and application to other management programs often implemented to benefit other natural resources.

Research Findings

Summaries of important findings about the contributions of watershed research to multiple-use, ecosystem-based management in the Colorado River Basin follow. Additional details are in the cited literature.

Subalpine Forests

The original water-balance study in the United States was done on 2 watersheds at Wagon Wheel Gap on the headwaters of the Rio Grande in southwestern Colorado (Bates and Henry 1928). Streamflow was measured from 1911 to 1919, and then one watershed was clearcut. Of 530 mm of annual precipitation falling on these watersheds, about 150 mm was returned as streamflow, with almost 380 mm lost to evapotranspiration. Following the clearcut treatment, evapotranspiration was reduced and flow increased an average of about 25 mm. Bates and Henry concluded that much of the observed increases in flow came from net reduction in winter losses, and that reduction in overstory transpiration was offset by increased understory transpiration and ground evaporation.

A status-of-knowledge publication presented a discussion of the forest hydrology and an in-depth discussion and review of studies about the effects of watershed management practices on snow accumulation, melt, and subsequent runoff in subalpine forests (Leaf 1975). Many of the water-balance studies in the spruce fir and lodgepole pine forest were done on the Fraser Experiment Forest in north central Colorado. Simulation models designed to predict the hydrologic impacts of timber harvesting and weather modification on water yields were also addressed. Information presented in this publication was later updated by Troendle et al. (1987). Important finding for the subalpine-fir type included:

- The potential is good for increasing water yield in the subalpine type by managing for snow redistribution and transpiration reduction in small forest openings (Hibbert 1979, Leaf 1975). Increases in water yield of from 25 to 75 mm can be expected, depending on site factors and management strategies.
- Suggested harvest procedures in lodgepole pine is a series of patch cuts, 5 to 8 tree heights in diameter, each covering about 1/3 of the planning unit. The cuts would be made at 30-year intervals over a planning period of 120 years with periodic thinning in the regenerated stands.
- The harvest procedures for spruce fir is similar to lodgepole pine, except that the patch cuts would be made at 50-year intervals. Patch cutting in much of the Rocky Mountain area is considered ecologically sound if the management objective is to maintain the spruce-fir ecosystem (Alexander 1974).

Mountain Brush

There has been an insufficient amount of research in the mountain brush type to accurately predict how treatment will affect water yield (Hibbert 1979). However, results from plot studies in Utah (Johnson et al. 1969) suggested that responses to brush conversion might be less than in the chaparral type of the Lower Basin. A rough estimate is 25 to 75 mm of additional water from type conversion. If shrub regrowth is not controlled, the increase will be short-lived; probably about 3 to 5 years. It is also difficult to estimate the amount of mountain brush that would be converted to grass, in view of other resource values and social and economic factors that should be considered in resource management decisions.

Big Sagebrush

The potential for increasing water yield in big sagebrush is poorly defined, although type conversion on favorable sites might increase yield by 15% or up to 13 mm (Hibbert 1979, Sturges 1975). Additional increases of 25 mm or more might be possible by trapping blowing snow behind snow fences in areas where the winter snow water equivalent is at least 200 mm (Tabler 1975).

Mixed Conifer Forests

Research on mixed conifer watersheds at Workman Creek on the Sierra Ancha Experimental Forest in central Arizona (Lower Basin) demonstrated that increases in stream flow could be obtained by replacing the trees with a grass cover on large and strategically located parts of a watershed or by greatly reducing overstory densities (Baker 1999). However, many of these treatments compromised other resource sustainability. Additional research by the USDA Forest Service expanded its watershed program in mixed conifer and high elevation ponderosa pine forests to the White Mountains of eastern Arizona in the late 1950s and early 1960s. Major experiments in the White Mountains were designed to confirm results from Workman Creek experiments and to test multiple-use forest management treatments.

A status-of-knowledge publication presented the early results of water-yield improvement experiments and other research conducted on the watersheds in the mixed conifer forests 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 and, in some cases, expanded upon and subsequently reported in other publications (Baker 1999). For example:

- Treatment of mixed conifer vegetation can result in water yield increases that have remained constant for 13 years on Workman Creek (Baker 1999). Treatments included both moist-and-dry-site clearcuts and single-tree selection prescriptions.
- There were minor changes in sediment yields, but a wildfire on the South Fork of Workman Creek had a greater effect on soil movement than the timber harvesting treatments.
- Using management strategies similar to those described for subalpine forests, the potential for increasing water yield in the mixed conifer forests is estimated to be about 25% less than in the subalpine, although large clearcuts appear to give greater increases in the mixed conifer (Hibbert 1979). In the drier, warmer climate of the mixed conifer forests, more of the response is attributed to reduction in transpiration and less to redistribution of snow. Increases in water yield of 75 to 100 mm are possible from clearcutting (Rich and Thompson 1974). However, without type conversion to an herbaceous cover, the increases would decline as the forest regrows. The overall estimate is a 40 mm average increase from maintaining about 1/3 of the area in small openings on sites where streamflow normally averages 100 to 125 mm.

Ponderosa Pine Forests

A status-of-knowledge publication presented the early results of water-yield improvement experiments and other research conducted on the pilot watersheds in ponderosa pine forests on the Beaver Creek Watershed (Brown et al. 1974). These results were refined and expanded upon in subsequent publications listed in an annotated bibliography of 40 years of investigations on the Beaver Creek watershed (Baker and Ffolliott 1998). Watershed management problems and opportunities for the Colorado Front Range ponderosa pine were also addressed by Gary (1975). Results of findings for the ponderosa pine forest type include:

- The potential for increasing water yield in ponderosa pine is less than from other commercial forest types, presumably because the pine forests are drier. Short-term (3 to 10 yr) increases of 25 to 75 mm can be expected from clearcutting ponderosa pine with basal area in excess of 23 m^2/ha.
- Under a multiple use management framework, where timber, range, wildlife, recreation, and water are all considered in the product mix, the long-term increases of 2 to 25 mm are a more realistic expectation (Brown et al. 1974). Low to intermediate stocking levels on approximately 2/3 of the ponderosa pine sites (Schubert 1974) can preclude water increases from these areas regardless of the management emphasis, except for clearcutting.
- No meaningful changes in total sediment production or water quality occurred as a result of the treatments applied in ponderosa pine forests. Average sediment production from untreated pine areas was 45 kg/ha and increased to 225 kg/ha after the clearing treatment (Brown et al. 1974). Relationships between the amount of sediment in suspension and streamflow discharge differed among the treated watersheds (Lopes et al. 1996). The highest sediment concentrations occurred after clearcutting, followed by stripcutting, thinning by group selection, and the combined shelterwood-seed tree silvicultural treatment. While changes in suspended sediment concentration are significantly different following treatment, these concentration are relatively low (generally less than 100 mg/l).

- Repeated inventories of the pine timber resource indicate that volume production has often been sustained, although at generally lower levels than those represented by pretreatment conditions (Baker 1999). Exceptions to this finding were found on a watershed that was totally clearcut in 1966 and 1967, and on a watershed that had been converted from ponderosa pine forest to grass in 1958 and subsequently subjected to livestock grazing in the spring and fall starting in 1968. While these 2 watersheds, particularly the watershed cleared in 1966 and 1967, have Gambel oak and alligator juniper growing on them, the areas have been withdrawn from pine production.

- Reductions in the density of ponderosa pine forest overstories have generally resulted in increases in the production of herbaceous plants (Baker 1999) and vice versa. These increases can approach 560 kg/ha after complete overstory removal including forage and non-forage plants. The untreated pine areas produced 225 kg /ha.

- Reducing densities of ponderosa pine forests have increased food for deer and elk, while retaining protective cover (Larson et al. 1986). Total clearcutting is detrimental to big game and Abert squirrel, although cottontail habitat can be enhanced when slash and Gambel oak thickets are retained.

- Fire can be prescribed to consume portions of the accumulation of dead organic material on mineral soil, impacting 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 into the *H* layer (well decomposed organic material) affects postfire infiltration rates and erosion potentials. Other effects of fire can include thinning forest overstories from below, increasing seedling establishment, increasing production of herbaceous plants, and temporarily reducing fire hazard. Wildfire of moderate severity can have similar effects as observed with prescribed fire. However, wildfire of high severity often burns the forest floor to the mineral soil and induces a water-repellent layer in sandy soils (Campbell at el. 1977). The reduced infiltration rates can increase surface runoff from the burned site, causing soils to erode and removal of nutrients that have been mineralized. All small trees and many large trees can be killed, resulting in large increases in herbage.

- 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 esthetics preferences for alternative landscapes , the more natural-appearing watersheds were preferred by most publics (Baker 1999). This conclusion adds weight to the often heard, but seldom substantiated, claim that "naturalness" is a desirable forest landscape characteristic.

- 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, and production functions describing the trade offs among the affected natural resources. This work resulted in a variety of publications related to hydrology, vegetation, and wildlife responses (Baker 1975, Bojorquez-Tapia et al. 1990, Brown and Daniel 1984, Ffolliott 1985, Ffolliott and Guertin 1988, Larson 1975, Larson et al. 1979, Li et al. 1976, O'Connell 1971, Rogers 1973, Rogers et al. 1982). A complete listing of publications on modeling and simulation techniques is found in Baker and Ffolliott (1998).

- Results from the Beaver Creek Watershed project 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 Southwest. However, extrapolation of the results from Beaver Creek to sites on sedimentary soils requires prior validation (Ffolliott and Baker 1977).

Additional watershed-related research in the ponderosa pine forests of the Colorado River Basin were obtained from Castle Creek in eastern Arizona (Baker 1999) and from the Colorado Front Range (Gary 1975). The Colorado Front Range, generally regarded as the eastern foothills of the Rocky Mountains, extends from southern Wyoming to Canon City, Colorado. Results from an irregular, block, harvesting treatment on a predominately ponderosa pine watersheds were:

- An average water yield increase of 30% (13 mm) remained stable for 20 years after the treatment. The initial increase in water yield was attributed to reduced evapotranspiration and increased snow accumulations in the openings. This posttreatment water regime was 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 (Baker 1999).

- No increase in water yields occurred after a prescribed burn. This was expected because the fire did not affect the forest overstory conditions or consume much of the forest floor.

For the Colorado Front Range pine type:

- Clearcut openings are necessary to significantly increase water yields (Gary 1975).
- Minimal water increases can be expected on grazed lands with adequate soil cover and highly permeable soil.
- Problems with the chemical and bacteriological quality of water due to expanding foothill communities, indicates a need for careful land use planning and wise use of the forest and forage resources.

Pinyon-Juniper Woodlands

Another state-of-the-art paper from research from the Beaver Creek Watershed described the effects of removing pinyon-juniper woodlands on natural resource products and uses (Clary et al. 1974). These results are listed in an annotated bibliography of 40 years of investigations on the Beaver Creek watershed (Baker and Ffolliott 1998). Finding include:

- The potential for increasing water yield in the pinyon-juniper type is negligible on most sites (any sites receiving less that 450 mm of precipitation/year), although small increases (less than 13 mm) are possible by type conversion on the wettest sites (Hibbert 1979). Overall, the potential for increasing water yield is considered poor for pinyon-juniper sites.
- 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 was believed responsible for the increased sediment concentration. While sediment concentrations are significantly different following treatment, they are relatively low (generally less than 5 mg/l). Average sediment production in untreated areas was 225 kg/ha. Water quality (nutrients) remained unchanged following conversion.
- Herbage production, generally lower in the pinyon-juniper woodlands than in the ponderosa pine forests, increased several-fold as a result of the conversion treatments (Baker 1999). The value of this increase for livestock or wildlife is variable, however. It is likely that the levels of increased herbage production will slowly 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. However, cottontails can increase, providing that a sufficient canopy cover remains (Ffolliott 1990). Overstory-dependent, non-game birds leave after treatment. These species are replaced by ground-feeding species.

Chaparral Shrublands

An earlier status-of-knowledge publication presented the results of increasing water yields and other multiple use values in chaparral shrublands through the early 1970s (Hibbert et al. 1974). These results were refined and expanded upon in subsequent publications (Baker 1999):

- The potential for increasing streamflow by type conversion of chaparral is good on favorable sites where precipitation averages 500 mm or more (Hibbert 1979). The key to increasing water yield is the replacement of deep-rooted shrubs with shallow-rooted grasses and forbs that use less water. The average is 100 mm increase in water yield in areas receiving 560 mm of average precipitation.
- Some discounting or reduction in potential water yield increases is necessary before extrapolating results to larger areas where conversions may not be as intensive, continuous, or as well maintained as on experimental watersheds. Some of the increased flow will also be lost to riparian vegetation downstream before it reaches storage or points of use. Therefore, the average increase expected downstream from type conversion is estimated to be about 2/3 of the on-site increase or 60 mm (considered average for treatable chaparral).
- Further discounting of potential water-yield increases is necessary for the exclusion of wilderness areas, sites too dry and open (cover density less than 30%), slope steepness, and operational restrictions or geographic location (chaparral on slopes of isolated mountain ranges). These factors

would reduce treatable acreage to 1 ha in 5. Therefore, use of 20% of the acreage (146,000 ha) and the 60-mm increase in water yield is probably the most optimistic potential attainable by large-scale management efforts in chaparral (Hibbert 1979).

Semi-Desert Shrublands

Owing to the relatively low precipitation input and high evaporation potential of the desert shrub type, it is the least important water-yielding area in the Colorado River Basin. In evaluating water-yield potential for this vegetation type as an entity in the lower basin (both the northern and southern desert areas) water-yield averages of between 1 and 8 mm have been reported, but these amounts are highly variable from year to year (Ffolliott and Thorud 1975).

The USDA Agricultural Research Service has maintained the Walnut Gulch Experimental Watershed in southeastern Arizona as a research facility to quantify the influence of upland conservation practices on downslope water supplies since the middle 1950s (Goodrich et al. 1994). Situated in the transition between the Chihuahuan and Sonoran Deserts, the Walnut Gulch Experimental Watershed is part of a national effort to establish highly instrumented watersheds in the primary hydro-climatic regions of the United States. The extensive hydrologic network and the data- and knowledge-bases from Walnut Gulch have had far-reaching impacts on development of semidesert shrubland water management and technology (Goodrich and Simanton 1995). Some of the contributions from the research efforts at Walnut Gulch to the general knowledge of watershed management in semidesert shrubland environments include:

- Quantification of the spatial and temporal variability of precipitation and development of design-storm characteristics used for design and construction purposes throughout the Southwest.
- Quantifying the role of stream-channel transmission losses in water balance relationships of semi-desert shrubland watersheds.
- Development of flood-frequency relations for ephemeral streams used for design and construction purposes in the Southwest.
- Quantifying the impacts of ephemeral streams on sedimentation and groundwater recharge.
- Determining the consequences of possible climatic change on soil, water, and plant resources characterizing semiarid environments.

Research in recent years has included natural resource models developed from Walnut Gulch data bases into user-friendly decision-support systems to analyze alternative watershed management practices for the efficient and sustainable use of water and soil resources in semiarid environments (Renard et al. 1993). These decision-support systems facilitate selection and analysis of watershed management practices designed to optimize resource use while maintaining the integrity of the fragile ecosystems in these environments.

Riparian Ecosystems

The potential for increasing water yield in the upstream riparian areas can be greater per unit area than for any other vegetation type in the Colorado River Basin (Hibbert 1979). That is:

- Water-yield increases from 150 to 610 mm appear possible when riparian vegetation is eradicated along permanently flowing streams (Horton and Campbell 1974). However, extensive removal of trees and shrubs from these areas would impair scenic and recreation values, adversely affect channel stability, and destroy some of the most productive wildlife habitat in the river basin.
- Less than complete removal of trees and shrubs would reduce the water savings potential. Thus. it appears unlikely that upstream riparian areas can be counted on for significant augmentation of the water supply.
- Although there is a public perception that riparian areas are fragile, current information indicates, that riparian ecosystems can be resilient. Although much of our Southwestern riparian areas were destroyed around the turn of the century (1890), these areas had been exposed to thousands of head of cattle for years (1880s to 1900s), severe logging practices, and characteristic periods of drought and flooding (Cooperrider and Hendricks 1937).
- Many riparian areas are functioning “at risk” because of external stresses (overgrazing, drought, and flooding) that have caused the system to loose its dynamic equilibrium (Baker and Medina 1997). However, once this stress is relieved, many riparian systems regain their equilibrium within a few years because of the resiliency of the native riparian plants.
- Although expensive, engineering activities, such as use of instream structures, channelization, bank

modification, and rip-rap, can be used to provide flood control, irrigation development, and wetland conversion, many restoration projects have actually resulted in further site degradation and reduction in the condition of the affected streams (Baker 1999). Often, the importance of the interactions between the riparian and aquatic systems are not recognized as an integral factor in maintaining productivity of the system. Channel systems are continually adjusting to varying flows and sediment loads, which is not always compatible with placement of fixed structures.

- Aquatic vegetation allows the stream to function naturally and provides resiliency to a variety of environmental conditions.
- Restoration of a degrading channel system often only requires the reestablishment or placement of riffle bars and grazing control for a few years (Baker 1999). Riffle bars slow down the water velocities, reduce or terminate channel downcutting, and provide spawning habitat. Removal of the grazing stress allows the aquatic plants to regain vigor, and their functioning ability to detain flood flows and trap sediments and nutrients.

Management Implications

Watershed-research in the vegetation types of the Colorado River Basin has mostly evolved from single resource evaluations (e. g., increased water yield) to evaluations that consider the multiple benefits of from vegetation management treatments. Research has determined that vegetation can often be managed to increase water yields, while providing timber, forage, recreation, wildlife, and other amenities. However, one question should be answered: To what extent can the established research framework and available data bases be used to meet future management-oriented informational needs in the Colorado River Basin? Long-term monitoring and evaluations, based on reinventories of permanently-located sampling units on the study sites, represent a valuable use of the cumulative research efforts. A better framework for conservation and the sustainable use of the region's natural resources should evolve from the evaluations obtained.

Repeated measurements of permanent inventory locations provide a basis for long-term monitoring and evaluations, which 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, more coherent view of how ecosystems function (Baskin 1997).

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