Hydrology and Watershed Management in the Madrean Archipelago

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Abstract.—Interactions among hydrologic processes, soils, and vegetation that has been subjected to a wide array of watershed management activities have not been well studied in the Madrean Archipelago biogeographic region. As a result, better measurements of storm runoff, soil erosion, and sediment yields are needed to adequately characterize many of the representative ecosystems hydrologically. Many sensitive ecosystems are sustained in a delicate balance under a limited water regime and a highly variable climate. This balance has frequently been overwhelmed by land uses and abuses, resulting in severe and widespread watershed degradation. This paper discusses existing hydrologic and watershed information for the Madrean Archipelago, and supplements this information with data from similar ecosystems located outside of this region. It also provides suggestions for the restoration of severely degraded watersheds.

INTRODUCTION

The climate of the Madrean Archipelago is mainly arid, with the higher-elevation mountain ranges subjected to a more semiarid climate. This biogeographic region is thus especially sensitive to climatic fluctuations and human impacts. Therefore, knowledge of the hydrologic processes regulating these water-limited ecosystems is essential to understand the soil-vegetation relationships responsible for sustaining landscape stability. The overall hydrologic response of this region to potential global climate changes is also important because of the delicate equilibria and interrelationships existing between precipitation and soil-vegetation assemblages.

Only a few comprehensive hydrologic studies have been reported for the Madrean Archipelago region (Lopes and Ffolliott 1992). One notiable exception is the long-term research effort at the Walnut Gulch Experimental Watersheds in southeastern Arizona. This paper characterizes the hydrology of the Madrean Archipelago by summarizing existing information obtained from within, and supplements this information with data extrapolated from similar ecosystems located outside the region.

VEGETATION

The Madrean Archipelago is the area in the southwestern United States and northern Mexico where scattered, isolated mountains occur in a sea of largely evergreen woodlands and semidesert grasslands. According to Brown (1982), the cold-temperate forests occupying the mountain tops are Rocky Mountain montane forests, which extend from southern Colorado, Utah, and Nevada through Arizona, New Mexico, Chihuahua, and Sonora. These forests, which are recognized as recreational centers, unique wildlife habitat, critical watershed areas, and sources for lumber and livestock grazing, reach their characteristic development between elevations from 2,300 to 2,650 m (fig. 1).

The lower limits of the pine forests, which make up a significant portion of the montane forest type, interface with evergreen oak woodlands and, to a lesser extent, coniferous woodlands. The evergreen woodlands are centered in the Sierra Madre of Mexico, reaching northward to the mountains of southeast Arizona and southwest New Mexico (Brown 1982). Elevations range from 1,200 to about 2,200 m. These woodlands are open

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stands of evergreen oaks, or intermixtures of oaks, alligator and one-seed juniper, and Mexican pinyon. The lower contact of the evergreen woodlands is semidesert grasslands, or desertscrub. This boundary is influenced largely by the soil depth and type, since these types occupy similar elevational ranges.

Brown (1982) indicates that the semiarid grasslands in the Madrean Archipelago region were historically encountered at elevations of 1,000 m on level plains and along the larger river valleys. These areas are typically grass-dominated systems with scattered woody plants—a savanna landscape. Since grasses have intensive and woody plants extensive root systems, respectively, the removal of grasses by livestock overgrazing can reduce water loss near the soil surface. As a result, more water becomes available for use by woody plants, and scrub or bush encroachment begins. If grasses are not allowed to recover and increase the likelihood of lightning or human-caused fires, woody plants continue to invade at the expense of the grass species (Brown 1982).

Desert grassland vegetation generally grows on alluvial soils (Hendricks et al. 1985). These are well-drained soils on valley plains and wide floodplains in the Santa Cruz, Sulphur Springs, and San Simon Valleys. These soils support some of the best rangeland in the Madrean Archipelago.

The two desert biomes found in the Madrean Archipelago are those associated with the warm-temperate Chihuahuan Desert, centered in the arid highland plains and basins of north-central Mexico, and the subtropical Sonoran Desert, centered at the head of the Gulf of California (Brown 1982). The Chihuahuan desertscrub is dominated

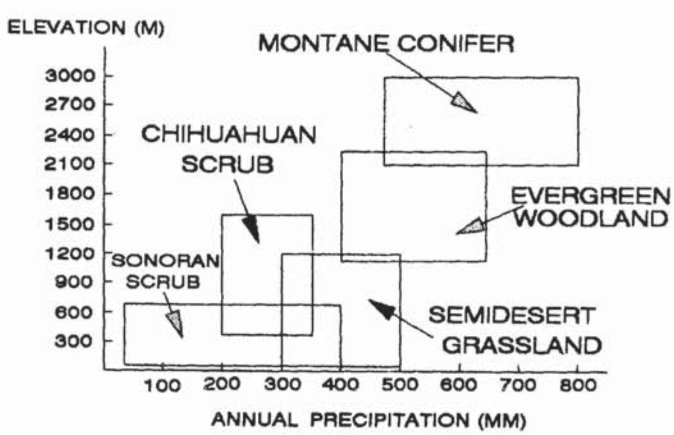

Figure 1.—Elevation and precipitation relationships of biotic communities in the Madrean Archipelago Region.

by cresosotebush, and over 80 percent of the type resides on limestone parent material. This biome maintains a recognizable homogeneity in its dominants and receives most of its scanty precipitation during summer months.

The unifying theme of the Sonoran Desert is that of an unreliable and uneven biseasonal rainfall pattern, separated by periods of spring and fall drought. This desertscrub type merges in southeastern Arizona with the semidesert grassland type, and occasionally with the Chihuahuan desertscrub. Its flora is clearly derived from subtropical elements and its affinities are to the south.

HYDROLOGY

Precipitation

The Madrean Archipelago receives from less than 100 mm of annual precipitation (on the average) in the lower desertscrub to over 800 mm on the higher mountain peaks (Sellers et al. 1985; Brown 1982) (fig. 1). One-half or more of the annual precipitation falls during the growing season from July to September (Osborn et al. 1987). These precipitation events are mainly high-intensity, short-duration convectional storms originating in the Gulf of Mexico. Winter precipitation is generally rain that comes during November through April, with occasional snow in the higher elevations. Moisture for winter precipitation normally comes as frontal storms from the Pacific Ocean.

The high-intensity precipitation events that frequently occur in this region often create overland flow from both vegetated and nonvegetated areas, and as a result, significantly increase erosion.

Plants growing in the Madrean Archipelago are engaged in a race against time. Green and Martin (1967) show that the effectiveness of precipitation in relation to plant growth in the semi-desert grassland-shrub community varies with season. The length of time that the soil remains wet after a rain is much longer in winter than in summer. Evaporation from a free water surface in Tucson is 8 times greater in June than December, and soil moisture after each rain is available only until it evaporates or is used in plant growth. Plants grow little in December and January, regardless of the availability of water, because ambient temperatures are low. Athough plants can grow rapidly in the summer, they only have a few days to use water made available by rain because of high evaporation losses.

Green and Martin (1967) pointed out that heavier rains will often produce visible growth on shrubs or perennial grasses, and germinate annual grass and forb seeds. A deep wetting of the soil in summer can produce significant amounts of perennial grass herbage, but it rarely produces substantial usable annual plant growth. Most southern Arizona soils require from 6 to 8 mm of precipitation to wet the surface 8 cm of soil. However, rains of 6 mm or even less a day or two apart, interspersed with heavier rains, can maintain usable soil moisture levels. The surface layers of many soils in the region hold about 38 mm of water per 30 cm of soil at field capacity, and 13 mm of water per 30 cm of soil at the point where herbaceous plants wilt. Therefore, about 25 mm of water per 30 cm of soil is required to support rapid plant growth.

Summer rains produced 90 percent of the perennial grass herbage on the Santa Rita Experimental Range (Culley 1943) and are responsible for major plant growth in New Mexico (Nelson 1934). Green and Martin (1967) showed that the amount and distribution of rainfall affects not only the amount of forage produced, but composition as well. Perennials account for only 20 percent of the grass herbage at the lower elevations, compared to 70 percent at the higher elevations where rainfall is greater. An additional 25 mm of summer rainfall can increase average perennial grass yields by about 140 kg/ha.

Temperature

Brown (1982) reported that nighttime freezing temperatures in the montane forest type usually begin by mid-September and do not end until the end of May. Freezing temperatures in the evergreen woodlands range from occasional in the south to an average of almost 150 days per year at the northern limits of its range. Freezes in the grassland savanna can be expected during any winter, but these freezes are not of long duration and temperatures rarely drop far below -4°C. Killing frosts are infrequent. Therefore, evaportranspiration loses can occur all year long at the lower elevations in the Archipelago.

Evaporation

Information on water losses from the soil, by both evaporation from the soil surface and transpiration from vegetation, has been used to calculate water balances. Buol (1964) calculated annual potential evapotranspiration (PET) values (by the Thornthwaite method) for Arizona from available climatic records. Calculated PET in the Madrean Archipelago ranges from 760 to 1,020 mm of water per year, and actual evapotranspiration ranges from 250 to 760 mm per year. In general, these values agree with measured annual ET values of 989 mm from an area supporting riparian grasses along the Gila River (Leppanen 1981), and 493, 389, and 335 mm for actual ET measured in a 150-day growing period from a forested area, clear cut area, and cienega, respectively, in the White Mountains (Thompson 1974). Estimates of evaporation from a free water surface in the Madrean Archipelago range from 1,525 to 1,780 mm (NOAA 1982).

Interception and Throughfall

Precipitation falling on a watershed is partitioned into water intercepted by leaves, twigs, or stems and returned to the atmosphere by evaporation; water channeled to the soil surface as stemflow, or drip from the foliage; water passing through the foliage to the soil surface as throughfall; and water falling directly on the soil surface in areas having sparse vegetation.

Throughfall in taller vegetation can be intercepted by low-growing vegetation, litter, or the soil surface. Crouse et al. (1966) indicated that the water storage capacity of grasses is proportional to the product of the average plant height and percent of ground cover. Interception losses in storms with total rainfall greater than the storage capacity of the plants varies from 0.2 to 9 mm. Corbett and Crouse (1968) found that the amount of water evaporated from surface litter is governed primarily by the moisture-holding capacity of the litter, and the evaporation potential during and following storms. Interception losses from small storms are high, while those from larger storms range between 2 and 5 percent. Approximately 20 percent of the gross precipitation intercepted in the coniferous woodland canopies is lost to evaporation (Skau 1964) and from 10 to 25 percent from the ponderosa pine canopies (Aldon 1959).

A study of rainfall distribution in the evergreen woodlands of southeastern Arizona showed that up to 70 percent of the late summer-early fall rains are intercepted directly under the canopies of Emory oak trees (Haworth 1992). Throughfall varied from 100 percent (all trees, large storms) to about 30 percent (large trees, small storms). Rainfall was distributed evenly under and around trees in storms generally larger then 25 mm.

Infiltration

Once precipitation reaches the land surface it can infiltrate into the soil, evaporate, or contribute to overland flow and eventually runoff. The rate that water enters the soil depends upon the nature of the precipitation, vegetation, topography, and soil properties. Important soil properties are texture and restricting subsurface layers.

Montane forests in the Madrean Archipelago grow on soils that are shallow to deep, gravelly and cobbly, moderately coarse-textured, and hilly to very steep (Hendricks et al. 1985). The soils are well-drained and formed in residuum weathered from granite, gneiss, schist, and other igneous rocks.

Soils in the evergreen woodlands are similar to those found in the San Rafael Valley and Canelo Hills areas (Lopes and Ffolliott 1992). Dominant soils in the San Rafael Valley are formed from old alluvia developed largely from mixed sedimentary and igneous parent materials (Hendricks et al. 1985). They are deep, moderately fine to very finely textured, gravely, and have moderate rates of infiltration. Soils in the Canelo Hills area are typically shallow, moderately fine to moderately course in texture, gravely and cobbly, and also have moderate infiltration rates. Soils typically supporting evergreen woodlands often have a layer that impedes the downward movement of water, further influencing the pathways of water flow through this ecosystem.

Beutner et al. (1940) studied infiltration in a wide range of Arizona desert soils. All of their infiltration curves for dry soils began with high infiltration rates, which declined rapidly for the first 10 minutes until a nearly constant infiltration rate was reached. Final infiltration rates varied from 7 to 56 mm/hr when rainfall was applied to dry soils, compared to from 5 to 32 mm/hr when applied to soils at field capacity.

Infiltration rates are influenced by grazing animals that remove plant material and compact the soil (Branson et al. 1981). As a result, runoff often increases as range condition deteriorates. Hendricks (1942) found that infiltration is improved if grazing management allowed for the accumulation of grass litter on semiarid rangelands.

In more arid climates, water-repellent soils found under various oak, chaparral, and coniferous woodland communities may affect infiltration (DeBano 1981).

Runoff

If water reaching the soil surface does not infiltrate or evaporate, it becomes runoff. Of the three major components of runoff—surface or overland flow, storm seepage or interflow, and groundwater flow—surface runoff is the most common component in arid environments. Surface runoff normally occurs only briefly during summer rainfall events when intensities exceed the infiltration capacity of the soil, or during periods of rapid snowmelt in the spring.

Studies of runoff relationships in arid and semiarid areas are complicated by infrequent runoff events and variable precipitation. Studies using comparable amounts of artificially applied rainfall on adjacent small areas show that differences in runoff can be attributed to variations in soils, plant type, and range condition (Branson and Owen 1970; Kincaid and Williams 1966; Schreiber and Kincaid 1967).

Much of the surface runoff originating on the mountain tops of the Madrean Archipelago flow into ephemeral stream channels in the lower evergreen woodlands, and finally into the semidesert grassland and desertscrub types. Therefore, it is important that these areas be protected from accelerated erosion and sedimentation which impact water quality and can eventually lead to a decrease in long-term site productivity (Lopes and Ffolliott 1992; Marsh 1968).

Osborn et al. (1980) reported that normally dry ephemeral stream channels in arid and semiarid regions can accommodate large volumes of runoff. Storm movement has little effect on major flood peaks from small watersheds. However, storm movement can affect flood peaks and volumes for smaller runoff events. If storms move too rapidly across a watershed, the reduced surface runoff can be entirely (or mostly) absorbed by the channels above the watershed outlet.

Surface runoff in the Madrean Archipelago is often linked directly to groundwater regimes (Davis, 1993b), as is illustrated by the upper San Pedro River Basin (Jackson et al. 1987). Both inhabitants of this river basin and government officials are concerned about groundwater depletion resulting from accelerated pumping. Water use throughout the upper portion of the basin, which reduces streamflow in the San Pedro River, is also a major concern. A University of Arizona study (1991) indicated that pumping from the regional aquifer in the Sierra Vista area is depleting stored groundwater reserves, and future pumping will only accentuate this trend. Although the depletion rate is small compared to the total volume of water in aquifer storage, these withdrawals directly affect surface flows, which are particularly important in stream reaches supporting riparian habitat vegetation (e.g., the BLM's San Pedro Riparian National Conservation Area).

Erosion and Sedimentation

Streamflow in the Madrean Archipelago is generated mainly from higher elevation forests, while the majority of the sediment originates in ecosystems at lower elevations (Branson et al. 1981). For example, Dortignac (1956) found that the Rio Puerco, which represents less than 20 percent of the Upper Rio Grande Basin, contributes nearly half of the sediment but produces less than 8 percent of the water yield from the area. Langbein and Schumm (1958) concluded that maximum sediment yields occur at about 300 mm of annual precipitation, and decrease on the dry side because there is a lack of runoff to transport sediment, and on the wet side because denser vegetation protects the soil and reduces sediment production. Sediment is frequently the major source of non-point pollution in streams (Branson et al. 1981).

Information on sediment yields in the Madrean Archipelago is generally lacking. However, some insight can be gained by data from similar vegetation types outside this biogeographic region. For example, in coniferous woodlands, a type that intermingles with the evergreen woodlands, Clary et al. (1974) reported annual sediment yields from volcanic soils of 2,000 to 4,500 kg/ha. Conversion treatments on these volcanic soils did not increase sedimentation. Sediment losses, however, from coniferous woodlands occupying other soil types (such as sedimentary soils) were greater.

Chaparral brushlands intermingle with evergreen woodlands on the flanks of isolated mountain ranges in southeastern Arizona. Sediment yields from chaparral watersheds with soils derived from granitic parent materials are often of the same magnitude as those observed in the coniferous woodlands. Sediment production, however, can be accelerated immediately after conversion treatments, especially when burning is involved (Hibbert et al. 1974; Morenno 1968).

Sediment yields at Walnut Gulch went from an average annual production of 3,740 to 290 kg/ha following vegetation conversion of brush to grass (Simanton, Osborn, and Renard 1977). Although runoff increased during the transition period, it decreased once grass became established—contributing to the reduction in erosion.

Sediment yields depend upon the magnitude of overland flow and stability of stream channels. Important climatic, geomorphic, and hydrologic parameters controlling sediment production and transport are: high intensity thunderstorms, which can produce large peak discharges per unit area; limited areal extent of rainfall, which can result in partial area runoff; transmission losses in normally dry stream channels, which can decrease downstream sediment transport capacities; steep channels, which can produce high flow velocities with increased potential for transporting sediment; and unconsolidated stream channel material and unprotected stream banks, which supply sediment (Lopes and Ffolliott 1992).

WATERSHED MANAGEMENT

Watershed management in the Madrean Archipelago region must consider the soil and water resource as related to forestry, livestock production, wildlife habitats, and recreational use within the context of sustaining the uniqueness of this biogeographic region. Conservation of the soil and water resource is important because of the fragile nature of the soils and limited amounts of available water in the region (Lopes and Ffolliott 1992). Therefore, watershed management practices should be carefully planned and implemented to ensure protection and (wherever possible) enhancement of the soil and water resource.

Soil and Water Conservation

Numerous attempts have been made to control erosion, particularly on rangelands, but failures have been frequent (Branson et al. 1981). Peterson and Hadley (1960) reviewed the effectiveness of a number of erosion abatement practices (including nearly 200 erosion control structures) on semiarid rangelands in the Upper Gila River Basin. They found vegetation was not benefitted appreciably by structures. In addition, excessive maintenance costs would likely limit widespread use of this practice.

Peterson and Branson (1962) evaluated the effectiveness of various land treatments undertaken by the Civilian Conservation Corps in the mid-1930s. Treatments included earth fill dams, earth dike spreaders, loose rock spreaders, hand placed rock spreaders, brush spreaders, "cement worm" spreaders, cable and wire spreaders, and rock rubble gully control structures. More than half of these structures breached within a few years after construction. However, vegetative cover was improved where earth dikes were not breached and water was distributed by the spreader system.

Lusby and Hadley (1967) studied the influence of low dams and barriers on sedimentation. They concluded that slope of deposition was largely dependent upon the particle-size distribution of transported sediment, and the rate steep-sided gullies filled was dependent upon availability of material approaching the size of the original channel bed material. Deposits behind low permeable barriers had steeper surface gradients than the original stream channels, and deposits behind low dams had lower gradients than the original channels.

The extreme variability in climate in the Madrean Archipelago region makes it difficult to isolate natural erosion and sedimentation rates from those induced by human activities. However, much of the severe erosion and sedimentation observed in the woodlands and semidesert grasslands in southeastern Arizona has been attributed to overgrazing by livestock, mainly during the last half of the 19th century.

Cox et al. (1984) estimated that cattle numbers in the desert southwest exceeded 500,000 between 1830 and 1840, and increased to a peak of about 1.5 million in the late 1880s. Large areas of sacaton and grama grass existed here prior to 1870, and beaver dams often restricted water flow. But, human disturbances between 1870 and 1901 (including the plowing of sacaton bottoms, channeling of rivers to provide irrigation water, overgrazing by livestock, and extermination of beaver by trappers) dramatically changed this landscape. Most of the water sources were dried up by 1893, and about 65 percent of the cattle had died because of these changes, which were amplified by a severe drought. Although the drought ended by 1895, the added effects of overgrazing, farming, drought, and subsequent flooding resulted in accelerated sheet and gully erosion throughout the region.

Restoration efforts in the San Simon Valley illustrate the benefits arising from the implementation of proper engineering and land management practices. Historically the area was a broad grassy valley that was bisected by an intermittent stream with little apparent erosion prior to the 1880s. The broad, flatter areas were covered by sacaton and tobosa grass with few trees. Willows grew in the wetter areas, and cottonwoods were found in San Simon Cienega, near the current Arizona-New Mexico state line. Little channel erosion was present, and the bottom was well vegetated.

From 1883 to 1916, head cutting of San Simon advanced 60 miles up the channel, and ranged from 3 to 10 m in depth and 12 to 245 m in width. Factors contributing to this rapid erosion included overgrazing by livestock, widespread drought, subsequent flooding, and construction of a drainage ditch, a wagon road, and a railroad. By 1919, the San Simon had been recognized (by the U.S. Government) as needing extensive restoration.

Numerous erosion control measures have been implemented on San Simon since 1934, including diversion dikes, water spreaders, detention dams, gully plugs, and rangeland seedings. After 50 years of observing the results of the various control measures, main channel structures were judged to be most effective. Side channel structures have been largely ineffective in regrading steep channel slopes, although these structures stopped further headcutting of the side channels, and reduced water velocities.

Watershed Improvement Practices

Watershed improvement practices can be grouped into three general categories: those which minimize adverse impacts to the soil and water resource; those designed to increase water yields; and rehabilitation practices used to improve watershed condition.

Minimizing Adverse Impacts

Fragile soils and limited water make it important to protect the Madrean Archipelago from further deterioration of the soil and water resource. Past degradation has been contributed to overgrazing by livestock, reduction in wildfires by man, and precipitation events at both extremes—high intensity rains, and droughts. Therefore, a positive plan of action is needed to protect this unique resource from further degradation. Management practices that minimize adverse impacts on the soil and water resource are similar to those used to prevent excessive rates of erosion (Lopes and Ffolliott 1992). Roads should not be constructed in or near stream channels. When roads are closed to public travel, roadways should be seeded with herbaceous plant species to protect against erosion. Logging operations should be restricted during periods of excessive rainfall, and grazing and recreational use should be monitored to minimize impacts on stream channels, riparian areas, and water quality. These practices are all essential components of an integrated watershed management program that accommodates multiple uses.

Increasing Water Yields

Vegetative management was advanced during the 1950s and 1960s to increase water yields. Experiments conducted throughout the world (and more specifically in Arizona) demonstrated that water yields could be increased (to varying magnitudes and duration) by changing the structure and composition of the vegetative cover on a watershed (Baker 1986; Bosch and Hewlett 1982; Clary et al. 1974; Davis, E. A. 1993a; Hibbert 1979; Hibbert et al. 1974; Rich and Thompson 1974). Additional water yields, when obtained, were attributed largely to decreases in transpiration.

An analyses by Hibbert (1979) showed that vegetative manipulations could increase water yields only on areas receiving more than 480 mm of annual precipitation. His reasoning was that precipitation below 480 mm is efficiently utilized by any remaining overstory vegetation and subsequent increases in herbaceous plant cover. This finding suggests it is unlikely that water yields can be increased in the Madrean Archipelago by vegetation manipulation. Vegetation manipulation thus does not appear to a viable watershed management option.

Watershed Rehabilitation

Management practices used to rehabilitate watersheds include: controlling gullies and mass wasting with properly constructed check dams (Heede 1970); establishment of protective tree, shrub, or herbaceous plant covers on degraded sites (Cox et al. 1984); and (when necessary) curtailment of wood harvesting, livestock grazing, and other exploitative practices (Lopes and Ffolliott 1992).

Artificial seeding of rangeland plants has been studied for nearly a century in the Madrean Archipelago. The results of these studies provide information necessary for rehabilitating severely degraded watershed. For example, Cox, et al. (1984) found several grass species that can be successfully established in the Chihuahuan and Sonoran deserts. Unfortunately, frequent drought and continual abuse by man has caused the deterioration of semidesert grasslands through accelerated erosion, brush invasion, and reduced forage production. However, even though revegetation is difficult and costly, it is possible.

CONCLUDING REMARKS

The ecosystems in the Madrean Archipelago represent a wide assemblage of hydrologic conditions within the context of an arid to semiarid environment. Many sensitive ecosystems are delicately balanced within an environment having limited water and a highly variable climate. This balance has frequently been overwhelmed by past land abuses, resulting in severe and widespread watershed degradation. Careful implementation of existing watershed and hydrologic information has successfully restored some highly degraded sites. However, widespread application of existing technology will depend on a more thorough understanding of the fundamental hydrologic processes operating in this unique environment.

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