Hydrology and Watershed Management in Semi-Arid Grasslands
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ABSTRACT

Ecosystems in the semi-arid southwestern United States and northern Mexico are sustained in a delicate balance under a limited water regime and a highly variable climate. This balance has frequently been overwhelmed by past land use and abuse, resulting in severe and widespread watershed degradation. This paper discusses existing hydrologic and watershed information for the semi-arid grassland vegetation type and provides suggestions for the restoration of severely degraded watershed areas.

INTRODUCTION

The climate of the southwestern United States and northern Mexico is mainly arid, with the isolated higher elevation mountain ranges being subjected to a more semi-arid climate (Baker et al. 1995). This biogeographic region, also known as the Madrean Archipelago, is especially sensitive to climatic fluctuations and human impacts. Therefore, a knowledge of the hydrologic processes regulating these water-limited ecosystems is essential to understand the soil-vegetation relationships that are responsible for sustaining landscape stability in this region (Ffolliott and Thorud 1975). The 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 hydrological studies have been reported for the semi-arid grassland type (Lopes and Ffolliott 1992). Probably the best known study is the long-term research effort at the Walnut Gulch Experimental Watersheds in southeastern Arizona (Renard 1978). The objectives of this paper are to characterizes the hydrology of the semi-arid grassland type by summarizing existing information obtained from within the vegetation type, and to supplement this information with data extrapolated from associated ecosystems in the region.

VEGETATION

Brown (1982) indicates that the semi-arid grasslands in the southwestern United States and northern Mexico were historically found at elevations of between 1,000 and 1,600 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 the root system of grasses is generally shallow, and of woody plants is generally deeper, removal of grasses by animal grazing can reduce

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water loss near the soil surface. As a result, more water becomes available for use by the deeper and more extensive root systems of the woody plants, and scrub or bush encroachment begins. If grasses are not allowed to recover and the likelihood of lightning or human-caused fires to increase, woody plants will continue to spread at the expense of the grass species (Brown 1982).

**CLIMATE AND HYDROLOGY**

**Precipitation**

The southwestern United States receives an average of less than 100 mm of annual precipitation in the lower desertscrub to over 800 mm on the higher mountain peaks (Sellers et al. 1985; Brown 1982, Ffolliott and Thorud 1975) (Figure 1). One-half or more of the annual precipitation falls during the growing season between July and September (Osborn et al. 1980). 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 occurring in the higher elevations. Winter precipitation normally comes as frontal storms from the Pacific Ocean.

Precipitation supplies moisture for plant maintenance and growth and in turn vigorous plant growth tends to reduce soil erosion. However, 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 semiarid grasslands are engaged in a race against time. Green and Martin (1967) show that the effectiveness of precipitation in relation to plants 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 eight times greater in June than December, and soil moisture after each rain is available only until it evaporates or is used by plants. Plants grow little in December and January, regardless of the availability of water, because ambient temperatures are low. Although plants can grow rapidly during 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 provide conditions for the germination of 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 annual plant growth. Most southern Arizona soils require from 6 to 8 mm of
precipitation to wet the surface 8 cm of soil (Green and Martin 1967). 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 wilting point of herbaceous plants (Green and Martin 1967). Therefore, about 25 mm of water per 30 cm of soil is available to support 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 elevation where rainfall is greater. An additional 25 mm of summer rainfall can increase average perennial grass yields by about 140 kg/ha.

Temperature

Freezing temperatures in the grassland savanna can be expected during any winter, but these freezes are not of a long duration and temperatures rarely drop far below -4°C (Brown 1982). Killing frosts are infrequent. Therefore, evapotranspiration losses can occur year-long in this region.

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 (1948) method) for Arizona from available climatic records. Calculated PET in the southwestern United States ranges from 760 to 1,020 mm of water per year, while actual evapotranspiration ranges from 250 to 760 mm per year. In general, these values are within the range of measured annual ET values of 989 mm from an area supporting riparian grasses along the Gila River (Leppanen 1981), and of 493, 389, and 335 mm for actual ET measured in a 150-day growing period from a forested area, a clear cut forest area, and a cienega, respectively, in the White Mountains (Thompson 1974). Estimates of evaporation from a free water surface in this region 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 streamflow, 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 (Brooks et al. 1991).

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 vary 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 normally much higher (i.e., up to 90 percent), 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 is lost from the ponderosa pine canopies (Aldon 1959).

A study of rainfall distribution in the evergreen woodlands of southeastern Arizona, plant communities that are largely evergreen or a mix of evergreen and deciduous species (Brown 1982), 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 (Brooks et al. 1991). Important soil properties are texture and restricting subsurface layers.

Desert grassland vegetation generally grows on alluvial soils (Hendricks et al. 1985). These are well-drained soils on valley bottoms and floodplains in the Santa Cruz, Sulphur Springs and San Simon Valleys. Native vegetation is mainly grasses at the higher elevations, while desert shrubs and cacti dominate the lower elevations. These soils support the best rangeland in the Southwest.

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 during the first 10 minutes until a nearly constant infiltration rate was reached. Infiltration rates varied from 7 to 56 mm/hr when rainfall was applied to dry soils compared to 5 to 32 mm/hr when applied to soils at field capacity.

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

Soil wettability is a phenomenon found on many rangelands and forested areas. In more arid climates, water repellency has been found particularly under various species of oak, chaparral, and coniferous woodland communities and often affects water infiltration into the soil (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 runoff 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 semi-arid areas are complicated by the variability in precipitation and by the infrequent nature of runoff events. Studies using comparable amounts of artificially applied rainfall on small, adjacent plots show that differences in runoff can occur, and that these differences are 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 in the mountain tops of southwestern United States and northern Mexico flow into ephemeral stream channels in the lower elevation woodlands, grassland,
and desertscrub types (Baker et al. 1995). Therefore, it is important that watershed management practices protect these areas from accelerated erosion and sedimentation because of their eventual negative impact on water quality and on long-term site productivity (Lopes and Ffolliott 1992; Marsh 1968).

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

Streamflow in southwestern United States is often linked directly to groundwater regimes (Davis, 1993), as is illustrated in the upper San Pedro River Basin (Jackson et al. 1987). Local citizens and government officials are concerned about groundwater depletion resulting from accelerated pumping in this river basin in both Mexico and the United States. A University of Arizona study (1991) indicated that pumping water from the regional aquifer in the Sierra Vista area is depleting stored groundwater reserves, and that future water pumping will only accentuate this trend. Although the depletion rate of groundwater is currently small compared to the total volume of water in aquifer storage, these withdrawals can directly affect surface flows in the San Pedro River, which are particularly important to the riparian vegetation and existing wildlife.

Erosion and Sedimentation

As mentioned, streamflow in southwestern United States is generated mainly from the higher elevation forested areas, while the majority of the sediment originates in lower elevation ecosystems (Branson et al. 1981). For example, Dortignac (1956) found that the Rio Puerco watershed in New Mexico, which represents less than 20 percent of the Upper Rio Grande Basin, contributes nearly half of the total sediment supply but produces less than 8 percent of the total water yield from the area. Langbein and Schumm (1958) concluded that maximum sediment yields, under natural vegetation regimes, occur at about 300 mm of annual precipitation. Sediment yields decrease on the dry side of this curve because there is a lack of runoff to transport sediment, and decrease on the wet side of this curve because the naturally denser vegetation produced by higher precipitation regimes has a greater ability to protect the soil from erosion. This relationship is complicated by removal of vegetation by such activities as grazing and logging (DeBano and Wood 1992). As a consequence of all these factors, sediment is frequently the major product of non-point source pollution in southwestern streams (Branson et al. 1981).

Sediment yields at Walnut Gulch decreased 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.

Clary et al. (1974) reported annual sediment yields from the woodland vegetation type on volcanic soils of 2,000 to 4,500 kg/ha. Vegetation conversion treatments on these volcanic soils did not increase sedimentation, however, sediment losses on other soil types (such as sedimentary soils) following conversion 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 greatly accelerated immediately after treating
chaparral vegetation, especially when burning is involved (Overby and Baker 1995; Hibbert et al. 1974; Morenno 1968).

Sediment yields depend upon the magnitude of overland flow and the 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 can produce a large supply of sediment (Lopes and Ffolliott 1992).

WATERSHED MANAGEMENT

Watershed management in the semi-arid grassland region must consider the soil and water resource as related to livestock production, wildlife habitats, and recreational use on the watershed and along the riparian areas of the stream channels. 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.

Riparian areas are closely related to their surrounding watershed area (LaFayette and DeBano 1990). These riparian plant communities stabilize stream channels, provide repositories for sediment, serve as nutrient sinks for surrounding watersheds, and improve quality of water leaving the watersheds. Riparian areas also provide temperature control through shading, reduce flood peaks, and serve as recharge points for renewing ground-water supplies. Riparian areas, however, must be managed within the context of the entire watershed because all tributary effects cumulate to influence riparian plant stability (DeBano and Schmidt 1989). A delicate balance exists between the riparian community and its surrounding watershed. DeBano and Schmidt (1989) describe this scenario, upland watersheds in satisfactory condition absorb storm energies, provide regulation of stormflows through the soil mantle, and bring stability to the entire basin. This condition results in sustained flows necessary for supporting a healthy riparian ecosystem.

In contrast, watersheds receiving past abuse have developed more extensive channel systems throughout the watershed, including ephemeral, gully networks. These gullies are formed in response to increased runoff resulting from the production of more rapid and concentrated surface runoff. These gully networks also produce higher peak flows and increases in erosion and resulting sedimentation. Past abuse and overuse of wildlands throughout the southwestern USA by grazing, trail and road construction, timber and fuelwood harvesting, mining, and other land uses have destroyed plant cover, increased soil erosion, and in the process have reduced riparian habitat (DeBano and Schmidt 1989). Riparian communities in the southwestern USA are particularly sensitive to overuse because they exist in a semi-arid climate and are subjected to wide variations in annual precipitation (Leopold 1946).

The sensitive hydrologic interrelationship that exist between watershed condition and the health of associated riparian areas has been illustrated by DeBano and Schmidt (1989) and the use of watershed treatments and properly designed, constructed, and maintained structures for enhancing riparian habitats have been presented (DeBano and Schmidt 1990; DeBano and Hansen 1989; DeBano and Heede 1987). Objectives of the use of these structures are to affect streamflow hydraulics and sedimentation, and therefore, create a more favorable environment for riparian
Watershed improvement practices can be grouped into two general categories, those which minimize adverse impacts to the soil and water resource and rehabilitation practices used to improve watershed condition.

**Minimizing adverse impacts**

Fragile soils and limited water make it important to protect the semi-arid grasslands 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 native herbaceous plant species to protect against erosion. 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.

Numerous attempts have been made to control erosion with various types of structures and management practices, 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 semi-arid rangelands in the Upper Gila River Basin. They found that vegetation was often not benefitted appreciably by structures and that excessive maintenance costs often make there use prohibitive or resulted in no maintenance being applied.

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 that 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.

As previously mentioned, properly constructed and maintained structures can have a positive influence on riparian vegetation (DeBano and Schmidt 1990; DeBano and Hansen 1989; DeBano and Heede 1987). Therefore, why have so many failures been observed? The key is in understanding where and how to use structures. One needs a good understanding of the hydrology of the area and the interrelationships with and between the geology, soils, and native vegetation. Monitoring of the short- and long-term functioning of the structures can also provide more specific
information about the functioning of various types of structures and their successful use in specific areas.

The extreme variability in climate in southwestern United States 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).

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, 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 (Baker et al. 1995). 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 day 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 had advanced 60 miles up the channel, and had 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 valley was 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 monitoring the results of the various control measures, installation of main channel structures were judged to be most effective. Side channel structures have been largely ineffective in reggrading steep channels slopes although these structures have stopped further headcutting of the side channels, and have reduced water velocities.

Watershed rehabilitation

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

Artificial seeding of rangeland plants has been studied for nearly a century in the Southwest. 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 semi-desert 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 Southwest represent a wide assemblage of hydrologic conditions within the context of a arid and semi-arid environment. These ecosystems sustain themselves in a delicate balance within an environment having limited water and a highly variable climate. This balance has frequently been overwhelmed by past land abuse, resulting in severe and widespread watershed degradation. Careful implementation of existing watershed and hydrologic information has been demonstrated by the successful restoration of some highly degraded sites. However, widespread application of existing technology is dependent upon a more thorough understanding of the fundamental hydrologic processes operating in the unique environment of the semi-arid grasslands.

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