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Shrub control and streamflow on rangelands: A process based viewpoint

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Abstract

In this paper, the linkage between streamflow and shrub cover on rangelands is examined, with a focus on the extensive Texas rangelands dominated by mesquite and juniper. The conclusions drawn are consistent with results from field studies and with our understanding of runoff processes from rangelands. Whether and how shrub control will affect streamflow depends on shrub characteristics, precipitation, soils, and geology. Precipitation is perhaps the most fundamental of these factors: there is little if any real potential for increasing streamflow where annual precipitation is below about 500 mm. For areas in which precipitation is sufficient, a crucial indicator that there is potential for increasing streamflow through shrub control is the presence of springs or groundwater flow to streams. These conditions often occur at locations where soils are shallow and underlain by fractured parent material. Under such conditions, reducing shrub cover may increase streamflows because water that would otherwise be lost through interception by the canopy instead moves into the soil and quickly travels beyond the root zone. If, on the other hand, there is no obvious subsurface connection between the hillslope and the stream channel and when runoff occurs it occurs as overland flow, shrub control will have little if any influence on streamflow. In assessing the potential for shrub control to increase streamflow, the runoff generation process should be explicitly identified. An improved understanding of the linkages between shrubs and streamflow on rangelands will require additional research on (1) hillslope hydrologic processes and how these are altered by shrub cover (2) groundwater-surface water interactions and (3) hydrologic scale relationships from the patch to the hillslope to the landscape levels.

Resumen

En este artículo se examina la conexión entre las corrientes y la cobertura de los pastizales con enfoque a los pastizales extensivos del Texas dominados por mezquite y junípero. Las conclusiones a las que se llegó son consistentes con los resultados de los estudios de campo y con nuestro entendimiento de los procesos de escurrimiento de los pastizales. Si el control de arbustos afecta, y la manera en que afectará las corrientes, depende de las características de los arbustos, la precipitación, los suelos y la geología. La precipitación es quizá el más fundamental de estos factores: Hay muy poco potencial para incrementar las corrientes en lugares donde la precipitación anual es menor de aproximadamente 500 mm. En áreas donde la precipitación es suficiente, un indicador crucial de que hay potencial para incrementar las corrientes mediante el control de arbustos es la presencia de de manantiales o flujo de agua subterránea a las corrientes. Estas condiciones a menudo ocurren en localidades donde los suelos son someros y están sobre material parental fracturado. Bajo tales condiciones, reduciendo la cobertura de arbustos se pueden incrementar las corrientes, porque el agua que sería perdida a través de intercepción por la copa en su lugar se mueve hacia el suelo y viaja rápidamente a zonas mas alla de la zona radical. Por el contrario, si no hay una conexión subsuperficial obvia entre la pendiente de la montaña y los canales de las corrientes y que cuando el escurrimiento ocurra sea sobre la superficie terrestre, el control de arbustos tendrá poco, si no es que ninguna, influencia en las corrientes. En la evaluación del potencial del control de arbustos para incrementar las corrientes, el proceso de generación del escurrimiento debe ser explícitamente identificado. Un mejor entendimiento de las conexiones entre los arbustos y las corrientes en los pastizales requerirá de investigación adicional sobre: (1) los procesos hidrológicos en las pendientes de las montañas y como estos son alterados por la cobertura de arbustos, (2) las interacciones del agua subterránea con el agua superficial y (3) las relaciones a escala hidrológica de nivel parche a nivel montaña y hasta nivel de paisaje.

Key Words: water yield, range hydrology, runoff, shrub control, ecohydrology, streamflow, semiarid

In this paper, I review the evidence for whether streamflow can be increased through modification of shrub cover on non-riparian rangelands. The focus is on Texas rangelands, because shrub control is viewed as a viable management option for alleviating many of the urgent water supply problems in the State. The recent drought—in conjunction with an increasing demand for water—is focusing attention on water shortages, and any management strategies that may combat these shortages elicit tremendous interest. The State is in the midst of a comprehensive water planning process designed to ensure that water is used in the most efficient manner possible and to explore options for increasing the amount of water available, one of which is shrub control.

The perception is widespread that streamflow from Texas watersheds can be significantly augmented, and therefore water supply substantially increased, through aggressive control of mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*) and juniper (*Juniperus ashei* Buckholtz, *Juniperus pinchotii* Sudw). For example, some have argued that in the San Angelo area of West

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Texas, shrub control could convert now intermittent streams into perennial ones and dramatically increase the rate at which water supply reservoirs are filled (UCRA 1998). A similar argument is made regarding the Edwards Aquifer recharge area farther south. In that region, many believe that the spreading juniper communities are contributing to reduced groundwater recharge and springflow (Wright 1996).

Some recent modeling studies support this notion (UCRA 1998, Bednarz et al. 2001, Wu et al. 2001). One of these—the 1998 UCRA study—was cited as the major justification for a multi-million-dollar, state-funded program to subsidize brush control on the North Concho watershed in West Texas. And the more recent studies will certainly be taken into account as the State considers whether to allocate additional funding for brush control aimed at increasing streamflow in other regions of the State.

However, results from many field studies do not fully concur with the predictions of these modeling studies, particularly for mesquite-dominated rangelands. It is true that in humid landscapes, changes in vegetation cover—particularly from woody to herbaceous—can radically alter the water cycle (Jackson et al. 2000). For example, in humid areas of Australia the widespread replacement of *Eucalyptus* and other deep-rooted woody species by pasture and crop species has raised the water table and led to serious salinization problems (Greenwood 1992, Walker et al. 1993). A similar relationship between timber harvesting and streamflow is well documented in many other forest types (Stednick 1996), as is the converse: declines in streamflow as a result of afforestation (Trimble et al. 1987, Calder 1990). But *in drylands, the correlation between woody cover and streamflow is weaker.* (Drylands are zones in which the ratio of precipitation to potential evapotranspiration is less than 0.65—conditions found in arid, semiarid, and even subhumid regions (Middleton and Thomas 1997). In some dryland ecosystems, such as chaparral woodlands in the southwestern United States, there is unmistakable evidence that streamflow increases when woody cover is reduced, but in other semiarid environments the linkage is tenuous at best (Blackburn 1983, Hibbert 1983). How streamflow in drylands responds to changing vegetation cover will depend on many factors, including precipitation amount and pattern, characteristics of the soil, geology, and vegetation. The amount of precipitation is especially important. In general, there is no real potential for increasing streamflow unless annual precipitation exceeds 450–500 mm (Hibbert 1983).

Shrub control as a water management tool does warrant serious consideration in Texas, because there are large tracts of rangeland that are in a relatively high rainfall belt, receiving 600–1,000 mm of precipitation a year. These areas, which were once grasslands, are now predominantly high-density shrublands in which water supply is insufficient to meet all of the competing demands. As a means of assessing the potential for success of shrub control in such regions, I have used the limited data available to (1) delineate as clearly as possible the important hydrologic processes, and (2) identify whether, how, and under what conditions shrub cover may modify those processes. The conclusions are germane not only to Texas rangelands but to other semiarid shrublands as well. Given that the programs being considered will involve large expenditures of limited public funds, investigation of the scientific basis for brush control programs is both timely and important.

Background

The widespread conversion of grasslands and savannas to shrublands during the last 50–100 years has provoked considerable debate concerning the cause(s) of these changes and given rise to a number of investigations. On the basis of several comprehensive reviews of the literature, we can conclude that the primary mechanism behind the increase in shrub cover has been a dramatic shift in patterns of herbivory and fire frequency during this time, although shifts in climate and CO_2 concentrations have also been cited as possible factors (Archer 1994, Van Auken 2000). In Texas, the increase in shrub cover has been particularly pronounced for mesquite (Archer et al. 1988, Archer 1994, 1995), ashe, and redberry juniper, especially during the last 50–80 years (Ansley et al. 1995, Fuhlendorf and Smeins 1997, Smeins et al. 1997, Phillips et al. 2000).

A logical question is, “Are increases in shrub cover modifying the hydrologic cycle, and if so, in what way and to what extent?” In Texas, the perception is widespread that changes in shrub cover have led to significant and even dramatic reductions in the amount of runoff or streamflow coming from rangeland watersheds. This issue was examined in detail during the 1980s, but at that time only a few studies had been conducted in Texas. Blackburn (1983) conducted a thorough review of the pre-1980 literature on the linkages between streamflow and shrub cover on rangelands and concluded that much of what had been learned from other semiarid rangelands was not relevant for Texas because of the differences in climate, soils, and vegetation. In the absence of substantiated data, the major argument for the effectiveness of brush control was based on the “Rocky Creek Story” (documented by Kelton [1975]), an anecdote that has taken on mythic proportions. Rocky Creek is reported to have dried up in the 1930s and to have remained dry until around 1960, when an extensive program of brush removal was carried out within the 74,000-acre watershed. Rocky Creek again began to flow, and has continued flowing since that time. Beginning in the 1990s, several key field studies have been conducted on Texas rangelands that provide more definitive information about the linkages between shrub cover and water yield.

Relationships between Shrub Cover and Hydrologic Processes

The hydrologic cycle and corresponding water budget are a simple yet powerful framework for examining how changes in vegetation cover influence water availability. The linkages between shrub cover and the various components of the water budget are discussed below.

Equation 1 presents a simplified interpretation of the water budget, partitioning precipitation (the major determinant of the potential for shrub removal to modify streamflow) into (1) evapotranspiration, (2) runoff, (3) groundwater, and (4) soil water:

$$P = ET + R + G + \Delta S, \qquad \textbf{(1)}$$

where

P = Precipitation
ET = Evapotranspiration
R = Runoff
G = Groundwater recharge
ΔS = Change in soil water storage

Evapotranspiration is a process that includes (1) evaporation from the soil, (2) transpiration from the plant, and (3) evaporation from plant or litter surfaces (commonly referred to as interception loss). As shrub cover increases, so too does the potential for transpiration and/or interception losses.

Soil water is the amount of water held in the soil, which over a period of several years or more is assumed to remain constant. Woody vegetation, by virtue of being more deeply rooted, generally extracts soil water from greater depths (provided deep water exists) than does herbaceous vegetation. Soil water that moves beyond the root zone is considered to be *groundwater recharge*, because eventually it will move to an underlying water body. In semiarid environments, flux rates of water moving to groundwater are very low, particularly if soils are deep and of low permeability and/or if aquifers are located at great depths (Scanlon 1994). If, on the other hand, the soils are shallow and the parent material highly permeable—as in the Edwards Plateau region of Texas—groundwater recharge may be very rapid (Maclay 1995).

Runoff is water that travels from the hillslope toward the stream channel, a portion of which (not captured by soils or evaporated en route) becomes streamflow. Runoff travels via a number of pathways, including (1) Horton overland flow, (2) saturation overland flow, (3) shallow subsurface flow, and (4) groundwater flow. Horton overland flow, which occurs when precipitation intensity exceeds soil infiltration capacity, is assumed to be the dominant mechanism of streamflow generation for most rangelands, particularly semiarid ones (Dunne 1978). Saturation overland flow occurs when soils become saturated. In more humid environments, soil saturation commonly results when a rising groundwater table brings water to the surface; this is the primary mechanism for variable-source-area runoff (Hornberger et al. 1998). Saturation overland flow may also result from the presence of a shallow impermeable horizon that prevents water from percolating down through the upper soil layer. This mechanism has been documented on some rangelands (Lopes and Ffolliott 1993) and likely occurs on many others. Shallow subsurface flow, sometimes referred to as interflow, is that portion of runoff that travels laterally through the soil, generally because of some impeding soil horizon. Shallow subsurface flow is more common in humid environments, but it can be important in semiarid environments and can be very rapid, especially when macropores are present in the soil (Wilcox et al. 1997, Newman et al. 1998).

Groundwater flow is generally the source for the base flow of a stream (prolonged flow, not attributable to a specific precipitation event), but probably is not an important pathway for storm flow (streamflow that can be directly attributed to a specific precipitation event) because the pace of groundwater travel is slow. A perennially flowing stream is an indication that groundwater flow is important, whereas one characterized by ephemeral or "flashy" flow suggests that either Horton overland flow or shallow subsurface runoff is the dominant source.

Woody vegetation may modify the *runoff* and *groundwater recharge* components of the water budget in myriad ways, direct and indirect. It may (1) alter soil infiltration characteristics, through root penetration and the addition of organic matter; (2) preserve soil moisture, through shading and mulching; (3) draw off soil moisture, through transpiration or interception; and (4) alter subsurface flow paths through root activity that leads to the formation of macropores (Blackburn 1975, Seyfried 1991, Breshears et al. 1998, Breshears and Barnes 1999, Ludwig et al. 1999, Jackson et al. 2000). But it is through modification of the *evapotranspiration* component that woody plants most influence streamflow. To understand the potential for augmentation of streamflow in these rangelands through removal of mesquite and juniper, therefore, it is important to examine not only how these woody plants modify runoff and groundwater recharge processes, but also how they might affect evapotranspiration.

Evapotranspiration

Environmental characteristics that favor evapotranspiration. When considering the process of evapotranspiration in semiarid and subhumid landscapes, it is important to remember that these environments are by definition *soil-water-deficient*, because the evaporative demand is much higher than precipitation. Figure 1, in which average monthly potential evapotranspiration (Larkin and Bomar 1983) is compared with average monthly precipitation for the San Angelo area of Texas, shows that in this area evaporative demand is about 4 times greater than precipitation. To a large extent, this disparity explains why runoff typically accounts for such a small portion of dryland water budgets—although there are exceptions, as will be discussed later. The consequence is that no matter what the vegetation cover, most of the water in a soil-water-deficient system will be lost through evapotranspiration. This fact alone would suggest that removal of shrub cover to minimize evapotranspiration in the hope of increasing streamflow has a limited chance for success, because most water stored in the soil will be either evaporated or used by whatever vegetation is present. A major exception would be a system in which conditions allow water to travel very rapidly to the stream channel, minimizing opportunities for evaporation.

An important component of total evapotranspiration is *interception.* Although the available data are somewhat limited, those we do have strongly indicate that interception is much higher from juniper than from mesquite rangelands. The greater interception capacity of juniper may be attributed

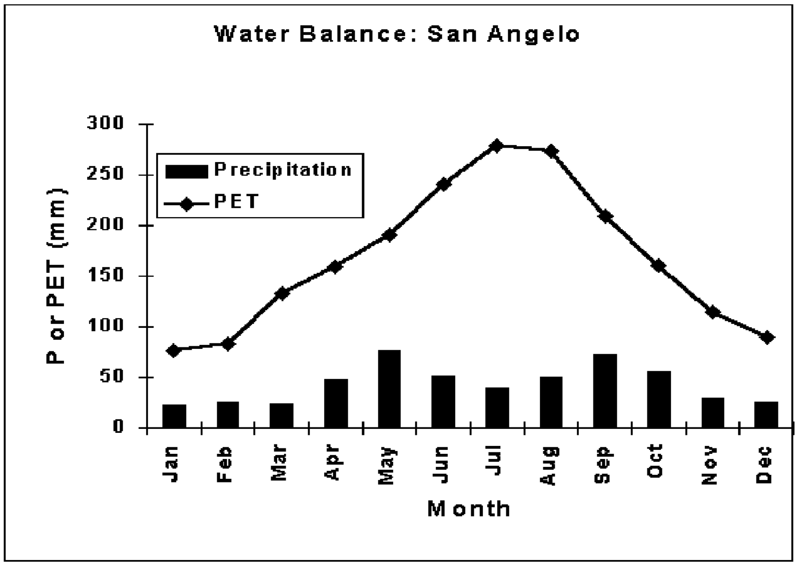

Fig. 1. Average monthly precipitation (1969–1998) and potential evapotranspiration (Larkin and Bomar, 1983) for the San Angelo area.

to the fact that juniper is an evergreen and has a high leaf-area density. Working in the Sonora region of Texas, Thurow and Hester (1997) found that as much as 70% of the precipitation is intercepted by the juniper canopy and litter layer. Findings from other juniper rangelands, although not showing such high percentages, also suggest that capture of water by juniper canopies can be substantial (Collings 1966, Young et al. 1984). Recent work indicates that the actual percentage of interception by juniper canopies is highly dependent on the amount and intensity of precipitation (Keith Owens, personal communication). In contrast, interception by mesquite canopies is reported to be between 15 and 30% (Desai 1992, Martinez-Meza and Whitford 1996). For both juniper and mesquite, a much smaller percentage of the precipitation is intercepted during large, high-intensity storms than during smaller, low-intensity storms.

Measuring evapotranspiration. Evapotranspiration at the plant community level can be measured directly using the Bowen Ratio approach, which is based on calculations of the ***energy budget*** (Evett 2000). Two studies, one of a mesquite rangeland (Dugas and Mayeux 1991) and the other of a juniper rangeland (Dugas et al. 1998), have used Bowen Ratio methodology to examine changes in community-level evapotranspiration rates following brush control.

For the first study, located in the Rolling Plains of Texas, mesquite was removed from one site while a second site was left untreated. Dugas and Mayeux concluded that “under circumstances of low grazing and low runoff potential, honey mesquite removal would provide little if any additional water for off-site uses in the short term.” Evapotranspiration was somewhat greater from the treated site under dry conditions, but under wet conditions there was no significant difference. The small difference between the 2 sites was attributed to the vigorous growth of herbaceous vegetation following mesquite eradication on the treated site, a phenomenon noted by many other researchers documenting the effects of mesquite control in other areas of Texas (Dahl et al. 1978, Jacoby et al. 1982, McDaniel et al. 1982, Bedunah and Sosebee 1984, Heitschmidt et al. 1986, Heitschmidt and Dowhower 1991).

The second Bowen-Ratio study was in a juniper-dominated rangeland. Dugas et al. (1998) found that brush control did result in significantly lower evapotranspiration rates at the community level, but only for 2 years. The authors estimate that groundwater recharge during those 2 years was 70–130 mm greater than if the site had not been treated. However, it should be noted that by the third year these effects were no longer measurable because of the regrowth of herbaceous and woody vegetation.

An alternative approach to assessing the evaporative demand of shrublands is an indirect one, the ***water budget*** approach, in which all the components of the water budget except evapotranspiration are measured directly; evapotranspiration is then assumed to be the difference between the sum of these components and the total water budget. For this approach to be applied successfully on rangelands, detailed tracking of soil water is essential. Four studies have relied on the water budget approach to assess how eradication of mesquite (3 studies) or juniper (1 study) affects hydrologic processes.

The 3 studies in mesquite rangelands did not all yield similar results. In the earliest study, Richardson et al. (1979) found that in the Blackland Prairie of Texas, where annual precipitation is around 870 mm, deep soil moisture (>2 m) increased by about 80 mm/year following eradication of mesquite. In contrast, Carlson et al. (1990) found that mesquite eradication in the Rolling Plains of Texas, where average annual precipitation is around 640 mm, had minimal if any influence on soil moisture—or, by inference, on community-level evapotranspiration—largely because of the flush of herbaceous growth following mesquite removal (Heitschmidt and Dowhower 1991). And the third study, by Weltz and Blackburn (1995) in south Texas (where average annual precipitation is around 700 mm), found little difference in soil moisture storage or evapotranspiration between adjacent mesquite- and grassland-dominated communities. The fact that soil moisture increased in the Blackland Prairie but not in the other 2 mesquite rangelands is probably explained by the formation, during dry periods at this site, of vertical soil cracks that allow water to move deep into the soil profile.

The fourth study was the only detailed analysis of water budgets on juniper rangeland in Texas. From the results, Thurow and Hester (1997) concluded that groundwater recharge could be greatly increased through removal of all or most of the juniper cover. Following complete removal of juniper at the site, they carried out long-term measurements of soil water, by means of weighing lysimeters; of canopy and litter interception; and of surface runoff. They calculate that groundwater recharge increased by around 75 mm/year, a difference they attribute largely to the much greater interception of water by juniper than by grasses.

In summary, most field studies of mesquite rangelands, whether based on the energy budget or the water budget approach, have found that eradication of mesquite does not lead to increased soil moisture and groundwater recharge, unless conditions are such that water can move rapidly through the herbaceous rooting zone. For juniper rangelands, however, both the studies based on the energy budget approach (Dugas et al. 1998) and those based on the water budget approach (Thurow and Hester 1997) indicate water savings resulting from juniper eradication.

Runoff

When evaluating the impact of shrubs on streamflow, it is important to explicitly consider which runoff pathway dominates in the area being studied. For example, if most of the water in rivers and creeks is generated from storm flow (either Horton overland flow or shallow subsurface flow) rather than base flow (groundwater flow), evapotranspiration by shrubs has little effect on streamflow because water is moving through the system too rapidly to be transpired. If, on the other hand, base flow is an important component of the runoff regime, then there exists the potential for evapotranspiration by vegetation to modify streamflow.

For flood producing precipitation events, shrub cover has relatively little effect on stream discharge. Large precipitation events (generally more than 100–120 mm) that result in flood conditions can overwhelm the capacity of the landscape to store water, regardless of the extent of tree or shrub cover (Leopold and Maddock 1954). This conclusion has been largely borne out by several studies (Ward 1978, Dunne 1988, Leopold 1997). In other words, the large and relatively infrequent flood events that fill many of the rangeland reservoirs would contribute essentially the same quantities of water whether shrub cover was present or absent. (This is not to say that rangeland vegetation is unimportant during these events; but that its major role is protection of the soil resource not modulation of flood flow.)

Horton overland flow. Factors that contribute to the generation of this type of flow are high-intensity precipitation and soils having low infiltration capacity, both commonly found in semiarid regions. Runoff processes in mesquite and juniper rangelands have been explicitly examined only rarely; nevertheless, we can be confident that Horton overland flow is an important, if not the dominant mechanism of runoff generation for the majority of these regions, on the basis of field evidence—including the presence of debris dams, signs of channel flow, and the absence of any obvious pathway for rapid subsurface flow. My personal observations of runoff during flash flooding also confirm this assertion.

Differences in overland flow between grass-dominated and shrub-dominated plots or small watersheds have been documented for several mesquite and juniper rangelands (Wright et al. 1976, Richardson et al. 1979, Carlson et al. 1990, Thurow and Hester 1997, Dugas et al. 1998). Interestingly, Horton overland flow is often reduced following shrub control because (1) herbaceous vegetation often grows vigorously after brush is removed, and the new growth enhances the infiltration capacity of surface soils; and (2) the increased surface roughness resulting from the scattered woody debris (and perhaps partly from herbaceous growth) impedes overland flow. Both Dugas et al. (1998) and Richardson et al. (1979) report dramatic reductions in Horton overland flow following juniper eradication, whereas a long-term study on small watersheds in Sonora showed that removal of juniper had little or no effect on surface runoff (Thurow, personal communication). For mesquite rangelands, Carlson et al. (1990) found that Horton overland flow was lower following mesquite eradication.

In contrast, Wright et al. (1976) found that Horton overland flow was significantly greater for 2–3 years following removal of juniper by burning, particularly on steep slopes; presumably it took this much time for the vegetation to completely recover (in addition, there would be less debris to impede flow following a burn than following mechanical treatment). In another study, in the Blackland Prairie of Texas, Richardson et al. (1979) observed a 10% increase in Horton overland flow after eradication of mesquite, which they attribute to higher soil moisture in the treated area.

For regions characterized by Horton overland flow, then, what we need to be examining is how vegetation and land use are modifying *surface conditions*, which are the major determinant of runoff amounts. Depending on those conditions, shrub control could result in either a decrease or an increase in Horton overland flow. Much will depend on the method of control and the follow-up management practices: if surface cover (live or dead vegetation) is encouraged and enhanced, overland flow should be reduced; if surface cover is diminished and the amount of bare ground increases, overland flow may increase. Blackburn (1983), in his review of the Texas literature, concludes that mesquite control either decreases runoff (by increasing infiltration) or has no effect (Bedunah 1982, Brock et al. 1982, Knight et al. 1983, Franklin 1987). It is probable that many shrub-dominated rangelands, especially former grasslands and prairies that are now in a degraded condition, are experiencing greater streamflow than previously because of overall lower soil infiltration capacities. In such degraded environments, we would expect higher peak flows and "flashier," less sustained runoff.

Shallow subsurface flow. Shallow subsurface flow on rangelands has received little attention, but it obviously occurs in some areas where soils are shallow and underlain by highly permeable parent material—like the Edwards Plateau. It also makes up a small portion of streamflow in the Blackland Prairie of Texas.[1] In the Edwards Plateau region, I have observed absolutely clear water flowing in stream channels in the wake of prolonged but low-intensity rains, while at the same time there was no evidence of Horton overland flow on the hillslopes. Obviously, water was traveling a subsurface route—an occurrence consistent with the presence of shallow soils underlain by permeable or fractured parent material, which allows water to travel rapidly through the subsurface to the stream channel or a groundwater body. Many of the areas occupied by juniper exhibit such characteristics. Where shallow subsurface flow is rapid, plant evapotranspiration rates would not directly influence runoff amounts. However, interception of water by the plant canopy could affect those amounts, especially in the case of juniper (Skau 1964, Young et al. 1984, Thurow and Hester 1997).

Groundwater flow. Streamflow from rangelands is by nature flashy, but for some areas—particularly the more humid ones—base flow does occur and can be important. The presence of base flow or spring flow is an important indicator of the potential for increasing streamflow by manipulating shrub cover. Base flow is prolonged and indicates relatively slow movement of the subsurface water, which means there is the potential for augmenting flow via shrub removal.

Groundwater/surface water interactions in rangelands have been little investigated, partly because of the impression that groundwater flow is not an important mechanism for runoff. Hence, there is much that we do not understand and about which we can only speculate. For example, base flow in many cases is probably provided by alluvial aquifers—but by what mechanism(s) are these aquifers recharged, and at what rates? Does recharge occur slowly via the hillslope, or does it occur quite rapidly, via the stream channel or other collection point, during a runoff event?

In many rangeland areas the soils are deep (>1 m), and there is no obvious subsurface connection between them and the stream channel or groundwater aquifer. Under such conditions, little if any water moves beyond the root zone. The presence of a calcic, or especially a petrocalcic, horizon is a convincing indicator that the downward flux of water is very small. In contrast, in landscapes in which soils are shallow and the parent material is permeable or fractured, such as the Edwards Plateau, the subsurface connections to groundwater aquifers often allow for rapid recharge. Spring flow is common in such regions, as are perennial or intermittent streams. There are numerous anecdotal reports of spring flow appearing or increasing after shrub control, and such evidences have been documented for juniper rangelands on the Edwards Plateau (Wright 1996) and for piñon-juniper watersheds in Utah (McCarthy et al. 1999). That said, it is important to point out that although increased spring flow is vitally important on the local or "on site" level, it should not be looked upon as a way of increasing water supply at larger scales.

In summary, the mechanism or pathway by which water travels from the hillslope to the stream channel to a large extent dictates the degree to which shrubs may modify streamflow. Modification of the evapotranspiration regime will influence streamflow only if significant amounts of that streamflow come from subsurface water sources. Subsurface runoff has been little studied in rangelands, even though it is likely to be important—especially in the higher precipitation zones. Overland flow is probably the dominant runoff process for most rangelands, but it too has been inadequately examined or quantified. Where overland flow is the dominant runoff mechanism, modifications of shrub cover will probably have little influence on runoff. In fact, the few rangeland stud-

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[1] Clarence Richardson, personal communication.

ies that have documented overland flow following removal of mesquite or juniper indicate that if surface disturbance is minimal, herbaceous cover rapidly replaces the shrubs and runoff can actually be lower after shrub removal.

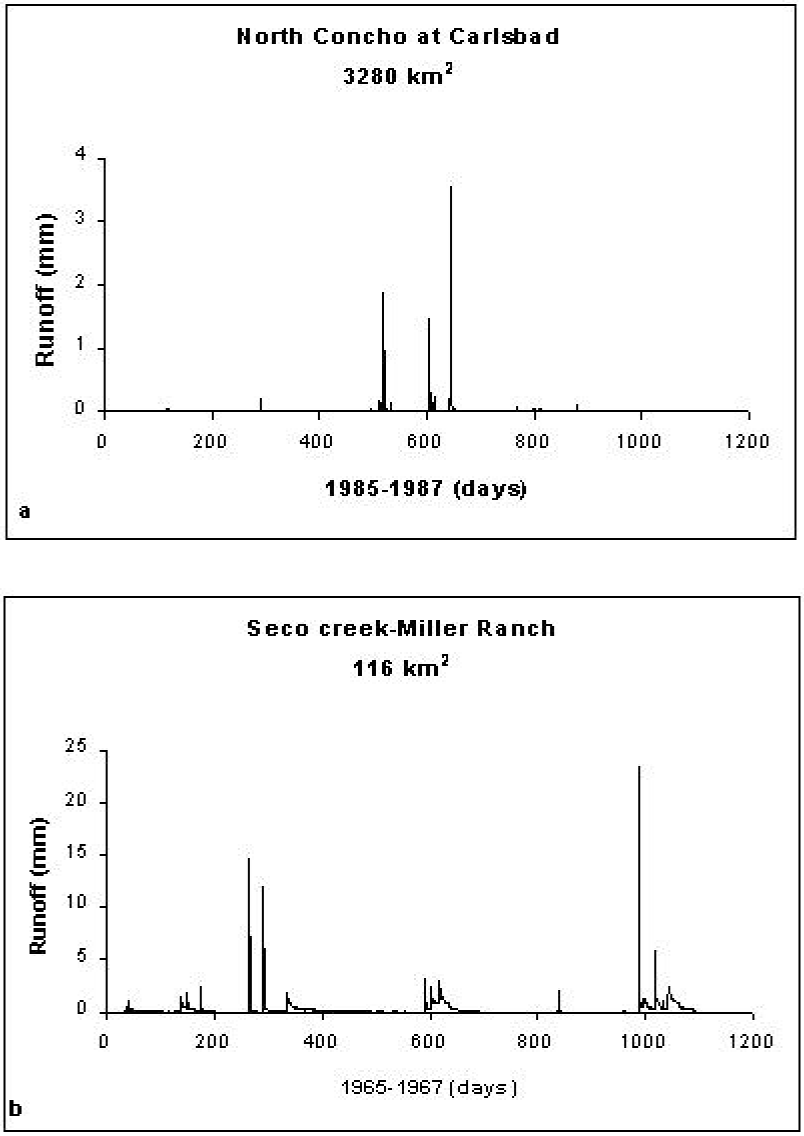

Fig. 2. Daily runoff for a 3-year period for the North Concho and the Seco River watersheds. Runoff data provided by the United States Geological Survey.

Examples from Two Texas Watersheds

Additional insights into runoff processes—and thus into the potential for modification of streamflow through manipulation of vegetation—may be gained via analysis of streamflow hydrographs. Below we discuss such analyses from 2 Texas watersheds: the North Concho in West Texas, near San Angelo, and the Seco Creek watershed, on the Edwards Plateau in central Texas.

The North Concho (lat. 31° 35' 33", long. 100° 38' 12") is a comparatively large watershed (3,280 km^2). Average precipitation is around 500 mm/year, whereas average long-term runoff is only about 5 mm/year (i.e., only about 1% of the water budget). From the almost 80-year period of records (USGS historical streamflow data) for the North Concho, it is apparent that runoff in this area is “flashy” (Fig. 2a shows runoff for a recent 3-year period). Many of the soils, being high in clay content, have a low infiltration capacity when wet. These soils are moderately deep and often underlain by a caliche layer with no obvious subsurface flow pathways. Channels that normally transport little or no water will periodically transport very high flows or even floodwater (Fig. 2a). Storm-flow runoff (most likely generated as Horton overland flow) makes up a large percentage of the total runoff. These large flood events are important from a water-supply standpoint, because they are the ones that fill downstream reservoirs.

On the Seco Creek Watershed (lat. 29° 34' 23", long. 99° 24' 10"), runoff is also “flashy” but is sustained for considerably longer periods than in the North Concho region. Here, it makes up almost 25% of the total water budget (Fig. 2b). It is likely that runoff from the Seco Creek watershed is generated by multiple processes. Storm flow is rapid and must be accounted for by either Horton overland flow or shallow subsurface flow, both of which have been observed in the region; and groundwater flow is significant. Runoff averaging 25% of the water budget and reaching more than 50% in some years (e.g., 1992) (Brown et al. 1998) is astoundingly high for a semiarid watershed. This unusual situation is explained by the low storage capacity of the soils and the high permeability of the underlying parent material. Runoff from a comparable rangeland watershed having different soil properties and parent materials would be much lower.

The strikingly different patterns of runoff from these 2 watersheds highlight the importance of considering specific site conditions when attempting to estimate the potential influence of woody vegetation on streamflow. Although runoff from both watersheds is dominated by flood events, base flow from groundwater is an important component of the water budget in Seco Creek. In contrast, at North Concho base flow is insignificant.

We can speculate, on the basis of this evidence, that on rangelands similar to the Seco Creek watershed a reduction of shrub cover has the potential for increasing streamflow and/or groundwater recharge. However, on rangelands similar to the North Concho, where runoff is primarily Horton overland flow, reduction of shrub cover would likely have little if any influence on streamflow.

Summary and Conclusions

Mesquite Rangelands

For most mesquite-dominated uplands (non-riparian), shrub control is unlikely to affect streamflow significantly, for 4 reasons: (1) evaporative demand is high, and the herbaceous vegetation that typically grows vigorously following eradication of the shrubs uses most of the available soil water; (2) soils on these sites are typically deep, effectively isolating the groundwater zone from the surface; (3) runoff is generated primarily as Horton overland flow; and (4) runoff is very flashy in nature: most of it is generated by flood-producing precipitation events, in amounts so overwhelming as to render insignificant the effects of other factors, such as interception by vegetation and even soil moisture storage.

Juniper Rangelands

The available field research data suggest that there is some potential for increasing streamflow from juniper rangelands. Two studies have indicated that groundwater recharge will increase following juniper removal (Thurow and Hester 1997, Dugas et al. 1998), and 1 study shows increased spring flow (Wright 1996). **As yet, there have been no documented increases in streamflow as a result of juniper control,** but the greater potential of these rangelands for increased streamflows or groundwater recharge is based on two factors: (1) juniper canopies have a high capacity for interception of moisture; and (2) juniper are often found in regions where soils are shallow and parent materials are permeable, features conducive to subsurface flow. A recent modeling study also concluded that increased water yields (groundwater recharge and/or streamflow) would result from a reduction in juniper cover (Wu et al. 2000).

In those regions where juniper are found on deep soils and subsurface flow does not occur, eradication is not likely to increase streamflow, for the same reasons noted earlier for deep-soil mesquite sites. But even in the shallow-soil regions, such increases will occur mainly during wet years and at relatively small scales; during dry years, and especially during droughts, it is doubtful that removal of shrub cover will affect streamflow. Further, when extra water is generated, storage of that water becomes an issue. To be available for water supply, any extra water would have to be stored either in a reservoir or as groundwater.

Criteria for Successful Brush Control/Streamflow Augmentation

For upland zones, the following factors should be considered:

1. *Average amount of precipitation.* As the amount of precipitation increases, the difference between the incident precipitation and the amount of potential evapotranspiration diminishes (i.e., the soil water deficit becomes smaller). Hibbert (1983) has proposed as a rule of thumb that no increase in streamflow should be expected where annual precipitation is lower than 450 mm/year. Although Hibbert's recommendation was not based on work in Texas, it has been commonly applied to Texas conditions (Bednarz et al. 2001).
2. *Amount of shrub cover.* All else being equal, the clearing of a high-density stand of shrubs will have a greater effect on streamflow than will clearing of a lower-density stand.
3. *Runoff and subsurface flow characteristics.* If runoff occurs primarily as Horton overland flow with occasional flood events, and base flow/groundwater recharge is insignificant, streamflow will be little influenced by woody plant cover. This is probably the case for most Texas rangelands—although there are exceptions, such as the Edwards Plateau region.
4. *Interception characteristics.* In juniper rangelands, because the canopy is evergreen and very dense, and litter production is high, water losses through interception are very high. For mesquite rangelands, interception loss via the canopy is probably comparable to interception loss in grasslands. For this reason, removal of juniper is likely to be more effective than removal of mesquite.

Future Research

Runoff processes at the hillslope scale. For any given rangeland watershed, the dominant mechanism by which runoff is generated greatly influences that landscape's streamflow potential, erosion potential, and response to land management strategies. Relatively few studies on rangelands, however, have examined runoff processes in an explicit and detailed manner. Process-based, hillslope hydrology studies that couple detailed measurements of individual runoff events with long-term monitoring are required to gain a better understanding of runoff pathways on rangelands, especially at the hillslope and small catchment level. In New Mexico, we have attempted to implement studies of this type (Wilcox 1994, Wilcox et al. 1996a, 1996b, Wilcox et al. 1997, Newman et al. 1998, Reid et al. 1999).

Influence of shrub cover on runoff processes. It is commonly assumed that accelerated erosion and increased overland flow accompany thicketization, particularly in the case of juniper watershed areas. It has also been argued that increases in shrub cover reduce base flows. But actual changes in streamflow following changes in shrub cover have yet to be documented; inferences concerning this issue have been made mostly on the basis of measured changes in evapotranspiration or soil water. If such changes are occurring, we should be able to verify them through comparison with the historical record. For example, trend analysis of long-term streamflow should give some indication of whether runoff has decreased as shrub cover has increased.

Groundwater-surface water interactions. Related to the issues of runoff and vegetation cover is the question of how ground and surface waters interact within rangeland watersheds—a question especially crucial for semiarid landscapes. We cannot modify one without modifying the other (Jackson et al. 2000). We do not fully understand how alluvial aquifers are recharged (from the stream channel or from the hillslope?), nor their role in runoff generation.

Landscape-scale processes. Our understanding of vegetation and water interactions on a landscape scale is limited. For example, where streamflow may be augmented through shrub control, we do not know at what scales we would see an effect. In this paper, I have suggested that any influence of shrub cover on streamflow is likely to be at a small scale and may not manifest itself at larger scales. But these scale relationships have yet to be documented.

Finally, apart from any potential effects on streamflow, there are other reasons—and perhaps more compelling ones—to practice shrub control as a means of restoration of both mesquite and juniper rangelands in Texas. One reason—especially with regard to juniper rangelands—is to prevent thicketization, in the wake of which these rangelands quickly degenerate into areas of extremely low productivity, low plant and animal biodiversity, and generally poor wildlife habitat, posing difficult management challenges. It has been suggested, although not yet demonstrated, that under these degraded conditions overland flow is greater, erosion increases, and water quality declines.

In other words, brush control can have positive effects, but for most Texas rangelands increased streamflow is not necessarily one of them. The high soil-water deficits, high rates of evapotranspiration, weak hillslope-to-stream channel subsurface connections, and predominance of overland runoff of a "flashy" nature all limit the possibilities for modifying streamflow. The use of brush control in the hope of increasing streamflow should be targeted to those areas in which it is most likely to work.

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