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DO WOODY PLANTS AFFECT STREAMFLOW ON SEMIARID KARST RANGELANDS?

BRADFORD P. WILCOX,[1,4] M. KEITH OWENS,[2] ROBERT W. KNIGHT,[1] AND ROBERT K. LYONS[3]

[1]*Department of Rangeland Ecology and Management, Texas A&M University, College Station, Texas 77843 USA*
[2]*Texas Agricultural Experiment Station, Uvalde, Texas 78801 USA*
[3]*Texas Cooperative Extension, Uvalde, Texas 78801 USA*

Abstract. There is considerable public and political pressure to reduce woody plant cover on rangelands as a means of increasing water yield, despite the lack of studies documenting that such a strategy is effective. In the Texas Hill Country, runoff from the Edwards Plateau recharges the highly productive and regionally vital Edwards Aquifer. The dominant woody plant on the Plateau is Ashe juniper (*Juniperus ashei* Buchholz). To understand how woody plant cover may affect the amount and timing of runoff in this region, we monitored streamflow from nine small (3- to 6-ha) watersheds over a 13-year period. After the first two years (initial observations), 100% of the shrub cover was removed from three of the watersheds and ~70% from another three. Following these treatments we continued to monitor runoff for four years, suspended monitoring for four and a half years, and then resumed monitoring for an additional three years. Runoff from these nine first-order watersheds generally accounted for <5% of the total precipitation and occurred entirely as stormflow (there was no baseflow before or after treatment). Some runoff was generated as subsurface flow, as indicated by hydrographs showing prolonged runoff (typically lasting hours longer than the rainfall). We evaluated the influence of woody plant cover on streamflow by comparing streamflow during the four-year treatment period with that during the posttreatment period (when considerable recovery of woody plants had taken place). Our findings indicate that changes in woody plant cover had little influence on the amount, timing, or magnitude of streamflow from these watersheds. On the basis of this work and other observations in the region, we hypothesize that, for small watersheds, changes in shrub cover will have little or no effect on streamflow except where springs are present.

Key words: ecohydrology; Edwards Plateau, Texas (USA); juniper; range hydrology; runoff; semiarid; streamflow.

INTRODUCTION

In semiarid and arid ecosystems, water—already limited—is coming under increased pressure as human populations grow (Jackson et al. 2001). For this reason, understanding connections between water yield (streamflow, groundwater recharge) and woody plants in drylands is an important and challenging issue. In many such regions, woody plant cover has increased dramatically in the last 100 years (Archer 1994, Van Auken 2000, Ansley et al. 2001).

In humid landscapes, increased woody (forest) cover causes total evapotranspiration to rise and thus reduces recharge (Bosch and Hewlett 1982, Trimble et al. 1987); but this relationship is not universally applicable for drylands (Wilcox 2002, Huxman et al. 2005). In some drylands, runoff is more affected by changes in woody plant cover than in others. In riparian landscapes, for example, if woody plants directly access groundwater in stream corridors, the influence on streamflow can be dramatic (Scott et al. 2000), especially when certain types of woody plants are present. Saltcedar (*Tamarix ramosissima*), an invasive shrub now common in many waterways of the southwestern United States, provides a striking example of extravagant water use by riparian vegetation (Sala et al. 1996, Zavaleta 2000). The connection between shrub cover and streamflow and/or recharge is also well established for upland drylands in mediterranean climates; for areas in which winter precipitation is dominant, such as chaparral shrublands in California (Ffolliott and Thorud 1974, Hibbert 1983); and for Eucalyptus scrub in southern Australia (Hatton et al. 1993, Pierce et al. 1993, Walker et al. 1993). For many other semiarid woodlands, however, the hydrologic connection between surface and subsurface is quite small (groundwater recharge is a very small percentage of the overall water budget), and in these regions it is unlikely that changes in woody plant cover have any appreciable effect on streamflow (Wilcox 2002, 2005).

Using shrub control as a means of augmenting water supply in the Edwards Plateau region of central Texas has attracted a great deal of interest. In fact, the Texas

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[4] E-mail: bwilcox@tamu.edu

Water Development Board has committed U.S. $4 million for control of shrubs and trees in the Pedernales basin; assessment studies predict that shrub control on 83 000 ha of a 330 000-ha watershed will lead to very substantial increases in streamflow, some 391×10^6 m^3 over a 10-year period (TSSWCB 2004).

The Edwards Plateau is underlain by highly productive karst aquifers that support a number of spring-fed and perennially flowing rivers, such as the Guadalupe, the Pedernales, the Frio, and the Nueces. Because of rapid growth in recent years, the region is facing increasing water demands from municipalities, agriculture, and industry (in addition to the need to maintain flow in streams). If water yields (streamflow and groundwater recharge) could be augmented by managing woody plant cover, the economic and ecological effects could be substantial.

Woody plant cover on the Plateau, consisting predominantly of Ashe juniper (*Juniperus ashei* Buchholz), has increased dramatically in the last century (Smeins and Fuhlendorf 1997). This increased cover is commonly believed to have contributed to lower streamflow and groundwater recharge, although such cause-and-effect has yet to be documented and many questions remain. For example, is the subsurface water being accessed by woody plants to a significant degree? Does canopy interception play a role? What are the runoff processes on the Plateau, and are they modified by woody plants?

Some research has suggested that the cause-and-effect relationship does exist. Using a Bowen ratio methodology, Dugas et al. (1998) found that evapotranspiration was lower after removal of juniper (but only for a two-year period). Further, Jackson and collaborators (Jackson et al. 1999, 2000) documented the accessing of free water in caves by juniper roots at a depth of >7 m. Finally, the numerous anecdotal reports of enhanced springflow following removal of woody plants should not be discounted. Several landscape-level modeling studies have also indicated that streamflow will be greatly increased if shrub control is implemented (Bednarz et al. 2001, Wu et al. 2001).

In this study, we examine the response of streamflow to vegetation change on small, first-order watersheds in the southwestern Edwards Plateau region (sometimes referred to as the Texas Hill Country). For all of these watersheds, streamflow is intermittent and occurs in response to individual precipitation events. The watersheds were monitored over a 13-year period, with the objectives of (1) better understanding the dynamics of streamflow (timing, magnitude, flow processes) and (2) assessing whether any changes in streamflow occurred as a result of removal of woody plants.

STUDY AREA AND METHODS

The study area is located on the Annandale Ranch, which lies within the topographically rugged Balcones Escarpment in the southwestern portion of the Edwards Plateau, and is about 50 km north of Uvalde, Texas (Fig. 1). It consists of nine first-order watersheds within the Edwards Aquifer recharge zone (Clark 2003), where the limestone composing the Edwards Aquifer intersects the surface. This highly fractured zone is thought to be the principal region of recharge of the Edwards Aquifer, receiving water from streams that traverse it from the north as well as directly from precipitation (Maclay 1995). Some recharge may also take place in areas outside of stream channels, but this is essentially unknown. Regionally, the western portion of the Edwards Plateau area (Uvalde County) is a very important source of recharge. Clark (2003) estimates that water entering this zone accounts for 45% of the total recharge of the entire aquifer. Such regional differences highlight the importance of understanding interactions between water and vegetation.

The average annual precipitation in this area between 1971 and the present has been ~710 mm (Fig. 2), ~70% of which occurs between May and October (Prade Ranch Raingage, National Weather Service). Average annual pan evaporation (an index of potential evapotranspiration) is ~1800 mm (Larkin and Bomar 1983). Soils, where they exist, are very shallow (<30 cm) and interspersed with exposed limestone ledges. The soil texture is clay loam and generally highly permeable (Stevens and Richmond 1976). The permeability of the underlying limestone is not known. Stone cover varies from 25% to as high as 90%. Vegetation in the area is characterized by a dense overstory of woody plants, mostly Ashe juniper and live oak (*Quercus virginiana* Mill.). Subdominant woody plants include Texas mountain laurel (*Sophora secundiflora* (Ort.) DC), netleaf elbowbush (*Forestiera reticulata* Torr.), and guajillo (*Acacia berlandieri* Benth.).

In the fall of 1987, the nine first-order watersheds, which range in size from 3 to 6 ha, were instrumented with 0.9-m H-flumes and FW-1 stage recorders (Belfort Instrument, Baltimore, Maryland, USA) for monitoring streamflow. In addition, precipitation collectors were installed at five locations within the study area. Before any manipulation of vegetation was done, woody vegetation cover was characterized by sampling within six randomly located 30-m transects on each watershed. The line intercept technique (Mueller-Dombois and Ellenberg 1974) was used to determine woody cover by species. Herbaceous vegetation was too sparse for cover or biomass to be accurately estimated.

In June of 1989, live woody vegetation was completely eradicated on three of the nine watersheds (watersheds 2, 3, and 9) and partially eradicated (70% removed, with some blocks of woody cover left intact) on three other watersheds (watersheds 1, 5, and 7). Watersheds 4, 6, and 8 were not altered. A herbicide (picloram) was applied directly to the soil surface, in a grid pattern, in all areas except those adjacent to stream channels; but it was largely ineffective because

FIG. 1. The location of the study area is indicated by the star above Uvalde, Texas. The inset is a Digital Orthophoto Quadrangle (DOQ) image (a composite of aerial photos that have been geo-referenced) from the Texas Natural Resources Information System web site ⟨http://www.tnris.state.tx.us/⟩. The aerial photos were taken in 1995 and 1996, 4–5 years after the woody plant removal treatments. The inset also shows the boundaries of the nine watersheds.

FIG. 2. Annual precipitation at the study area over the 13 years of the study (1988–2000), from the Prade Ranch precipitation station (except for the first four months of 1988, when precipitation was measured at the nearby Campwood Station). Average annual precipitation over the duration of the study was 788 mm. The three periods of streamflow monitoring are shown at the top of the figure: (1) pretreatment period (August 1987–June 1989); (2) treatment period (July 1989–May 1993); and (3) posttreatment period (January 1998–November 2000).

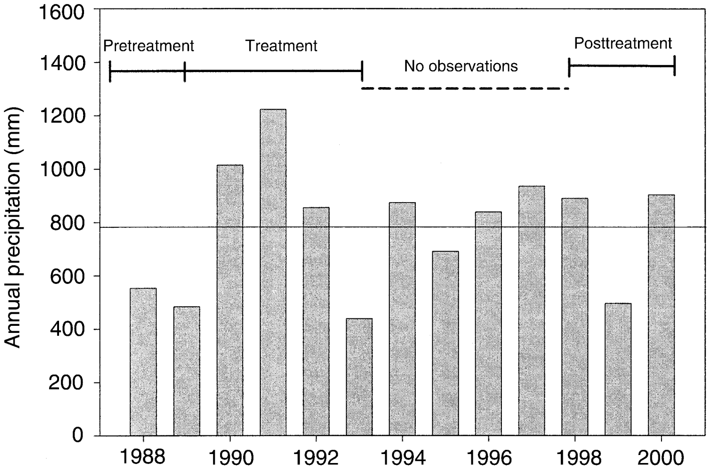

TABLE 1. Annandale Ranch watersheds: percentage of cover removed and the size, relief, and amount and percentage of runoff (Q) from precipitation (P) events (n) for different evaluation periods.

Watershed	1	2	3	4	5	6	7	8	9
Removal (%)	70	100	100	0	70	0	70	0	100
Size (ha)	5.3	5.3	3.8r	3.8	3.8	6.1	6.1	5.3	6.3
Relief (m)	85	88	67	70	82	64	73	70	55
Total evaluation period									
Total P (mm)	6744	6744	6744	6744	6744	6744	6744	6744	6744
Total Q (mm)	167	454	216	201	172	349	210	169	173
Events (n)	46	71	96	49	75	78	80	57	32
Q (%)	2.5	6.7	3.2	3.0	2.5	5.2	3.1	2.5	2.6
Pretreatment period runoff (Aug 1987–Jun 1989)									
P (mm)	971	971	971	971	971	971	971	971	971
Q (mm)	3	13	6	2	4	8	6	2	0
Events (n)	12	9	18	14	13	12	13	7	3
Q (%)	0.3	1.3	0.6	0.2	0.4	0.8	0.6	0.2	0.0
Treatment period runoff (Jul 1989–May 1993)									
P (mm)	3493	3493	3493	3493	3493	3493	3493	3493	3493
Q (mm)	84	260	117	109	74	193	116	77	95
Events (n)	18	39	58	27	40	42	44	32	19
Q (%)	2.4	7.4	3.4	3.1	2.1	5.5	3.3	2.2	2.7
Posttreatment period runoff (Jan 1998–Nov 2000)									
P (mm)	2280	2280	2280	2280	2280	2280	2280	2280	2280
Q (mm)	80	181	93	90	94	148	88	90	79
Events (n)	16	23	20	8	22	24	23	18	10
Q (%)	3.5	7.9	4.1	3.9	4.1	6.5	3.9	3.9	3.4

the soil was so rocky. Woody vegetation was then cut by hand and the debris left on site.

The nine watersheds were monitored for runoff until 1993, when funding problems forced the study to be temporarily discontinued. In 1998, when the work resumed, a continuous tipping-bucket precipitation recorder (Belfort Instrument, Baltimore, Maryland, USA) was also installed to monitor precipitation. By this time the woody vegetation had recovered to a significant degree; it was measured using the line intercept technique along five 30-m transects in each watershed. Herbaceous cover by species was estimated visually in 10 0.5-m^2 quadrats along each transect.

In summary, streamflow was monitored from each of the watersheds for three distinct periods between 1987 and 2000: (1) a pretreatment period, August 1987–June 1989; (2) a treatment period, July 1989–May 1993; and (3) a posttreatment period, January 1998–November 2000. Streamflow was not monitored for a period of four and a half years (June 1993–December 1997).

RESULTS

The nature of precipitation and streamflow

A summary of precipitation and runoff is presented in Table 1 for each of the three observation periods. Precipitation during the pretreatment period was below average, during the treatment period well above average, and during the posttreatment period slightly above average (Fig. 2). Runoff over the entire study period made up a relatively small part of the water budget, ~4% for most of the watersheds. It also occurred exclusively as stormflow, that is, all runoff was associated with specific precipitation events and baseflow was absent (no flow was measured between precipitation events). Very small amounts of runoff occurred during the pretreatment period (0.49%), which was considerably drier than the other two observation periods.

Runoff from watersheds 2 and 6 was two to three times higher than from the other watersheds (Table 1, Fig. 3A). Fig. 3A shows cumulative total runoff calculated from a series of runoff events ranked from largest to smallest (an example of such ranking, using watersheds 1 and 2, is displayed in Fig. 3B). In addition to highlighting differences in quantity of runoff and number of events among the watersheds, this analysis shows the relative importance of large vs. small events: most of the runoff was generated by a relatively small number of large events (the 10 largest events accounting for between 75% and 95% of the runoff). The number of runoff events ranged from a low of 32 for watershed 9 to a high of 96 for watershed 3. The actual number of events, however, had little bearing on the total amount of runoff. For example, most of the events from watershed 3 were very small and accounted for a small fraction of total runoff.

Runoff was generated by rainfall amounts as small as 10 mm, but appreciable runoff was generally seen only with 30 mm or more, as indicated by a significant curvilinear relationship between precipitation and runoff during the posttreatment period (Fig. 4). (Data anal-

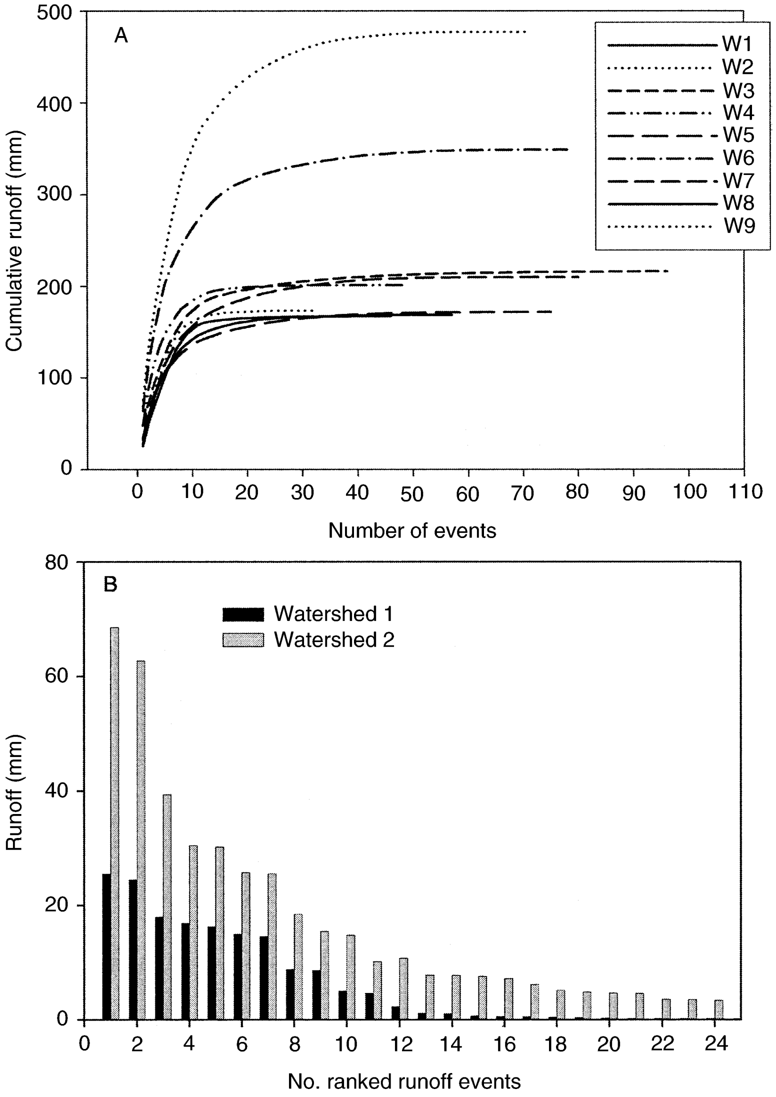

FIG. 3. (A) Cumulative runoff curves for the nine watersheds (W), calculated by progressively summing the ranked runoff for each, from largest to smallest. (B) An example of ranked runoff for watersheds 1 and 2.

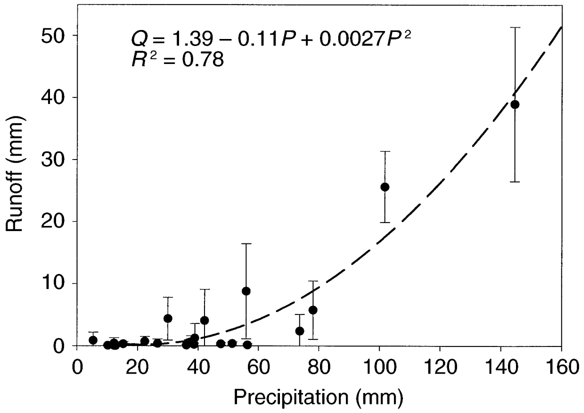

FIG. 4. Mean runoff from the nine watersheds plotted against precipitation for the posttreatment period (1998–2000). Error bars are ±1 SD.

ysis was restricted to the posttreatment period because it was during this time that continuous monitoring of rainfall allowed for better estimates of runoff-producing rainfall.) As rainfall amounts increased, the percentage that became runoff also increased. For the largest runoff-producing storms, runoff was ~25–40% of precipitation.

Runoff was episodic and linked closely to specific precipitation events. Individual runoff events, however, typically extended for hours (in some cases several days) after precipitation had stopped. One of the larger runoff events (depicted in Fig. 5) amounted to between 20% and 35% of precipitation and continued for many hours after the end of precipitation. The median length of runoff events was ~9 hours. Flow from watersheds 2 and 6 was typically not only greater but more sustained than from the other watersheds.

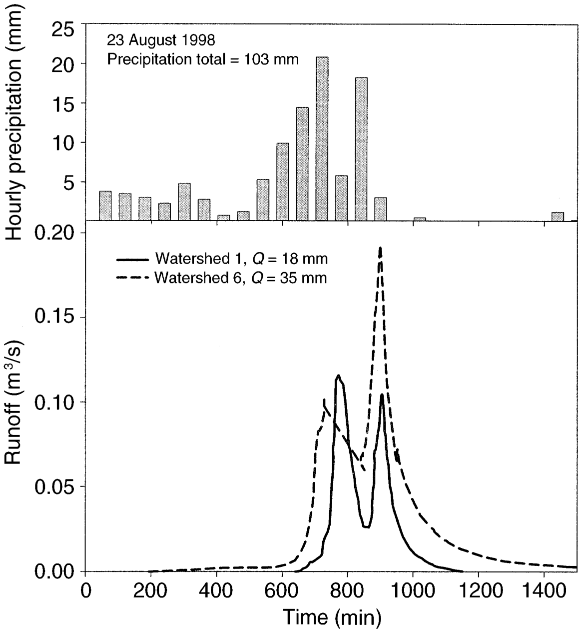

FIG. 5. Precipitation and runoff from watershed 1 (70% treated) and watershed 6 (control) for a precipitation event (23 August 1998). Runoff, expressed as m^3/s, continued for 2–10 h after the end of precipitation, indicating that at least a portion of runoff is derived from slower subsurface flow.

Vegetation change

In 1989, before any manipulation of the vegetation, the woody plant community of the study area was typical of Ashe juniper communities of the Edwards Plateau region. Mean woody plant cover ranged from 45% to 60% across all of the watersheds (Fig. 6). The diversity of woody plants was low—only nine species, the dominant ones being Ashe juniper (31.87 ± 3.66%, mean ± 1 SE), live oak (5.34 ± 2.52%), and Texas mountain laurel (8.24 ± 1.75%). Understory shrubs were generally scarce (<8% cover, except for watershed 4).

Eight years after the removal of woody plants from some watersheds, total woody cover had increased dramatically on all watersheds—by at least 30%; the greatest increase was 116% (Fig. 6). The results differed by species: Ashe juniper was significantly reduced on the watersheds that had undergone 100% cover removal (37.1% vs. 7.4%), was unchanged on the watersheds that had undergone 70% removal (32.5% vs. 32.7%), and was greater on the untreated watersheds (33% vs. 44.5%). In contrast, live oak and mountain laurel remained fairly constant among the watersheds, with the exception of extensive sprouting of live oak on the watersheds that had undergone 70% removal; in those cases, the increase ranged from 8.3% to 18.5%. In addition, eight years after the clearing treatments the number of woody plant species had increased from nine to 16. The understory species increased on the treated watersheds but not on the control ones.

Streamflow during the three study periods

We measured runoff for about nine of the 13 years of the study. As discussed previously, the pretreatment period (the first of the three periods of the study) was unfortunately characterized by low precipitation, which resulted in very low runoff, and thus is not as useful for comparison with later periods when precipitation was higher (Fig. 7). But since there was a hiatus in monitoring between the second and third periods (treatment and posttreatment) that allowed vegetation to regrow, we can still legitimately compare runoff from the treated watersheds before and after partial recovery of woody plants to assess their influence on streamflow. (Although not complete, especially for the 100% treated areas, this recovery in just 4.5 years was substantial [see Fig. 6].) Moreover, as reported by Dugas et al. (1998), even in just two years of partial recovery stand-level evapotranspiration rates return to pretreatment levels.

Among the low-runoff-producing watersheds, there was no significant difference ($P = 0.05$) in total streamflow between the treated (70% and 100%) and the control ones within a given study period (Fig. 7A). The average cumulative runoff from the 100%-treated watersheds was slightly greater than that from either the control or the 70%-treated watersheds during the treatment period. The picture was similar for the higher-runoff watersheds (Fig. 7B): the difference in runoff between watershed 2 (100% removal) and watershed 6 (control) was slightly larger during the treatment period than during the posttreatment period. These differences suggest the possibility of a small treatment effect on total streamflow, for the 100%-treated watersheds; but if real, this effect is most certainly a small one.

Another way of looking for treatment effects is to compare runoff amounts from treated and control watersheds on an individual-event basis for each of the

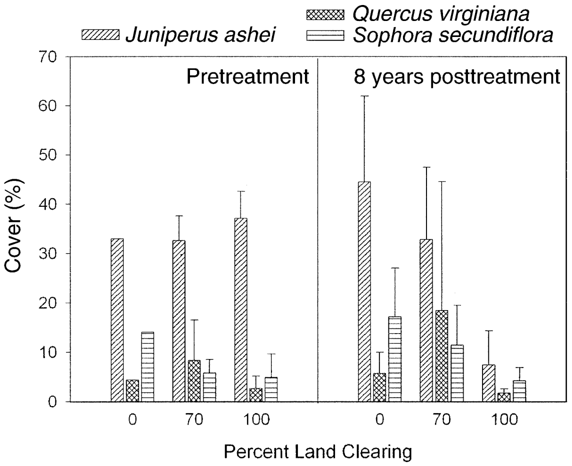

FIG. 6. Percent cover of the major woody plant species (mean + 1 SD) for the control, 70%-treated, and 100%-treated watersheds, during pretreatment vs. posttreatment periods.

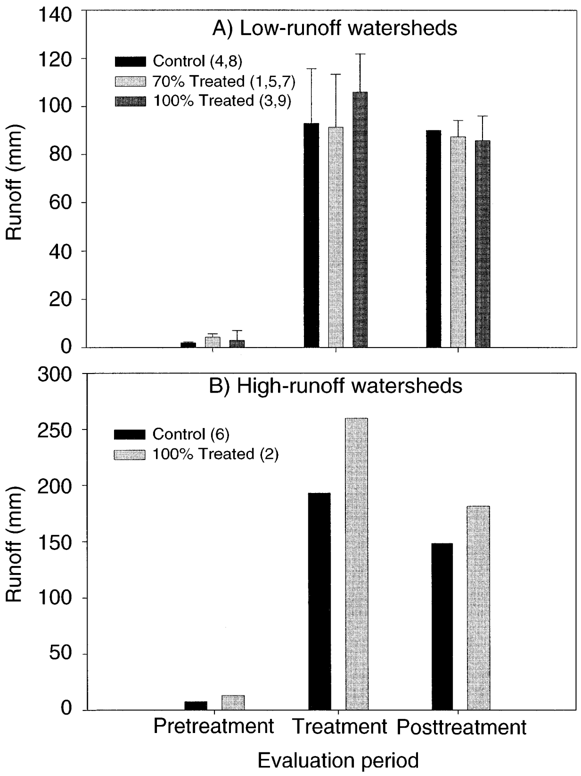

FIG. 7. (A) Comparison of total runoff (mean + 1 SD) from the seven "low-runoff" watersheds (numbers in parentheses) during the three evaluation periods. (B) Comparison of total runoff from the two "high-runoff" watersheds during the three evaluation periods.

study periods (Figs. 8 and 9). If the removal of woody plant cover did have an effect on runoff, we would expect that in comparison to the control watersheds, individual-event runoff from the 70%-treated and the 100%-treated watersheds would be higher during the treatment period than during the posttreatment period (which would be reflected by a steeper regression line during the treatment period than during the posttreatment period). This is not the case for either the low-runoff watersheds (Fig. 8A, B) or for the high-runoff watersheds (Fig. 9), a result consistent with that found by comparing cumulative flow: that streamflow was not markedly affected (if at all) by changes in woody plant cover.

DISCUSSION AND CONCLUSIONS

The issue of interactions between woody plants and streamflow in semiarid landscapes continues to spawn confusion, debate, and disagreement (Zhang et al. 2001, Wilcox 2002, Dugas et al. 2003, Huxman et al. 2005), in large part because of lack of data. Relatively few field studies have examined the issue at appropriate time and spatial scales. Some comparative watershed-scale studies of semiarid shrublands, now thought of as the "classic" work in this area, were conducted in

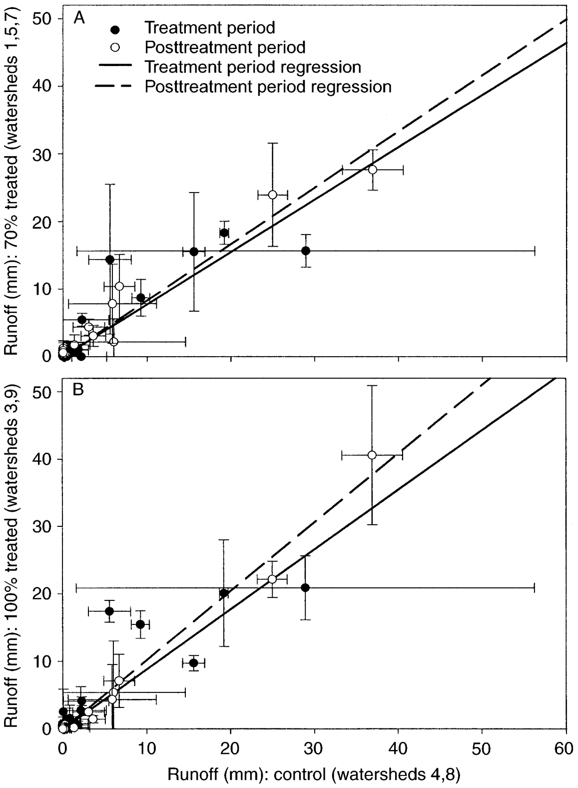

FIG. 8. Regression analysis comparing individual runoff events during the treatment and posttreatment evaluation periods, from the control watersheds vs. (A) 70%-treated watersheds and (B) 100%-treated watersheds. Error bars represent ±1 SD. The slopes of the regression lines were not significantly different at $P = 0.05$.

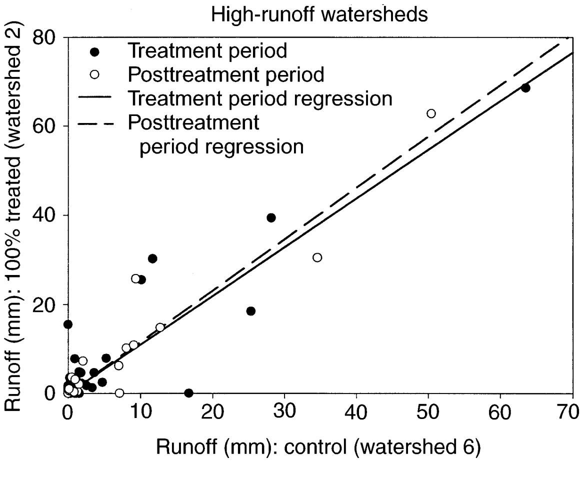

FIG. 9. Regression analysis comparing event runoff (mm) for the two high-runoff watersheds: numbers 2 (100% treated) and 6 (control). The slopes of the regression lines were not significantly different at $P = 0.05$.

the 1960s and 1970s (Clary et al. 1974, Ffolliott and Thorud 1974, Hibbert 1983, Baker 1984), but few have been done since then. The Annandale study is the most comprehensive watershed-scale study of juniper rangelands in Texas; it has provided important insights into the nature of runoff from these landscapes and how it may or may not be affected by vegetation management.

Major findings

The nature and magnitude of runoff.—For first-order watersheds on the Annandale Ranch in the Texas Hill Country, runoff made up ~4% of the annual water budget. It amounted to as much as 30–40% of precipitation in the case of some larger individual rainfall events. Although runoff consisted entirely of stormflow (there was no baseflow between storms), it often lasted well beyond the end of precipitation (sometimes several days beyond), evidence that some of the runoff was derived from more slowly moving subsurface flow, rather than overland flow. We have personally observed streamflow on the Annandale watersheds under conditions of very light and extended rainfall when overland flow was completely absent; in other words, subsurface flow contributes at least in part to runoff generation in this semiarid landscape. Overland flow may occur but we have not observed it. In addition, water clarity is very high during streamflow and there is little evidence of high sediment loads as would be expected if overland flow were important (M. K. Owens, *unpublished data*). As argued by Beven (2002), the widespread assumption that subsurface flow does not occur in semiarid settings is probably not correct.

Influence of woody plant cover on surface runoff.—The study findings indicate that for first-order watersheds characterized by an absence of preexisting spring flow, reducing woody plant cover (with minimal surface disturbance) has little or no influence on the nature of streamflow generation. This finding is especially interesting because it is contrary to two competing beliefs concerning the influence of shrubs on stormflow runoff. The first posits that overland flow runoff should be lower in shrublands than in grasslands; it is based on a considerable body of research (summarized in Wilcox 2005) that demonstrates higher soil infiltrability under shrubs than in grass-covered areas. Hester et al. (1997), for example, found that soil infiltrability was higher in Ashe juniper areas than in grass-covered areas, a finding that suggests surface runoff should be higher following shrub removal (and such an assumption has in fact been incorporated into some modeling assessments of shrub control and water yield). The second belief, a widely held one, is that overland flow and erosion will both be increased by higher coverage of woody plants. In the Edwards Plateau, for example, it has been widely observed (but not documented) that runoff and erosion are higher in the wake of invasion by Ashe juniper. Thurow and Hester (1997) suggest that increases in runoff and erosion following juniper encroachment are the result of overgrazing of the diminishing herbaceous cover.

Our findings at Annandale would indicate that at least in the short term, reductions in woody cover alone have relatively little impact on surface runoff.

Influence of woody plant cover on recharge and springflow.—An important element of the water budget that was not directly investigated by this study is that of groundwater recharge. In this complex geologic setting, direct measurements of recharge are difficult if not impossible. In the uplands, any recharge that occurs is likely to follow discrete fractures or other karst features and supply water to discontinuous and poorly connected groundwater bodies.

Water balance studies on the Plateau suggest that on average ~15% of precipitation ends up as recharge for the underlying Edwards Aquifer—most of it via transmission losses from stream channels that cross the Edwards Aquifer recharge zone (Maclay 1995). It is not known whether any recharge, or how much, occurs outside of stream channels (direct recharge), but estimates of evapotranspiration based on the Bowen ratio method suggest that direct recharge in this landscape could be substantial (Dugas et al. 1998). They estimated that removing woody plant cover reduced evapotranspiration by ~40 mm/yr for a period of at least two years.

The findings of the Annandale study do not address the effect of changes in woody plant cover on recharge to underlying groundwater. But if recharge did increase following shrub removal, the increase did not translate into on-site springs or seeps that could provide baseflow to the streams.

Where does this leave us?

On the surface, the Annandale study would seem to contradict much of the anecdotal wisdom concerning shrubs and water on the Edwards Plateau. It has been an ‘‘article of faith’’ that if shrub cover is reduced, springs will begin flowing, and this position is supported by ample anecdotal observations and at least one published report (Wright 1996). We believe that the key to the different findings at Annandale is the absence of springs or seeps, something to provide baseflow to streams. In other words, where springs are present, or have been historically, reduction of woody plant cover may increase the baseflow they feed (though this has yet to be documented in the peer-reviewed literature). On the other hand, if springs or seeps are not present, and never have been, it is unlikely that changes in woody plant cover alone will affect streamflow. In such landscapes, streamflow consists exclusively of stormflow, which by definition is a rapid process and is not affected directly by transpiration. In fact, as demonstrated by Richardson et al. (1979), if shrubs are removed mechanically in a way that increases surface roughness, surface runoff is likely to decrease. (Note: during our study, surface disturbance was minimal because shrubs were eradicated either with herbicides or by hand-cutting.)

On the basis of this study and a review of other work, we believe that drylands in which streamflow is most likely to be influenced by woody plant cover are those in which sustained flow takes place between precipitation events (indicating an active surface–subsurface connectivity). If woody plants can access deeper soil water, it is reasonable that greater numbers of woody plants would mean a greater potential for transpiration of water that would otherwise contribute to groundwater stores. In other words, semiarid landscapes exhibiting both extensive woody plant coverage and perennially flowing streams and rivers should be the prime candidates for increasing streamflow through manipulation of vegetation.

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