LARGE-SCALE RAINFALL SIMULATION EXPERIMENTS ON JUNIPER RANGELANDS

P. I. Taucer, C. L. Munster, B. P. Wilcox, M. K. Owens, B. P. Mohanty

ABSTRACT. *The effects of shrub clearing on surface and subsurface water movement in the Edwards Aquifer region were investigated using two large-scale rainfall simulation plots. Multiple replications of a large (168 mm) rainfall event were applied at an ashe juniper covered plot before and after shrub removal and at a plot with longstanding herbaceous cover. The study sites were equipped for monitoring of throughfall, stemflow, surface runoff, and soil water. Lateral subsurface flow was measured in a trench at the downhill end of each plot. The canopy plot produced high lateral subsurface flow during rainfall but no surface runoff, even for high rainfall intensities. In contrast, hydrologic response at the inter-canopy plot was dominated by rapid surface runoff. Following shrub removal at the canopy plot, water movement beyond the soil layer increased due to reduced canopy interception. Soil water storage capacity at the shrub plot remained small for both conditions, with much water apparently bypassing the litter and soil layers via macropore pathways. This additional water could move off site as macropore flow or remain on site as matrix and conduit storage. Differences in surface runoff and subsurfaceflow are attributable to vegetation and geologic differences.*

Keywords. *Ashe juniper, Interflow, Karst, Rainfall simulation, Runoff, Shrub removal.*

The conversion of grasslands or savannahs to woodlands, a process commonly referred to as woody plant encroachment, is a global phenomenon (Archer, 1994). For the southwestern U.S., this shift is often attributed to anthropogenic alterations caused by European settlement and development of large-scale ranching, including overgrazing and suppression of natural fires (Archer, 1994; Van Auken, 2000; Archer et al., 2001). Confined grazing by domestic livestock species created more damage than more mobile native herbivores (Smeins et al., 1997), in turn altering fire regimes by reducing fuel loads (Miller et al., 2000; Van Auken, 2000).

Woody plant encroachment is associated with decreased herbaceous production, possibly due to undercanopy shading, allelopathy, and prevention of germination by hydrophobic litter (Fuhlendorf et al., 1997; Smeins et al., 1997; Schott and Pieper, 1985). In addition to the more apparent ecological impacts on the landscape, shrub encroachment may also have complex hydrologic implications, altering canopy interception (Owens et al., 2006), soil infiltration characteristics (Thurow and Hester, 1997), and runoff (Wright et al., 1982; Schlesinger et al., 1999). Due to the large portion of the water budget occupied by evapotranspiration (Dugas and Mayeux, 1991; Kurc and Small, 2004; Seyfried et al., 2005) and the potential for shrubs to use more water than grasses due to deeper rooting structures and a longer transpirational period (Wu et al., 2001), changes in evapotranspiration (ET) in particular have been of interest in semiarid rangelands. While a linkage between shrub removal and water yield to the aquifer has been demonstrated for a number of humid landscapes (Wilcox, 2002) and some dryland areas, enhanced water yield through shrub removal is not universal for semiarid areas. Because the efficiency of this process increases with precipitation, vegetation management for water in drylands may not be as effective as for other landscapes (Graf, 1988) and in fact may be a viable method on less than 1% of western rangelands (Hibbert, 1983). The likelihood of enhanced yield depends on a number of factors, including precipitation regimes, shrub density, canopy interception capacities, runoff and streamflow generation characteristics, and capacity for subsurface water movement (Wilcox, 2002; Wilcox et al., 2005).

On rangelands in Texas, where increasing populations are placing pressure on already limited water supplies, the possibility of enhancing recharge to the aquifer and streamflow through shrub management has generated considerable interest and heated debate. To date, over $40 million have been allocated for shrub removal programs in the state (TSSWCB, 2006). The abundance of shrub species in Texas, particularly mesquite and ashe and redberry juniper, has increased markedly over the past 50 to 80 years (Ansley et al., 1995; Smeins et al., 1997).

The juniper rangelands of Texas hold some potential for increased water yield due to high interception capacities and a tendency to grow on areas with shallow soils and permeable parent materials, creating the possibility of subsurface flow (Wilcox, 2002). One such area is the Edwards Plateau / Edwards Aquifer region, where some studies have documented

Submitted for review in August 2007 as manuscript number SW 7133; approved for publication by the Soil & Water of ASABE in August 2008.

The authors are **Philip I. Taucer, ASABE Member Engineer,** Research Assistant, and **Clyde L. Munster, ASABE Member Engineer,** Professor, Department of Biological and Agricultural Engineering, and **Bradford P. Wilcox,** Professor, Department of Ecosystem Science and Management, Texas A&M University, College Station, Texas; **M. Keith Owens,** Professor, Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, Oklahoma; and **Binayak P. Mohanty, ASABE Member Engineer,** Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas. **Corresponding author:** Clyde L. Munster, Room 127 Hobgood Bldg., West Campus TAMU, College Station, TX 77843; phone: 979-847-8793; fax: 979-847-8627; e-mail: c-munster@tamu.edu.

changes in water yield after shrub removal (Wright et al., 1976; Richardson et al., 1979; Hester et al., 1997; Dugas et al., 1998; Huang et al., 2006).

Studies conducted on the Edwards Plateau over the past two decades have greatly increased understanding of several processes in these juniper rangelands, including stemflow (the portion of rainfall reaching the surface by flowing down the stem or trunk of vegetation), canopy interception (Owens et al., 2006), infiltration (Knight et al., 1987; Hester et al., 1997; Thurow and Hester, 1997), evapotranspiration (Dugas et al., 1998), shallow lateral subsurface flow (Sorenson, 2004; Dasgupta et al., 2006), recharge (Gregory, 2006), and runoff (Richardson et al., 1979). However, many of these studies have focused on only a limited number of water budget components. As such, there is a need for a more holistic understanding of how water is partitioned simultaneously among water budget components for juniper cover. To this end, this study seeks to develop a water budget for the major hydrologic processes for large rainfall events on both canopy and inter-canopy areas. In addition, this study also examines the effect of woody plant removal on the canopy plot water budget.

Study Area and Methodology

The Edwards Plateau, typically characterized by broad, rolling uplands, is one of the largest continuous areas of karst limestone geology in the U.S. (Smith and Veni, 1994). Karst landscapes derive primarily from chemical erosion processes, with caves, sinkholes, and sinking streams being typical features; subsurface steams and conduits can also occur, and permeability may span orders of magnitude (Veni, 2004). A prominent feature of the Edwards Plateau is the Edwards Aquifer, a region approximately 250 km long and 8 to 50 km wide on the eastern edge of the plateau (Dugas et al., 1998). This aquifer, with its high permeability and network of cavernous flow paths, is one of the most productive karst aquifers in the U.S. (Maclay, 1995).

The study area (29° 50′ N, 98° 29′ W) is located at Honey Creek State Natural Area (fig. 1) in western Comal County within the aquifer's drainage area. Annual precipitation averages 737 mm year^{-1}, with the majority of rainfall from intense summer thunderstorms (Maclay, 1995). Surface topography for the natural area is typical of the Texas Hill Country, with "stairstep" hills created by interbedding limestone layers (Woodruff et al., 1993). Underlying geology consists of the lower member of the Glen Rose Formation, described by Smith and Veni (1994) as a thick fossiliferous limestone formation containing many of the state's longer caves. Surface-expressed karst features, including sinkholes, are common within the natural area, with several sinkhole features within 100 m of the project site. Shallow (0 to 30 cm), gravelly clays and loams make up most of the soil profile, with an extensive presence of small rocks and solid outcrops. Vegetation consists of juniper scrubland and herbaceous interspaces. Ashe juniper (*Juniperus ashei* Buccholz) dominates woody growth, with some presence of scrub live oak (*Quercus virginiana* Mill.), agarita (*Berberis trifolioata* Moric.), and Texas persimmon (*Diospyros texana* Scheele). Herbaceous growth includes native species such as little bluestem (*Schizachyrium scoparim* Michx.), curly mesquite (*Hilaria belangeri*), Texas wintergrass (*Stipa leucotricha* Trim. and Rupr.), and switchgrass (*Panicum virgatum* L), as well as the introduced King Ranch bluestem (*Bothriochloa ischaemum*). Pricklypear is common within the interspaces and grows competitively even in areas of dense herbaceous growth.

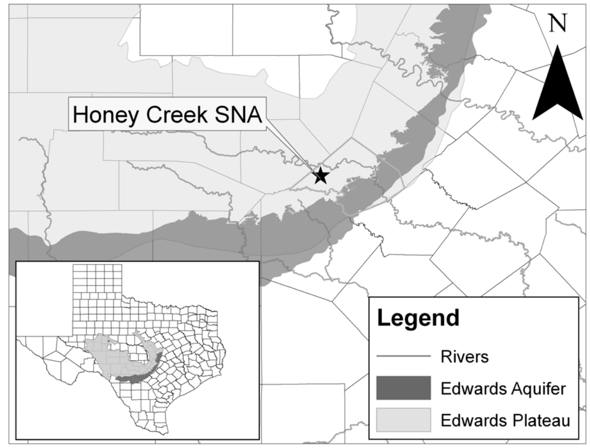

Figure 1. Location of the research site at Honey Creek State Natural Area, in Comal County, Texas.

Research Plots

Research plots (7 × 14 m) were established on hillslopes (2% slope) in both a juniper-covered landscape and an open (inter-canopy) grassland adjacent to juniper woodlands. The inter-canopy plot was approximately 200 m from the canopy plot. An above-canopy rainfall simulator was installed at each plot (Munster et al., 2006), and a 3.66 m wide border of polyethylene sheeting was placed around the perimeter of each plot to prevent infiltration of the overspray outside of the plots. The plots were hydrologically isolated from surface runoff generated on the surrounding area using galvanized sheet metal inserted 5 cm into the ground with 15 cm projecting above the surface. The plots were oriented with the 14 m dimension in the direction of the hillslope and the 7 m dimension in the cross-slope direction, and a trench approximately 2 m wide, 2.5 m deep, and 10 m long was installed at the downhill end of each plot to monitor lateral shallow subsurface flow. Fiberglass roofs were installed over the trenches to isolate them from rainfall simulator overspray. The canopy plot contained six ashe juniper trees with closed canopy cover and minimal under-story grass growth. Ground cover in the canopy plot was characterized by a 2.5 to 5.0 cm deep layer of juniper litter as well as surface rocks. The surface rocks and juniper tree trunks and roots resulted in a highly irregular surface topography. After three rainfall simulations in the canopy plot, shrubs were removed manually to minimize disturbance to the plot surface.

The inter-canopy plot was located in a grass-vegetated area that showed no indication of prior brush growth. The herbaceous cover in this plot was characterized by thick growth, predominantly little bluestem, sideoats grama, and Texas wintergrass. Pricklypear are common in the surrounding area, with several located within the plot itself. There were some small (up to 2 cm in diameter) near-surface rocks within the root layer, but there was minimal presence of the microtopographic features and an absence of surface impoundments found in the canopy plot.

Soils

Soils in the areas are mapped as part of the Real-Comfort-Doss group (SCS, 1984). They are generally rocky and shallow, and the A horizons are dark and high in organic matter. In the juniper plot, the A soil horizon was 0 to 30 cm in depth and was mixed with organic matter from decayed juniper litter. It consisted of about 25% mineral soil and 75% rock. The A horizon was overlying a fractured limestone layer with some of the fractures being infilled with A soil material. The soil on the inter-canopy plot was more shallow, with the A horizon being about 15 cm in depth on average. There were few rocks in the A horizon, which was directly overlying a massive and largely unfractured limestone.

Vegetation

Canopy cover was determined by measuring from the center of each shrub to the canopy edge, recording both distance and compass angle. Measurements were plotted on a fine grid, allowing for graphic estimation of canopy coverage. Herbaceous cover was estimated using a 0.5 m square frame, with readings taken along a regular grid within the plot. For the uncleared canopy plot, canopy cover was 100%, with <5% ground coverage of herbaceous growth. Remaining ground cover consisted of approximately equal areas of juniper leaf litter and limestone fragments ranging in size from 1 to 20 cm across. One year after brush removal, herbaceous and forb growth increased to 10% cover in the cleared canopy plot (fig. 2). At the inter-canopy plot, grass cover was >95% with a small portion of the plot occupied by pricklypear and small forbs.

Figure 2. Vegetation cover at the canopy plot prior to equipment installation (top) and one year after shrub removal (bottom). The simulator masts and polyethylene sheeting around the plot can be seen in the post-clearing photograph.

Hydrologic Measurement

Equipment in place at the plots measured throughfall, stemflow, surface runoff, soil moisture, and shallow lateral subsurface flow. Throughfall was measured using an array of 74 plastic rain gauges, each with a capacity of 140 mm, arranged in a 1.0 × 1.7 m grid within the plot. Gauges were read and emptied after each rainfall application to determine the amount and distribution pattern of rainfall. Custom stemflow instrumentation similar to that used by Owens et al. (2006) was installed on two of the six trees within the canopy plot. Collars around the main stems collected stemflow water and routed it through plastic tubing to a 1 L tipping-bucket unit for measurement. Measured stemflow water was subsequently released near the tree base to minimize the hydrologic impacts. Since not all trees were monitored, stemflow values were scaled up to represent all trees in the plot. Stemflow volume was assumed to be proportional to tree size. The ratio of total trunk basal area (for all six trees) to basal area for the two instrumented trees was used as a multiplier to scale up stemflow volumes.

Surface runoff from each plot was routed through a 15.25 cm (6 in.) H-flume at the downhill end of the plot (fig. 3). Water levels in the flume were measured with float-pulley-potentiometer instrumentation located in the flume stilling well. The flume was manufactured in-house to standard H-flume dimensions. The float-pulley-potentiometer unit was also assembled in-house. A wire with a float at one end and a counterweight at the other end was looped around a pulley connected to a rotational potentiometer that varied voltage from 0 to 2 V. The float was placed in the H-flume stilling well, causing the pulley to turn clockwise or counterclockwise as water levels rose or fell. The float-pulley-potentiometer instrumentation was calibrated in the laboratory to determine the relationship between voltage change and water level. The potentiometers were connected to a CR10X datalogger for actuation and data storage. Manual depth measurements in the flumes were also made periodically throughout the runs for validation of the runoff values.

Soil water was monitored using ten soil water sensors (Echo 10 dielectric aquameter, Decagon Devices, Inc., Pullman, Washington) located randomly throughout the plot.

Figure 3. The 15.25 cm (6 in.) H-flume with stilling well used to quantify surface runoff at the inter-canopy plot flume assembly. The gutter extension shown on the flume outlet conveys water over the trench and away from the plot. The grass cover shown in the background is typical of cover throughout the plot.

Due to the shallow and rocky nature of the upper soil layer at the canopy plot, sensors had to be installed in the mineral soil at shallow angles to ensure complete soil coverage of the sensor surface. This limited soil water measurement depths to the upper 5 cm of the A horizon. All water budget calculations relied on values from these sensors. Additional soil water readings were taken using a handheld impedance probe (theta probe soil water sensor, type ML2 and HH2 recording device, Delta-T Devices, Cambridge, U.K.) before and 20 min after a single standard simulation to gauge the reliability of the permanent sensors and develop a more detailed view of spatial patterns of soil water in the plot. Soil water was sampled from 0 to 6 cm using the theta probe, and the measured impedances were calibrated using gravimetric soil water samples. Manual readings were taken adjacent to each rain gauge and, where possible, were inserted entirely into mineral soil.

Lateral subsurface flow was measured in the downslope trenches. Water emerging from the trench face was routed along the sloping trench floor to a collection sump. A float-activated pump conveyed the water to a series of tipping-bucket gauges for measurement and recording.

Hydrologic observations for each rainfall event were limited to the period from the beginning of water application to the end of lateral subsurface flow (approx. 8 h). Due to the relatively short monitoring period, evapotranspiration (ET) is not explicitly accounted for in the water budgets. However, the evaporation component of ET is indirectly included in the form of canopy interception.

Subsurface Geology at the Trench Face

The subsurface geology was exposed at the downhill end of the canopy and inter-canopy plots in the trenches that collected lateral subsurface flow. There was a noticeable difference in the vadose zone geology at the canopy plot when compared to the inter-canopy plot. The limestone at the canopy plot exhibited many more cracks, fissures, and conduits. In addition, the preferential flow paths at the canopy plot extended to the bottom of the trench. The limestone at the inter-canopy plot tended to be massive with closed hairline fractures occurring primarily in the top 50 cm of the trench. Another significant difference is that there were more roots in the trench faces at the canopy plot. Very few roots were found in the trench at the inter-canopy plot and were entirely within the soil layer. It is hypothesized that the extensive cracks and fissures at the juniper site played a significant role in brush establishment at this site. While fractured geology is not necessary for ashe juniper establishment, it is possible that such geologic conditions provide a competitive advantage to deep-rooted vegetation.

In general, the subsurface geology at the canopy plot consisted primarily of parallel layers of limestone with numerous vertical and horizontal cracks and fissures. Thin loam and clay lenses, 1 to 10 mm wide, with tree roots were typically present in the joints between limestone layers (Dasgupta et al., 2006). Below the hard limestone rock layers were massive units of heavily weathered limestone known as marl or caliche. The marl units were rock-hard when dry but could store water and became soft and plastic when wet.

Rainfall Simulation

The above canopy rainfall simulator (fully described in Munster et al., 2006) consisted of six telescoping masts having a maximum extension of 11 m. Each mast was topped with a manifold equipped with four sprinkler heads. Each sprinkler head was equipped with independent valves, enabling the amount of water applied to be controlled by turning individual sprinkler heads on or off. The masts were located around the plot perimeter to avoid disturbance to the plot. The above-canopy rainfall simulator applied water at rates ranging from 2.5 to 25 cm h^{-1}, depending on the number of sprinkler heads per mast that were switched on. The median simulated raindrop size varied slightly with application rate and was consistent with natural rainfall events (Munster et al., 2006). Water for simulations was pumped from storage tanks located on site. An in-line flowmeter and pressure gauge monitored water flow (Munster et al., 2006).

A sequence of rainfall events were simulated at each plot. (3 pre-cut simulations, 3 post-cut simulations, and 3 inter-canopy simulations. Each replication consisted of three separate runs, each with a different intensity and duration. The first run was high intensity (102 mm h^{-1}) for 60 min, the second run was low intensity (25 mm h^{-1}) for 120 min, and the third run was very high intensity (152 mm h^{-1}) for 45 min. Lateral subsurface flow was allowed to stop before beginning the next rainfall simulation run. Due to variations in antecedent soil and subsurface moisture conditions prior to simulations, the first simulated run was primarily intended to create uniform antecedent moisture conditions for subsequent applications, permitting runs 2 and 3 to be replicated on different dates with similar soil moisture conditions for statistical analysis.

Results

Water Budgets

Water budgets for the canopy plot for both pre- and post-cut conditions are shown in tables 1 and 2. For outflow pathways, percentages are calculated with respect to the total volume of water reaching the plot surface (throughfall + stemflow) rather than to above-canopy precipitation. This removes the uncertainty associated with rainfall losses due to wind and canopy interception.

Unmeasured Flow Paths

Before discussing the measured flow pathways, it is important to note that a large amount of rainfall reaching the surface moved through pathways not monitored in this study. For the inter-canopy plot, a large amount of this water likely remained stored in the soil layer. However, this cannot account for all unobserved water. For some areas in the inter-canopy plot, surface and subsurface slopes may not correspond, allowing water to move along the soil-rock interface and exit the plot area without intersecting the trench. In addition, based on the limited knowledge of the subsurface, one must not rule out the possibility of unknown fractures or conduit features within the plot conducting water to the subsurface. Finally, although the grass species growing in the plot are documented to have low interception capacities, the very dense nature of growth in the plot could result in higher than expected interception.

For the canopy plot, the highly permeable nature of the subsurface and known hydrologic disconnects suggest that much of the unmeasured water likely moved through conduits and fractures not intersected by the trench. The final

Table 1. Water budget for standard simulations at the canopy plot prior to tree removal. Inputs are in mm and outputs are in both mm and percent of the total input.

Simulation		Inputs in mm			Outflow in mm (%)			
		Stemflow	Throughfall	Total	Soil Storage Change	Surface Runoff	Subsurface Flow to Trench	Other Subsurface Water
26 Oct. 2004	Run 1	13.3	50.3	63.6	4.0 (6.3)	0.0 (0.0)	19.6 (30.8)	40.0 (62.9)
	Run 2	7.4	20.4	27.8	5.0 (18.0)	0.0 (0.0)	23.0 (82.9)	-0.3 (-1.0)
	Run 3	0.0	53.1	53.1	-2.1 (-4.0)	0.0 (0.0)	40.3 (75.8)	15.0 (28.2)
	Daily total	20.6	123.8	144.5	6.9 (4.8)	0.0 (0.0)	82.9 (57.4)	54.7 (37.9)
1 June 2005	Run 1	8.5	39.9	48.4	4.4 (9.1)	0.0 (0.0)	4.0 (8.2)	40.0 (82.6)
	Run 2	4.0	21.0	25.0	1.3 (5.4)	0.0 (0.0)	11.2 (45.0)	12.4 (49.7)
	Run 3	9.5	44.1	53.6	1.7 (3.1)	0.0 (0.0)	37.2 (69.4)	14.7 (27.5)
	Daily total	21.9	105.1	127.0	7.4 (5.8)	0.0 (0.0)	52.4 (41.3)	67.1 (52.9)
9 June 2005	Run 1	9.6	44.0	53.5	4.8 (9.0)	0.0 (0.0)	23.3 (43.5)	25.4 (47.4)
	Run 2	4.1	21.9	26.0	0.4 (1.7)	0.0 (0.0)	20.3 (78.2)	5.2 (20.1)
	Run 3	11.7	41.2	52.9	1.2 (2.2)	0.0 (0.0)	50.3 (95.0)	1.5 (2.8)
	Daily total	25.3	107.1	132.4	6.4 (4.9)	0.0 (0.0)	93.9 (70.9	32.1 (24.2)
Total		67.8	336.0	403.9	20.7 (5.1)	0.0 (0.0)	229.2 (56.7)	154.0 (38.2)

Table 2. Water budget for standard simulations at the canopy plot after tree removal. Inputs are in mm and outputs are in both mm and percent of the total input.

Simulation		Inputs in mm			Outflow in mm (%)			
		Stemflow	Throughfall	Total	Soil Storage Change	Surface Runoff	Subsurface Flow to Trench	Other Subsurface Water
14 June 2005	Run 1	0.0	67.1	67.1	0.7 (1.0)	0.0 (0.0)	15.9 (23.8)	50.4 (75.2)
	Run 2	0.0	38.9	38.9	9.3 (23.9)	0.0 (0.0)	23.1 (59.3)	6.5 (16.7)
	Run 3	0.0	66.4	66.4	-9.8 (-14.7)	0.0 (0.0)	42.7 (64.3)	33.5 (50.4)
	Daily total	0.0	172.4	172.4	0.2 (0.1)	0.0 (0.0)	81.7 (47.4)	90.4 (52.5)
15 June 2005	Run 1	0.0	65.2	65.2	5.7 (8.8)	0.0 (0.0)	12.5 (19.2)	46.9 (72.0)
	Run 2	0.0	34.9	34.9	1.3 (3.8)	0.0 (0.0)	28.7 (82.3)	4.9 (13.9)
	Run 3	0.0	69.3	69.3	0.8 (1.1)	0.0 (0.0)	27.2 (39.2)	41.4 (59.7)
	Daily total	0.0	169.4	169.4	7.8 (4.6)	0.0 (0.0)	68.4 (40.4)	93.2 (55.0)
28 June 2005	Run 1	0.0	63.5	63.5	3.1 (5.0)	0.0 (0.0)	24.0 (37.8)	36.4 (57.3)
	Run 2	0.0	34.6	34.6	12.0 (34.8)	0.0 (0.0)	20.7 (59.8)	1.9 (5.5)
	Run 3	0.0	63.3	63.3	-10.4 (-16.5)	0.0 (0.0)	23.3 (36.8)	50.4 (79.6)
	Daily total	0.0	161.4	161.4	4.7 (2.9)	0.0 (0.0)	68.0 (42.1)	88.7 (55.0)
Total		0.0	503.2	503.2	12.7 (2.5)	0.0 (0.0)	218.1 (43.4)	272.2 (54.1)

destination of this water is unknown and cannot automatically be assumed to become recharge. Storage in conduits clearly accounted for some of this water, as indicated by the greater lag times during the first run as subsurface storage was filled. Additional storage occurred in the caliche/marl layer, as exchange between macropores and the caliche has been documented during simulations (Dasgupta et al., 2006). The total amount of this storage is unknown but could be large. A ground-penetrating radar survey of the plot revealed a number of fractures or karst features parallel to the trench (Sassen et al., 2008).

Interception, Throughfall, and Stemflow

Average canopy interception was determined by examining the differences in total water reaching the surface for the pre-cut and post-cut simulations. Canopy interception was approximately 33 mm, which was equivalent to about 20% of above-canopy precipitation. Throughfall averaged 112.0 mm for pre-cut simulations and 167.7 mm for post-cut simulations. The lag time between the start of water application and the initiation of stemflow varied from 3 to 12 min, with an average delay of 7 min. In most simulations, stemflow increased rapidly to peak levels and then remained at a steady state until the end of water application. Stemflow persisted for 3 to 6 min after the simulations were terminated, with an average residual flow time of 5 min. The peak rate of stemflow varied from 0.07 to 0.35 mm min^{-1} and showed clear linear relationship to rainfall application rate (r^2 = 0.88).

Surface Runoff

No surface runoff occurred from the canopy plot for any of the standard simulations. In addition, an initial rainfall simulation of 250 mm h^{-1} for a duration of 1 h did not produce any runoff from this site either. However, ponding of water was observed for all runs of the standard simulations in impoundments upslope of the juniper trees. These "juniper reservoirs" were created by the tree trunks, surface roots, and litter accumulations. The largest impoundment was approximately 2 m^2 in area and 2.5 cm in depth and was located at the end of the plot near the trench. Smaller reservoirs were located behind other trees and in various locations throughout the plot. Ponding of water occurred more quickly for runs 1 and 3 due to higher application rates, but even for the lower application rate of run 2, water began ponding within approximately 10 min. Water stored in surface depressions infiltrated completely within 4 min after the end of rainfall.

Table 3. Water budget for standard simulations at the inter-canopy plot. Soil moisture data was not available at the inter-canopy plot.

Simulation		Inputs in mm			Outflow in mm (%)		
		Stemflow	Throughfall	Total	Surface Runoff	Subsurface Flow	Other Subsurface Water
6 July 2004	Run 1	0.0	57.6	57.6	8.7 (15.1)	2.3 (4.0)	46.6 (80.9)
	Run 2	0.0	31.3	31.3	2.2 (7.0)	5.0 (16.0)	24.1 (77.0)
	Run 3	0.0	60.5	60.5	32 (52.9)	4.1 (6.8)	24.4 (40.3)
	Daily total	0.0	149.4	149.4	42.9 (28.7)	11.4 (7.6)	95.1 (63.7)
10 Aug. 2004	Run 1	0.0	68.1	68.1	11.4 (16.7)	0.5 (0.7)	56.2 (82.5)
	Run 2	0.0	28.3	28.3	2.2 (7.8)	1.0 (3.5)	25.1 (88.7)
	Run 3	0.0	60.9	60.9	38.8 (63.7)	2.7 (4.4)	19.4 (31.9)
	Daily total	0.0	157.3	157.3	52.4 (33.3)	4.2 (2.7)	100.7 (64.0)
11 Aug. 2004	Run 1	0.0	70.6	70.6	34.5 (48.9)	2.9 (4.1)	33.2 (47.0)
	Run 2	0.0	38.0	38.0	10.6 (27.9)	5.2 (13.7)	22.2 (58.4)
	Run 3	0.0	63.7	63.7	47.9 (75.2)	5.9 (9.3)	9.9 (15.5)
	Daily total	0.0	172.3	172.3	93 (54.0)	14.0 (8.1)	65.3 (37.9)
Total		0.0	479.0	479.0	188.3 (39.3)	29.6 (6.2)	261.1 (54.5)

For the inter-canopy plot, surface runoff occurred for all rainfall simulations and was the dominant component of the water budget (table 3). For the rainfall reaching the surface of the grass plot, surface runoff accounted for 19.5% to 54.0% of total daily simulations and up to 75.5% for individual simulation runs. Runoff began 20 to 30 min after initiation of rainfall for the first and second runs and in 3 to 15 min for the final run. Lag time to flow was linked to antecedent conditions, with lower response times for wet initial conditions and slower response for dry conditions. Surface runoff increased rapidly to a peak flow rate after runoff started. The highest runoff rates, which occurred during run 3, produced as much as 124 L min^{-1} (1.27 mm min^{-1}) of overland flow. Flow decreased rapidly after each rainfall simulation was terminated, but with trace flows of runoff continuing for up to 20 min after rainfall stopped.

The amount of water moving as surface runoff, both in terms of total volume and as a percentage of water applied to the inter-canopy plot surface, appeared closely related to antecedent moisture conditions as well. For the standard simulation on 10 August 2004, which was carried out under the driest conditions, surface runoff accounted for only 19.5% of applied water. Most of this water flowed during run 3, with a peak flow rate of 1.05 mm min^{-1}. In contrast, the simulation on 11 August 2004, which began under wet antecedent conditions, produced significant surface runoff for all runs, with overland flow accounting for more than 50% of applied rainfall and with a peak flow rate of 1.27 mm min^{-1}. Because soil moisture was not measured at the inter-canopy plot, any change in soil moisture storage would be included as "other subsurface water."

Soil Water

The change of surface soil water storage in the canopy plot was a relatively small proportion (0.1% to 2.9%) of applied rainfall (tables 1 and 2). Note that negative soil water change values for some of the run 3 datasets are the result of measurement methods. The final soil water for the first two runs had to be determined immediately before the start of the subsequent run. The final soil water for the third run was calculated 45 min after the end of the rainfall event, allowing some water to drain from the surface soil.

Approximately 5.1% of surface applied water was stored for pre-cut conditions and 2.5% for post-cut conditions. Due to the inherent variability (±2%) in the soil water sensors, the difference between pre- and post-clearing soil water storage change was not found to be significant. In addition, the soil water observations that were made in the surface soil layer using the manual TDR probe demonstrated spatially variable wetting of soils in the juniper plot (fig. 4). The area of greatest post-simulation soil water corresponds to the location with the greatest amount of surface water ponding.

In the canopy plot, the juniper litter was found to be hydrophobic, and probing in the plot immediately after rainfall simulations revealed numerous pockets of dry litter that re-

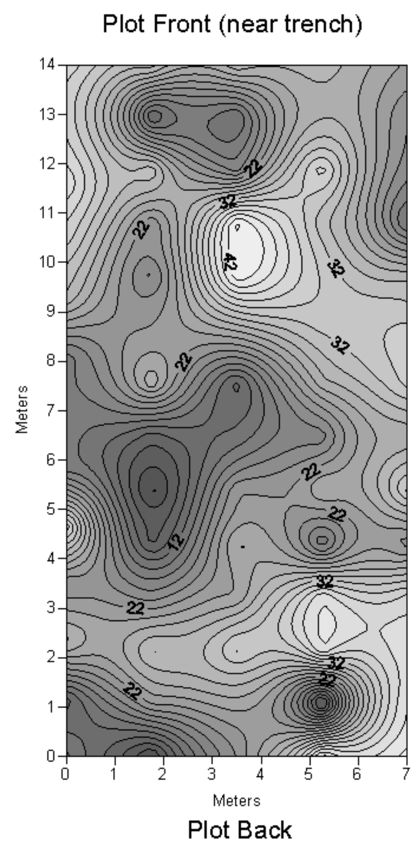

Figure 4. Volumetric soil water (mm mm^{-1}) distribution subsequent to a standard simulation on 9 June 2005. The downslope end of the plot is near the trench.

ceived little or no water. Soil water response to rainfall was rapid, with gauges responding within minutes of rainfall, producing a hydrograph-like response curve. Some gauges reported unusually high soil water readings, and the manual readings taken with the TDR theta probes indicated that these sensors were functioning properly. The rapid water response, unusually high readings, and coarse, hydrophobic nature of the litter suggest that much of this response could be due to macropore flow directly across the sensor. There was considerable variability among gauges, but each gauge responded similarly throughout the simulations.

Unfortunately, soil moisture data were not collected at the inter-canopy plot due to equipment problems. At the inter-canopy plot, observations of the surface soil layer at the trench face suggested a more uniform wetting of the soil profile than at the canopy plot. However, these observations were limited to the trench face without soil moisture data from additional locations within the plot.

Lateral Subsurface Flow

Canopy Plot

Shallow lateral subsurface flow (tables 1 and 2) to the trench at the canopy plot accounted for a large proportion of surface-applied water. The majority of this flow entered the trench through discrete conduit and fracture features, although a small amount entered as matrix flow through the soil layers in the trench face. Water emergence began 28 to 39 min after the start of rainfall for the first run and within 6 to 21 min for subsequent runs. Residual flow after rainfall continued for approximately 45 min for the first two runs and lasted 1 to 2 h for the final high-intensity run. Response times were greatest for simulations with dry initial conditions and lower for simulations with wet initial conditions. Flow from preferential paths was very rapid, with flow rates as high as 0.62 mm min^{-1} observed during standard simulations. Flow rates as high as 0.78 mm min^{-1} have been observed during very high (250 mm h^{-1}) non-standard applications. Very wet antecedent conditions produced the shortest lag times in both cases. The amount of surface-applied water emerging as lateral subsurface flow in the trench ranged from 40.4% to 70.9% on a daily basis. On a per-run basis, lateral subsurface flow ranged from 8.2% (run 1) to 95.0% (run 3).

As shown in tables 1 and 2, lateral subsurface flow accounted for an average of 56.7% of water reaching the canopy plot surface for the pre-cut condition and 43.4% for the post cut condition. Based on three replicated rainfall simulations, this represents a significant ($\alpha = 0.1$) reduction in flow to the trench for the post-cut condition. On a per-run basis, only the third run showed a significant difference, with a higher amount of observed lateral subsurface flow for the pre-cut condition. There was no significant ($\alpha = 0.1$) difference for the average lag time between the application of water and the start of flow into the trench for pre- and post-cut conditions.

Inter-Canopy Plot

For the inter-canopy plot, lateral subsurface flow to the trench represented a small amount of the water budget. On average, only 5.0% of water reaching the plot surface emerged as shallow subsurface flow. As with surface runoff, trench flow at the plot showed a clear relationship to antecedent soil water, with the least flow (2.7%) for the driest conditions and the highest flow (8.1%) for very wet conditions. Subsurface flow into the trench occurred almost exclusively at the soil-rock interface, with the remainder from the soil layer itself. Typically, flow began in discrete locations along the interface but rapidly transitioned to flow along the entire soil-rock joint. Although the soil-rock interface in the trench "wet-up" early in the simulations, generally lateral subsurface flow started only after surface runoff was initiated.

Discussion

Hydrologic Alterations

Before discussing the effects of brush removal on the water budget, the impact of the trench on lateral subsurface flow must be considered. The trench was a large artificial feature that may have affected the hydrologic properties of the plot. Careful inspection of the fractures in the trench face in the canopy plot revealed signs of weathering, discoloration, soil deposits, and the presence of roots, indicating that these fractures were not created during trench installation. Therefore, these fractures and conduits were pre-existing subsurface features that were hydraulically active prior to trench installation. Additionally, 24.2% to 55.0% of the water reaching the surface during rainfall simulations at the juniper plot moved through subsurface paths not intercepted by the trench. These subsurface pathways, which accepted large volumes of water, would not have been enhanced by the installation of the trench. This indicates that the overall infiltration capacity of the plot was very high prior to the installation of the trench. Large-scale ring infiltrometer measurements taken around a juniper adjacent to the plot demonstrated high infiltration capacity (6.31 cm h^{-1}) without trench presence (Lindley, 2005).

Interception, Throughfall, and Stemflow

The calculated value for interception (average = 33 mm) is much larger than previous documented interception for ashe juniper on the Edwards Plateau. Using the relationship developed by Owens et al. (2006), a 167 mm storm such as that applied during the rainfall simulations would be expected to generate 7.5 mm of canopy interception. Another study, by Gregory (2006), found up to 11.7 mm of interception during a 54 mm rainfall event for mixed ashe juniper and live oak cover. There are a number of potential causes for this substantial difference, including the large size of the rainfall event, the extended pause between runs, the hot and sunny conditions during most rainfall simulations, and a particularly dense, overlapping canopy for the project plot. Reported interception values of 1.8 mm for sideoats grama and 1 mm for curly mesquite (Thurow et al., 1987) for local herbaceous covers are very small in comparison.

As expected, throughfall increased significantly ($\alpha = 0.1$), from 112.0 mm pre-cut to 167.7 mm post-cut, due to the removal of the trees and the elimination of canopy interception losses in the juniper plot.

The amount of stemflow recorded in this study (average = 16.8%) was notably higher than other studies of ashe juniper on the Edwards Plateau. Stemflow values documented for natural rainfall events on the Edwards Plateau have varied from 0.48% for mixed oak-juniper woodland (Gregory, 2006) to approximately 5% for juniper cover (Thurow and Hester, 1997; Owens et al., 2006). Rainfall simulation studies carried out on the Edwards Plateau by Sorenson (2004) found 10.8% of the simulated rainfall moving as stemflow for events of similar or greater size than those used for this study. In addition, Gregory (2006) found 5.5% of simulated (above-canopy) rainfall moved as stemflow for mixed oak-juniper cover. The wide difference in values may be attributed to the numerous factors that affect stemflow, including precipitation characteristics, bark roughness, stem angle, vegetation type, and tree size (Martinez-Meza and Whitford, 1996). In addition, differences in rainfall event size may account for the wide variation, with smaller events (Gregory, 2006) producing less stemflow and larger events (Porter, 2005) producing more. Intensity of rainfall may also play a role, given the relationships between rainfall intensity and stemflow rate and initiation time documented in this study. Additional differences may stem from site-specific tree shape properties and from differences in scaling factors used to estimate flow for un-instrumented trees.

Infiltration and Soil Water

Water storage in the surface soil for the canopy plot, for both pre- and post-cut conditions, appears to be a relatively minor part of the total water budget. Differences in pre- and post-cut soil water changes were less than the range of error for the probes, and shrub removal had no noticeable impact on the volume of water stored as soil water. In the canopy plot, the preferential flow through the soil also minimized this component of the water budget.

The rainfall simulations revealed that water moves through the hydrophobic litter in preferential flow paths, thereby bypassing much of the litter matrix. Therefore, water storage in the litter at the plot was minimal. This bypass movement through the litter also means that the upper surface of the underlying soil also wets-up in discrete locations rather than uniformly. This was documented using the manual theta probe soil water content readings before and after rainfall simulations. In fact, many locations in the plot remained too dry for probe insertion even after rainfall simulations. Therefore, infiltration bypasses much of the soil matrix as well. The preferential nature of flow through the litter and the surface soil also explains why soil water storage changed very little before and after the rainfall simulations and why canopy removal created no significant change in soil storage capacity. However, water storage in soil and litter may be more significant beneath surface reservoirs where ponding occurs.

It is hypothesized that the juniper roots play a major role in the rapid infiltration by providing preferential flow paths through the litter and soil and into the cracks and fissures in the underlying geology. In addition, juniper roots may also expand pre-existing preferential flow paths in the limestone through mechanical widening and enhanced chemical dissolution (Dasgupta et al., 2006).

In contrast to the canopy plot, the inter-canopy plot did not have a hydrophobic litter layer to promote preferential flow. The relatively uniform distribution of the grass cover instead led to a uniform application of rainfall to the soil surface. As observed in the downslope trench at the inter-canopy plot, the soil profile appeared to wet-up uniformly. However, infiltration through inter-canopy plot soils was still very rapid, especially for dry antecedent soil water conditions.

Surface Runoff

The rainfall simulations on the canopy plot resulted in no surface runoff for either pre- or post-juniper conditions. In contrast, surface runoff was the largest component in the water budgets for the simulations on the inter-canopy plot. There were several surface and subsurface differences between the two plots that could be responsible for these very different runoff responses. The most important difference was the condition of the limestone rock that was present at or near the surface of the plots. The underlying geology at the canopy plot, as viewed from the downslope trench, was characterized by numerous cracks, fissures, and joints. A few of these preferential flow paths transmitted large quantities of lateral subsurface flow. In contrast, the underlying geology at the inter-canopy plot was characterized by relatively solid limestone units that transmitted very little lateral subsurface flow to the trench.

Another important factor of surface runoff retention on the canopy plot were the surface reservoirs, which were created by a number of factors, including subsurface topography, tree trunks, roots, and litter accumulation. These reservoirs were created on the upslope side of the juniper trees and ponded water at the base of the trees where the largest juniper roots were located. Prior to shrub removal, stemflow appeared to be a major contributor to these reservoirs. However, subsequent to shrub removal surface storage was not visibly reduced. In contrast, the inter-canopy plot did not have these surface reservoirs. Although these juniper reservoirs captured runoff, it is important to keep in mind that these features do not have large storage capacities; water infiltrated very rapidly and drained very quickly after the rainfall simulations were completed. Therefore, it was likely that a combination of surface depressions and reservoirs and the exceedingly high infiltration rates of the surface soils and underlying geology were primarily responsible for the lack of runoff for both pre- and post-cut conditions on the canopy plot. Litter microtopography under juniper has also been documented as a sink for overland flow from canopy interspaces (Thurow and Hester, 1997). This suggests that for the Edwards plateau juniper-induced microtopography changes may alter runoff processes considerably beyond the tree or plot scale.

Lateral Subsurface Flow

In the canopy plot, the percentages of ground-level water inputs (throughfall + stemflow) entering the trench as interflow represent a statistically significant ($\alpha = 0.1$) reduction after juniper removal. The probable cause of this reduction is a change in rainfall application to the plot surface from a preferential distribution characterized by irregular throughfall and focused stemflow to a more uniform distribution (fig. 5). Pre-clearing, the tree canopy captured water and redirected it toward the tree trunks. The preferential application of stemflow accounted for nearly 17% of the water reaching the plot surface and was focused in a very small area at the base of the juniper trees. Dye tracer tests conducted at the plot (Taucer et al., 2005; Dasgupta et al., 2006) detailed the connection between the juniper trees in the plot and the lateral subsurface flow into the trench. Dye tracing at the plot also demonstrated a hydraulic disconnect between the rear of the plot and the trench. Dye tracer testing began after the beginning of this research, and the presence of this disconnect was not known for the initial simulations. Since complex geologic features are a common characteristic of the karst Edwards Aquifer landscape, it was judged that the plot was still representative of the landscape. Due to this discovery, a single soaker hose test at the canopy plot applied 380 mm h^{-1}

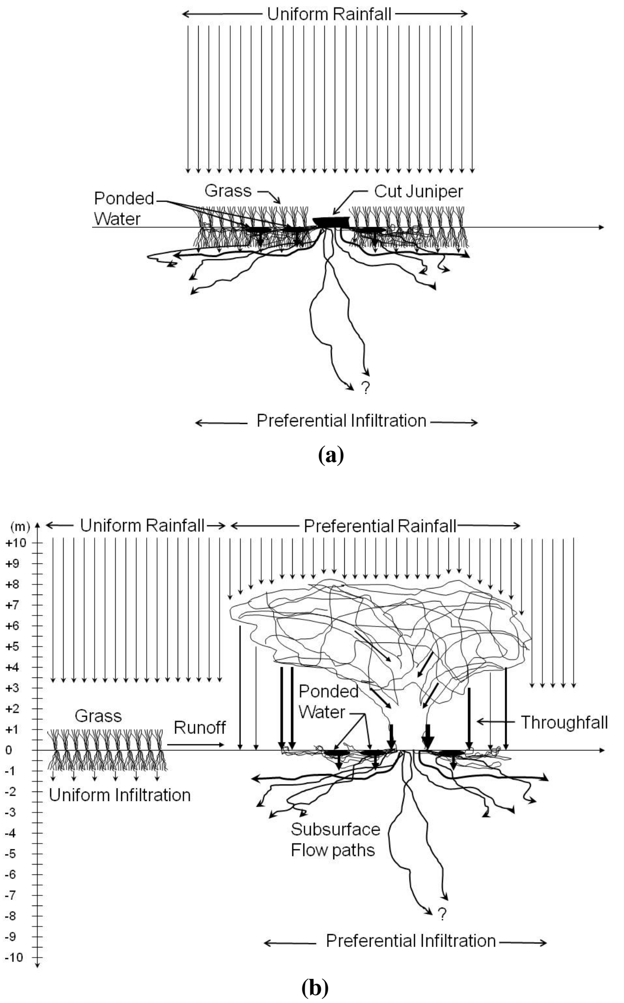

Figure 5. Comparison of conceptual rainfall application and infiltration patterns for (a) cleared juniper landscapes and (b) juniper-covered landscapes. In the cut juniper landscape, the rainfall application becomes uniform but the preferential flow paths caused by the juniper roots remain.

of water directly to the litter for approximately 45 min. The water application was limited to the top (upslope) quarter of the plot, farthest from the trench. This extremely large application of water produced no surface runoff and no flow into the trench. For the pre-cut condition, the canopy may have redirected some of the water falling over this area and routed it along the stem to an area of the plot linked to the trench. Thus, reduction in observed lateral subsurface flow may be due to reduced inputs to specific flow paths feeding the trench. Post-clearing, the elimination of stemflow resulted in rainfall more uniformly distributed over the plot. This in turn meant that less water was available at the base of the juniper trees, where documented preferential flow paths contributed lateral subsurface flow to the trench. Instead, some of the additional water was intercepted by other subsurface conduits not connected to the trench.

Given the similar surface runoff and soil water characteristics and subsurface response times for both vegetation treatments and the increased total water reaching the ground subsequent to shrub removal, one might expect increased lateral subsurface flow rather than the observed reduction. If this reduction is actually occurring, then several factors may contribute to the observed behavior. Sensitivity to antecedent soil water, combined with the limited number of simulations, could skew results; however, this is unlikely since antecedent soil water was generally greater for post-cut simulations. Alteration of subsurface paths by repetitive heavy rainfall simulations is also possible. Even prior to juniper removal, a slight shift in relative amounts of flow was observed for the two most productive conduits, although the majority of flow moved through the same few conduits for both vegetation conditions.

It is important to note that this alteration of rainfall partitioning is flow path and site specific and is calculated based on ground-level water applications rather than bulk precipitation. While flow to the trench decreased, total water reaching the subsurface increased by an amount roughly equal to canopy interception. Even though there is more uniform application of water after the trees are removed, the preferential flow system through the litter, soil, and vadose zone still exists, as does the network of surface depressions and reservoirs. Therefore, rainfall infiltrates very rapidly in the canopy plot for either vegetation condition with no runoff.

In comparing interflow at the canopy and inter-canopy plots, subsurface properties other than vegetation appear to control differences in subsurface flow generation. The presence of minor drips from large grass roots slightly above the soil-rock interface suggests that vegetation macropores may enhance lateral movement at the inter-canopy plot. However, these structures produced only a tiny fraction of total interflow. While the canopy plot displayed numerous active open macropores, no such flow paths were observed within the parent material at the inter-canopy plot. The massive subsurface at the inter-canopy plot may have limited water movement beyond the top of the limestone layer, forcing lateral flow along the soil-rock interface. This could occur throughout the plot, but this hypothesis is limited by a lack of subsurface observations beyond the trench face.

Conclusion

This study has documented simultaneous water movement through a number of flow pathways and revealed a number of impacts of shrub removal on the partitioning and distribution of rainfall among multiple water budget components. As expected, the volume of water reaching the plot surface as throughfall increased considerably after juniper removal for the canopy plot with a much more uniform distribution. The post-clearing increase in throughfall and total surface input are primarily attributed to high canopy interception, which accounted for 33 mm of water reaching the top of the plant canopy per simulation. This volume was much higher than expected and may represent high canopy storage capacity resulting from a dense, overlapping canopy and a large rainfall event. Stemflow, which was eliminated by shrub removal, represented a large input to the juniper plot for the pre-cut condition, with 16.8% of water reaching the surface as stemflow. The majority of stemflow infiltrated quickly, and some of this water was stored in the juniper depressions but infiltrated quickly after the end of rainfall.

Perhaps the most interesting conclusions of the study relate to runoff and subsurface water movement at the canopy plot. For the plots studied, surface runoff and interflow appear to be controlled by both soil and subsurface permeability, with juniper vegetation likely playing an important role in altering soil infiltration characteristics under shrub cover. The high infiltration capacities of litter, soil, and the fractured limestone subsurface at the shrub plot coupled with the juniper reservoirs precluded surface runoff but allowed rapid lateral subsurface flow, while the slower infiltration and seemingly solid subsurface of the inter-canopy plot resulted in considerable surface runoff but limited lateral subsurface flow.

The aforementioned highly preferential soil and subsurface systems allowed rapid movement for both vegetation conditions at the canopy plot. However, the presence or lack of stemflow contributions appears to have a major influence on which flow paths are taken by infiltrating water. Regardless of flow path, for all simulations a large percentage of rainfall reached the subsurface; for the post-cut condition, over 97% of precipitation moved beyond the soil layer. While high overall infiltration and increased post-cut inputs after shrub clearing are encouraging signs for increased water yield to streams or the aquifer, one must not automatically equate increased subsurface flow with increased recharge. Considerable amounts of water may be stored on site in near-surface conduits, fractures, and soil pockets, or in porous or unconsolidated caliche and marl layers in the subsurface. Thus, much of the water reaching the subsurface may eventually be lost to long-term evapotranspiration by herbaceous regrowth.

While this study suggests that shrub removal influences subsurface flow through increased water reaching the ground and alteration of routing through specific macropores, the impact of these alterations on streamflow and recharge remain unknown. Due to the high geologic variability of the Edwards Aquifer region and the scale-dependent nature of ecohydrologic processes, continued holistic examination of rainfall partitioning at multiple locations and scales will be necessary to determine effects of shrub removal on streamflow, recharge, and runoff processes.

Acknowledgements

This project was funded in part by National Science Foundation Grant No. 0233667 (Collaborative Research: WCR: Ecohydrology of Semiarid Woodlands: Role of Woody Plants in the Water Cycle). Support was also provided by the Texas Parks and Wildlife Department, San Antonio Water System, Bexar Met, and the Texas Water Resources Institute.

References

Ansley, R. J., W. E. Pinchak, and D. N. Ueckert. 1995. Changes in redberry juniper distributions in northwest Texas. *Rangelands* 17(2): 49-53.

Archer, S. 1994. Woody plant encroachment into southwestern grasslands and savannas: Rates, patterns, and proximate causes. In *Ecological Implications of Livestock Herbivory in the West*, 13-68. M. Vavra, W. A. Laycock, and R. D. Pieper, eds. Denver, Colo.: Society for Range Management.

Archer, S., T. W. Boutton, and K. A. Hibbard. 2001. Trees in grasslands: Biogeochemical consequences of woody plant expansion. In *Global Biogeochemical Cycles in the Climate System*, 115-138. E.-D. Schulze et al., eds. San Diego, Cal.: Academic Press.

Dasgupta, S., B. P. Mohanty, and J. M. Kohne. 2006. Impacts of juniper vegetation and karst geology on subsurface flow processes in the Edwards Plateau, Texas. *Vadose Zone J.* 5(4): 1076-1085.

Dugas, W. A., and H. S. Mayeux. 1991. Evaporation from rangeland with and without honey mesquite. *J. Range Mgmt.* 44(2): 161-170.

Dugas, W. A., R. A. Hicks, and P. Wright. 1998. Effect of removal of *Juniperus ashei* on evapotranspiration and runoff in the Seco Creek watershed. *Water Resources Res.* 34(6): 1499-1506.

Fuhlendorf, S. D., F. E. Smeins, and C. A. Taylor. 1997. Browsing and tree size influences on ashe juniper understory. *J. Range Mgmt.* 50(5): 507-512.

Graf, W. L. 1988. *Fluvial Processes in Dryland Rivers*. I. Douglas, F. Joly, M. Marcu, and B. Messerli, eds. Springer Series in Physical Environment. New York, N.Y.: Springer-Verlag.

Gregory, L. F. 2006. Water budgets and cave recharge on juniper rangeland in the Edwards Plateau. College Station, Tex.: Texas A&M University, Water Management and Hydrological Science.

Hester, J. W., T. L. Thurow, and C. A. Taylor. 1997. Hydrologic characteristics of vegetation types as affected by prescribed burning. *J. Range Mgmt.* 50(2): 199-204.

Hibbert, A. R. 1983. Water yield improvement potential by vegetation management on western rangelands. *Water Resources Bull.* 19(3): 375-381.

Huang, Y., B. P. Wilcox, L. Stern, and H. Perotto-Baldivieso. 2006. Springs on rangelands: Runoff dynamics and influence of woody plant cover. *Hydrol. Proc.* 20(15): 3277-3288.

Knight, R. W., R. K. Heitschmidt, R. J. Ansley, D. L. Price, M. K. Owens, M. A. Hussey, D. D. Briske, A. A. Desai, R. A. Hicks, P. A. Julien, G. L. Holmstead, T. A. Wright, D. H. Carlson, S. L. Dowhower, and C. L. Clark. 1987. Water yield improvement from rangeland watersheds. College Station, Tex.: Texas A&M University.

Kurc, S., and E. Small. 2004. Dynamics of evapotranspiration in semiarid grassland and shrubland during the summer monsoon season, central New Mexico. *Water Resources Res.* 40: WO9305.

Lindley, A. L. 2005. The hydrologic function of small sinkholes in the Edwards Aquifer recharge zone. MS thesis. Austin, Tex.: University of Texas at Austin.

Maclay, R. W. 1995. Geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas. Austin, Tex.: U.S. Geological Survey.

Martinez-Meza, E., and W. G. Whitford. 1996. Stemflow, throughfall, and channelization of stemflow by roots in three Chihuahuan Desert shrubs. *J. Arid Environ.* 32(3): 271-287.

Miller, R. F., T. J. Svejcar, and J. A. Rose. 2000. Impacts of western juniper on plant community composition and structure. *J. Range Mgmt.* 53(6): 574-585.

Munster, C. L., P. I. Taucer, B. P. Wilcox, S. C. Porter, and C. E. Richards. 2006. An approach for simulating rainfall above the tree canopy at the hillslope scale. *Trans. ASABE* 49(4): 915-924.

Owens, M. K., R. K. Lyons, and C. J. Alejandro. 2006. Rainfall partitioning within semiarid juniper communities: Effects of event size and canopy cover. *Hydrol. Proc*. 20(15): 3179-3189).

Porter, S. C. 2005. The use of a rainfall simulator for brush control research on the Edwards Plateau. College Station, Tex.: Texas A&M University, Biological and Agricultural Engineering.

Richardson, C. W., E. Burnett, and R. W. Bovey. 1979. Hydrologic effects of brush control on Texas rangelands. *Trans. ASAE* 22(2): 315-319.

Sassen, D. S., M. E. Everett and C. L. Munster. 2008. Near-surface ecohydrogeophysics at the Edwards aquifer: Insights from polarimetric ground-penetrating radar. *Near Surface Geophysics* (in review).

Schlesinger, W. H., A. D. Abrahams, A. J. Parsons, and J. Wainwright. 1999. Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: I. Rainfall simulation experiments. *Biogeochem.* 45(1): 21-34.

Schott, M. R., and R. D. Pieper. 1985. Influence of canopy characteristics of one-seed juniper on understory grasses. *J. Range Mgmt.* 38(4): 328-331.
SCS. 1984. Soil survey of Comal and Hays Counties, Texas. College Station, Tex.: Soil Conservation Service.
Seyfried, M. S., S. Schwinning, M. A. Walvoord, W. T. Pockman, B. D. Newman, R. B. Jackson, and F. M. Phillips. 2005. Ecohydrological control of deep drainage in semiarid regions. *Ecology* 86(2): 277-287.
Smeins, F. E., S. D. Fuhlendorf, and C. A. Taylor. 1997. Environmental and land use changes: A long-term perspective. In *Proc. Juniper Symposium*, 1.3-1.21. C. A. Taylor, ed. San Angelo, Tex.: Texas A&M University.
Smith, R. A., and G. Veni. 1994. Karst regions of Texas. In *The Caves and Karst of Texas: A Guidebook for the 1994 Conventions of the National Speleological Society with Emphasis on the Southwestern Edwards Plateau*, 7-12. W. V. Elliot, ed. Huntsville, Ala.: National Speleological Society.
Sorenson, J. R. 2004. The use of large plot rainfall simulation to investigate runoff generation on the Edwards Plateau, Texas. College Station, Tex.: Texas A&M University, Rangeland Ecology and Management.
Taucer, P. I., C. L. Munster, B. P. Wilcox, B. Shade, S. Dasgupta, M. K. Owens, and B. Mohanty. 2005. Plot-scale tracing of subsurface flow in the Edwards Aquifer epikarst. Paper read at 10th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impact of Karst, at San Antonio, Texas.
Thurow, T. L., and J. W. Hester. 1997. How an increase or a reduction in juniper cover alters rangeland hydrology. In *Proc. Juniper Symposium*, 9-22. San Angelo, Tex.: Texas A&M University.
Thurow, T. L., W. H. Blackburn, and C. A. Taylor. 1987. Rainfall interception losses by midgrass, shortgrass, and live oak mottes. *J. Range Mgmt.* 40(5): 455-460.
TSSWCB. 2006. Brush control program: 2006 annual report. Temple, Tex.: Texas State Soil and Water Conservation Board.
Van Auken, O. W. 2000. Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics* 31: 197-215.
Veni, George. 2004. Karst research in Texas and the Edwards Aquifer: Past, present, and future. Paper read at Edwards Aquifer Symposium.
Wilcox, B. P. 2002. Shrub control and streamflow on rangelands: A process-based viewpoint. *J. Range Mgmt.* 55(4): 318-326.
Wilcox, B. P., W. Dugas, Jr., M. K. Owens, D. N. Ueckert, and C. A. Hart. 2005. *Shrub Control and Water Yield on Texas Rangelands: Current State of Knowledge.* College Station, Tex.: Texas Agricultural Experiment Station.
Woodruff, C. M., Jr., William M. Marsh, L. P. Wilding, and Society of Independent Professional Earth Scientists (U.S.), Central Texas Chapter. 1993. Soil, landforms, hydrologic processes and land-use issues: Glen Rose limestone terrains, Barton Creek watershed, Travis County, Texas. Field report and guidebook, Rev. ed. Austin, Tex.: Society of Independent Professional Earth Scientists, Central Texas Chapter.
Wright, H. A., F. M. Churchill, and W. C. Stevens. 1976. Effect of prescribed burning on sediment, water yield, and water quality from dozed juniper lands in central Texas. *J. Range Mgmt.* 29(4): 294-298.
Wright, H. A., F. M. Churchill, and W. C. Stevens. 1982. Soil loss, runoff, and water-quality of seeded and unseeded steep watersheds following prescribed burning. *J. Range Mgmt.* 35(3): 382-385.
Wu, X. B., E. J. Redeker, and T. L. Thurow. 2001. Vegetation and water yield dynamics in an Edwards Plateau watershed. *J. Range Mgmt.* 54(2): 98-105.