THE USE OF LARGE PLOT RAINFALL SIMULATION TO INVESTIGATE RUNOFF GENERATION ON THE EDWARDS PLATEAU, TEXAS

A Thesis

by

JOSHUA RUSSELL SORENSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Rangeland Ecology and Management

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Approved as to style and content by:

Bradford P. Wilcox
(Chair of Committee)

Clyde L. Munster
(Member)

M. Keith Owens
(Member)

Steven G. Whisenant
(Head of Department)

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ABSTRACT

The Use of Large Plot Rainfall Simulation to Investigate Runoff Generation on the Edwards Plateau,
Texas. (December 2004)

Joshua Russell Sorenson, B.S., University of Wyoming

Chair of Advisory Committee: Dr. Bradford P. Wilcox

In this study, large scale rainfall simulation was used to evaluate runoff generation from canopy and intercanopy areas within an ashe juniper woodland of the Edwards Plateau. One 3 x 12 m site was established beneath the canopy of mature ashe juniper trees and two sites were established in intercanopy areas. At the base of each plot a trench was constructed for capturing and monitoring shallow subsurface flow. Rainfall simulations on the juniper site produced little surface runoff even though rainfall intensity exceeded 145mm/hour on some occasions. A total of 82.6% of the water applied to the juniper dominated site was accounted for as shallow subsurface flow. The dynamic nature of shallow subsurface flow indicate this process is driven chiefly by macropore flow. On the intercanopy site, 12.67% of the water left the site as surface runoff and ≤3% left as shallow subsurface flow. Large root channels and conduits, which were not present on the intercanopy site, within the soil may promote shallow subsurface flow beneath the juniper canopy. This study is the first to document and suggest shallow subsurface flow occurs on Texas rangelands. The results of this experiment indicate shallow subsurface flow is an important mode of runoff generation on the Edwards Plateau.

ACKNOWLEDGEMENTS

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I wish to thank Dr. Charles Taylor and the staff of the Texas Agricultural Experiment Station at Sonora for providing accommodations for field crews and equipment to conduct this project. Additional thanks must go to the people within the Biological and Agricultural Department at Texas A&M University for designing and helping to set up the rainfall simulator used to conduct the research studies. Shane Porter of the Biological and Agricultural Department was a great help when it came to running the rainfall simulations. I also thank Andrew Weichert for the time he spent away from home assisting me with this project.

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INTRODUCTION

Rangelands, by virtue of their extensive nature, can be important source areas for streamflow and aquifer recharge (Hibbert, 1979). Relatively few studies have explicitly investigated how runoff is generated from rangelands, especially in comparison with more humid landscapes. A complicating issue is that there has been significant vegetation change on many of these rangelands. Grasslands and savannas are converting into woodlands in a process described as woody plant encroachment (Van Auken, 2000). The extent to which this change has affected the hydrology, especially at the landscape level is one of some debate (Wilcox *et al.,* 2003; Huxman *et al.,* 2005). Much of the vegetation change is characterized as shrub encroachment on lands once dominated by grasses (Richardson *et al.,* 1979; Abrahams *et al.,* 1995; Parsons *et al.,* 1996; Schlesinger *et al.,* 1999; Van Auken, 2000; Wu *et al.,* 2001; Wilcox, 2002; Howes and Abrahams, 2003). Shrub encroachment potentially alters the hydrology of rangelands, especially at smaller scales (Hibbert, 1979, 1983; Carlson *et al.,* 1990; Dugas and Mayeux, 1991; Smeins *et al.,* 1994; Thurow and Carlson, 1994; Dugas *et al.,* 1998; Thurow *et al.,* 2000; Wu *et al.,* 2001; Wilcox, 2002), but how and to what extent is poorly understood (Wilcox, 2002). An increase in woody plants may result in higher evapotranspiration simply because of the increased transpiration capacity of woody plants in comparison to herbaceous ones (Hester et al., 1997; Hicks and Dugas, 1998). A key aspect to understanding how woody plants may affect the hydrology is to understand the fundamentals of runoff generation from these landscapes. How is runoff generated and are there differences in water budgets at the plot scale between canopy and intercanopy sites of rangelands? These questions were investigated using large plot rainfall simulations on the Edwards Plateau, Texas.

Aquifers such as the Edwards Aquifer provide 68% of the municipal and agricultural water used annually in Texas (Thurow and Carlson, 1994). Due to concerns pertaining to future water supplies and availability, the processes governing runoff generation in semiarid regions have received increased attention. Runoff is an important mechanism in semiarid landscapes yet is poorly understood because

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This thesis follows the style and format of *Hydrological Processess.*

relatively few detailed studies have been carried out in such areas (Wilcox *et al.,* 1997). For many rangelands, overland flow is the dominant mechanism for runoff generation. This is especially true for the more semiarid regions (Wilcox *et al.,* 1997; Newman *et al.,* 1998; Agnese *et al.,* 2001; Lange *et al.,* 2003; Wilcox *et al.,* 2003). Overland flow occurs via infiltration excess flow (Horton overland flow) or saturation excess flow (Agnese *et al.,* 2001). Horton overland flow is considered the dominant process associated with surface runoff in rangelands (Hibbert, 1983; Parsons *et al.,* 1996; Wilcox *et al.,* 1997; Agnese *et al.,* 2001). Horton overland flow occurs when rainfall intensity exceeds soil infiltration rate. Once precipitation intensity exceeds the infiltration rate of soils, the water moves along discreet surface pathways and rills (Beven, 2002).

Another, but less common mechanism of runoff generation in semiarid landscapes is that of lateral or shallow subsurface flow (Newman *et al.,* 1998). This process has been documented in humid and forested regions (Lane *et al.,* 2004), but is not considered an important hydrologic process in most semiarid landscapes (Wilcox *et al.,* 1997; Newman *et al.,* 1998). Shallow subsurface flow has been investigated in a New Mexico semiarid ponderosa pine forest and may be an important mechanism in runoff generation for other semiarid settings (Wilcox *et al.,* 1997; Newman *et al.,* 1998; Newman *et al.,* 2004). The dynamic nature of shallow subsurface flow indicates macropore flow along root channels drives this process (Wilcox *et al.,* 1997; Newman *et al.,* 1998, 2004; Lane *et al.,* 2004).

The Edwards Plateau of southwest Texas, which in part is located within the recharge area of the prolific and regionally important Edwards Aquifer, has seen an increase in the interest in processes pertaining to runoff generation and water infiltration. Like many areas of the American southwest, shrub encroachment has affected much of this area since European settlement (Smeins *et al.,* 1976; Blackburn, 1983; Schott and Pieper, 1985; Rasmussen and Wright, 1989; Owens, 1996; Hester *et al.,* 1997; Dugas *et al.,* 1998; Thurow *et al.,* 2000). It has been suggested but not definitively demonstrated that reducing the woody plant cover would result in substantial increases in streamflow and groundwater recharge. Runoff on the Edwards Plateau occurs when the amount of water at the soil surface exceeds the infiltration rate of the soils (Thurow and Carlson, 1994; Wilcox, 2002). As in other semiarid rangelands, Horton overland flow is considered the primary mechanism driving runoff generation following a precipitation event on the Edwards Plateau (Thurow and Carlson, 1994).

Infiltration characteristics within semiarid landscapes are modified by the amount and kind of vegetation (Knight *et al.,* 1984; Thurow *et al.,* 1988; Wilcox *et al.,* 1988). Infiltration is greater beneath shrub canopies than in adjacent intercanopy areas of shrub woodlands (Knight *et al.,* 1984; Thurow *et al.,* 1986; Thurow *et al.,* 1988; Hester, 1996; Hester *et al.,* 1997; Wilcox, 2002). Shrubs, in general, enhance soil infiltration capacity through a number of mechanisms including the input of leaf litter, capture of aolean sediments, and forming root channels that serve as conduits for the rapid movement of water into the soil (Wilcox, 2002). Small plot rainfall simulation studies indicate that surface runoff is generated from the intercanopy spaces of Texas shrublands, not beneath the shrub canopy (Thurow and Carlson, 1994). In addition, the presence of woody plants may alter the distribution of precipitation. Stemflow, for example, is one method by which shrubs redistribute precipitation (Martinez-Meza and Whitford, 1996; Owens and Lyons, 2004). Large volumes of water are rapidly concentrated at the base of shrubs by stemflow (Martinez-Meza and Whitford, 1996). The stemflow water infiltrates into the soil and follows preferential flow paths along shrub roots to deep soil layers. This water may then be available to the shrubs during times of drought, allowing them to remain viable (Martinez-Meza and Whitford, 1996; Owens and Lyons, 2004). Concurrent with the above changes under tree canopies, there are often significant intercanopy changes, which are predominately the reduction of intercanopy herbaceous cover due to increased competition for water from woody plants.

The increase in shrubs at the expense of native grasses on the Edwards Plateau may alter the hydrology of this semiarid environment (Carlson *et al.,* 1990; Dugas and Mayeux, 1991; Smeins *et al.,* 1994; Thurow and Carlson, 1994; Dugas *et al.,* 1998; Thurow *et al.,* 2000; Wu *et al.,* 2001; Wilcox, 2002). Some have suggested that woody plant encroachment may result in a decrease in water yield from selected rangelands (Thurow and Carlson, 1994; Owens, 1996; Hester *et al.,* 1997; Thurow *et al.,* 2000; Wilcox, 2002). Shrubs have the potential to modify the hydrology of semiarid rangelands via interception, redistribution of precipitation, increased evapotranspiration rates, and alteration of soil infiltration rates.

As yet, however, there have been no documented increases in streamflow or aquifer recharge as a result of brush control in Texas (Wilcox, 2002).

Ashe juniper (*Juniperus ashei* Buccholz) is one of the principal woody species that has encroached upon Texas rangelands (Owens and Schliesing, 1995). Ashe juniper woodlands encompass more than 8 million hectares of Texas rangelands (Ueckert *et al.,* 1994) and 4 million hectares of the Edwards Plateau. Ashe juniper, like other shrubs, potentially affects the hydrology of rangelands via increased rates of evapotranspiration (Owens, 1996) and redistribution of rainfall through processes of interception, stemflow, and throughfall (Hester, 1996). Juniper have the potential to use large amounts of water due to extensive roots, canopy cover, and size (Smeins *et al.,* 1994). Evapotranspiration studies in Texas indicate an individual juniper tree uses up to 125 l of water per day (Owens, 1996). One study concluded juniper shrubs prevent 375,000-935,000 l of water/ha/year from being utilized by herbaceous vegetation or contributing to aquifer recharge (Owens, 1996). A three year study analyzing interception of precipitation by juniper trees concluded 40% of ambient precipitation was intercepted and lost to evaporation (Owens and Lyons, 2004).

STUDY AREA

The study site is located on the Edwards Plateau of southwest Texas. The Edwards Plateau is approximately 60,000 km^2 (Taylor and Smeins, 1994) and in part is located within the recharge area of the Edwards Aquifer. The Edwards Plateau is second only to the Trans-Pecos region in length and frequency of drought in Texas (Knight *et al.,* 1984). The study site is located on the grounds of the Sonora Station of the Texas Agricultural Experiment Station (TAES), 56 km south of Sonora, Texas (31°N; 100°W). The landscape of the Sonora Station is rolling stony hill topography typical of the Edwards Plateau. Soils on the site are Tarrant stony clays and Tarrant silty clays of the Lithic Haplustolls family. There are large amounts of limestone fragments, stones, and gravel, underlain by a hard substratum that is fractured and porous (McGinty *et al.,* 1979; Richardson *et al.,* 1979). The substratum, commonly called caliche, is found in soils throughout much of the arid and semiarid southwestern United States (Hennessy *et al.,* 1983).

The growing season associated with the Sonora Station is 240 days. Dominant woody vegetation on the station consists of ashe juniper (*Juniperus ashei* Buccholz) and live oak (*Quercus virginiana* Mill.), both of which have significant litter layers beneath the canopy. The dominant herbaceous vegetation consists of curly mesquite (*Hiliaria belangeri* (Steud.) Nash), sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.), threeawn (*Aristida* spp.), and Texas wintergrass (*Stipa leucotricha* Trin. and Rupr.).

Most of the precipitation results from intense, convective storms of short duration. The mean average precipitation recorded at the station is 550 mm/year; however, this varies greatly from year to year. Records from 1918-1984 have annual precipitation ranges from 156-1054 mm (Thurow *et al.,* 1987).

METHODS

Runoff generation on semiarid rangelands is often the result of high intensity, convective storms of short duration (Parsons *et al.,* 1996; Wilcox *et al.,* 2003), which complicates the study of hydrologic processes. Due to the infrequent nature of such events, rainfall simulation has been used to investigate the hydrology of semiarid regions (Wilcox *et al.,* 1997). Rainfall simulations allow for a wide array of studies to be conducted by varying frequency, intensity, and duration of simulations. Rainfall simulators, unlike natural precipitation events, have the ability to create controlled, reproducible rainfall events. This study utilized rainfall simulation to investigate hillslope runoff generation and specifically evaluate differences between canopy and intercanopy areas.

The rainfall simulator used to investigate runoff processes is a portable unit that can be deployed in a variety of settings. The simulator consists of 6 masts, each with 4 sprinklers mounted on top. The sprinklers are S300 Pivot Spinners, manufactured by Nelson Irrigation Corporation based in Walla Walla, WA. Each sprinkler has a valve to help control the application rate during simulations. To effectively apply water over a study site the masts are arranged around the outside border of the study site. The masts are aluminum telescoping masts that can be adjusted from 4.5 to 10.6 m above the ground. The height adjustment capabilities of this simulator allow rainfall simulations to be conducted above the canopy of most Texas rangelands. Layflat hose supplies water to the sprinklers from a holding tank. Rainfall intensity is varied by limiting the number of sprinklers on each mast putting out water, and by adjusting the pressure of the Honda WP30X pump pushing water through the simulator.

Fourteen rainfall simulation experiments were conducted (Table I). During April of 2003, four separate simulations were conducted over the juniper dominated plot (Site 1). The first simulation was a trial run testing the functionality of the rainfall simulator and recording equipment. The second simulation was a high intensity, short duration storm on wet soils. The third simulation was a low intensity, long duration storm and the fourth simulation was a high intensity, short duration storm with wet soils. In May and June 2003, two simulations were conducted each month. The first simulation was a high intensity,

Table I. Sequence of rainfall simulations, intensities, and durations on juniper and intercanopy study sites at the Sonora Station

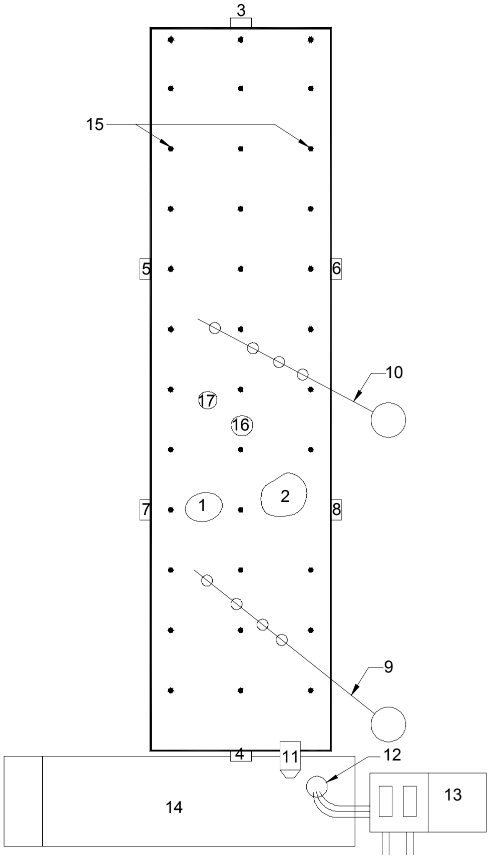
Site	Date	Duration	Total input (mm)	Intensity (mm/hr)
1	4/10/2003	27 min.	37	82.2
1	4/10/2003	41 min.	100.5	147.1
1	4/11/2003	420 min.	229.9	32.8
1	4/12/2003	89 min.	162.5	109.6
1	5/21/2003	42 min.	110.5	157.9
1	5/21/2003	281 min.	177.5	37.9
1	6/2/2003	39 min.	87.3	134
1	6/3/2003	421 min.	243.7	34.7
2	4/22/2004	15 min.	38.9	155.6
2	4/22/2004	85 min.	68.3	48.2
2	4/22/2004	35 min.	55.8	95.7
3	4/22/2004	15 min.	22	88
3	4/22/2004	85 min.	54.2	38.3
3	4/22/2004	35 min.	36.7	62.9

short duration storm on dry soils. The second simulation was a low intensity, long duration storm on wet soils.

In April 2004, a final set of simulations were conducted on two adjacent plots in intercanopy areas, with the right plot being designated as Site 2 and the left plot as Site 3. Simulations were conducted simultaneously on these two sites. This set of simulations consisted of three rainfall events. The first simulation was a high intensity, short duration storm on dry soils. The second simulation was a low intensity, long duration storm, and the third simulation was another high intensity, short duration storm on wet soils.

Juniper Site Layout

The experimental plot established on an ashe juniper dominated hillslope (Site 1) is 3 m wide and 12 m long (Figure 1). The plot is bordered by sheet metal driven 8-10 cm into the soil and sticks 15 cm above the soil surface. A trench has been installed at the base of Site 1, perpendicular to the hillslope, to capture any shallow subsurface flow resulting from rainfall simulations. Prior to experiments conducted in May 2003, the trench was expanded to the current dimensions of 5.2 m long, 1.5 m wide, and



1. Stem of tree 1: stem collar attached
2. Stem of tree 2: stem collar attached
3. Tower 1
4. Tower 4
5. Tower 2
6. Tower 6
7. Tower 3
8. Tower 5
9. Throughfall collector 1
10. Throughfall collector 2
11. H-Flume
12. Interflow sump
13. Interflow tipping buckets
14. Trench- 5.2 m long, 1.5 m wide, 1.5 m deep
15. Grid of rain gauges- spaced 1 m apart
16. Stem of tree 3
17. Stem of tree 4

Figure 1. Schematic of layout and equipment for a juniper dominated site at the Sonora Station

1.5 m deep. A sump was dug within the trench and three 12VDC 1000 gallon per hour (gph) bilge pumps connected to 1 liter tipping buckets were installed to record shallow subsurface flow. Prior to simulations in June, plastic was placed around the outside border of the plot to prevent water landing outside the plot from contributing to shallow subsurface flow.

A CR10X recorded the surface runoff, shallow subsurface flow, throughfall, stemflow, and soil moisture data. The observation interval was 10 seconds and there was a 60 second recording interval.

A 6-inch H-flume was placed at the base of Site 1 to capture and record surface runoff. A float and potentiometer was installed within the stilling well of the H-flume to quantify the amount and rate of surface runoff.

The two largest juniper trees rooted within the plot were fitted with stemflow collars as described by Owens and Lyon (2004). These collars diverted water to 1 liter tipping buckets quantifying intercepted precipitation directed to the base of the trees by the canopy through stemflow.

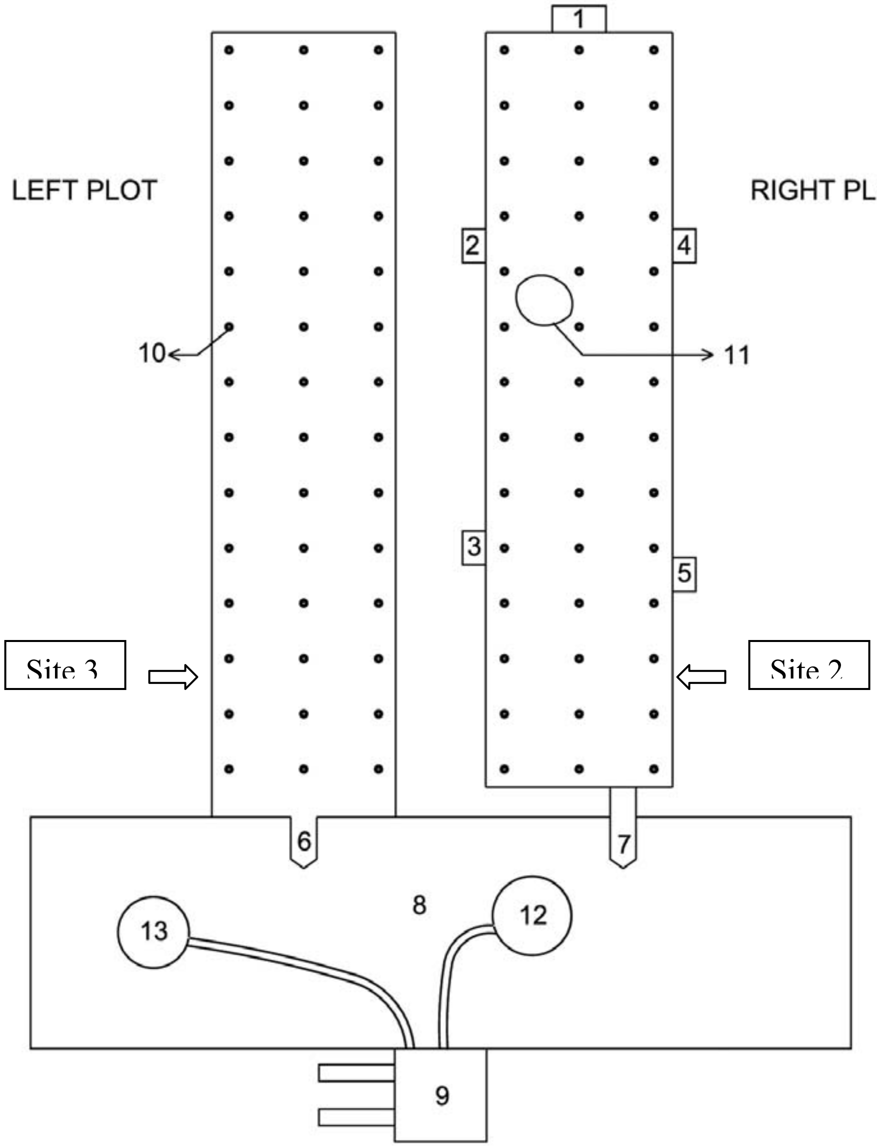
Throughfall data was collected via two methods, one which recorded the rate of throughfall and one which recorded spatial distribution of throughfall. To record the rate and amount of throughfall a system of four 8-inch diameter funnels were placed in two locations beneath the shrub canopy. The funnels collected throughfall precipitation and diverted it to reservoirs with floats connected to potentiometers that recorded throughfall water. Further information regarding this collection system is described by Owens and Lyons (2004). To determine the spatial pattern of throughfall, rain gauges were distributed on a regular pattern throughout the plot. Each meter up the length of the plot rain gauges were placed along the left and right edges of the study site and another was placed in the center of the plot. These rain gauges measured spatial variability and depth of applied moisture. Total input of water to the study plot was calculated by averaging the moisture in the rain gauges and adding stemflow to the average rain gauge value.

To measure changes in soil moisture during rainfall simulations, Echo 10 Probes, manufactured by Decagon Devices, Inc. were used. These dielectric probes measure volumetric water content of soils. Five Echo 10 Probes were placed randomly within the study plot.

Woody vegetation within Site 1 was estimated by measuring the distance from a central point beneath a shrub or cluster of shrubs to the edge of the shrub canopy and taking a compass reading of the measurement. The distance to canopy edge and corresponding compass readings were plotted on graph paper allowing us to estimate percent canopy cover over the study plot. Aerial cover of herbaceous vegetation was estimated beneath the canopy using a .5 m square frame and taking visual readings of aerial vegetation cover. One reading was taken on the on the left side, one in the center, and one on the right side of the site each meter up the length of the plot.

Intercanopy Site Layout

The intercanopy plots (Sites 2 and 3) were established adjacent to each other with the masts of the rainfall simulator placed around Site 2 (Figure 2). Site 3 (left plot) is 13 m long and 3.05 m wide. Site 2 is 12.5 m long and 3.1 m wide. The plots are bordered by sheet metal driven approximately 8-10 cm into the soil and extending 15 cm above the soil surface. Rain gauges were distributed on a regular pattern as described for Site 1 in both intercanopy sites to measure the depth of rainfall for each simulation. One, 6-inch H-flume was installed at the base of each site to quantify surface runoff. Floats connected to potentiometers were installed within the stilling wells of each flume to record the rate and amount of surface runoff. A trench 12 m long, 3.4 m wide, and 1 m deep was dug perpendicular to the slope of the hill at the base of the intercanopy plots. Sumps with 1000 gph bilge pumps hooked to 1 liter tipping buckets were placed within the trench to capture and quantify shallow subsurface flow. Echo 10 volumetric soil moisture probes were placed randomly within the study plots to monitor and record changes in soil moisture. A CR10X recorded surface runoff, shallow subsurface flow, and soil moisture data. The observation interval for these recordings was set at 10 seconds and the recording interval was set at 60 seconds. Data was collected simultaneously from both plots during rainfall simulations. Woody vegetation was estimated by measuring the circumference of the shrub canopy. Herbaceous vegetation was measured using the same method used to estimate herbaceous vegetation in Site 1. The layout of both intercanopy sites is shown in Figure 2.



1. Tower 1
2. Tower 2
3. Tower 3
4. Tower 4
5. Tower 5
6. Flume for Site 3
7. Flume for Site 2
8. Trench: 12 m long, 3.4 m wide, 1m deep
9. Shallow subsurface flow tipping buckets
10. Grid of rain gauges spaced 1 m apart
11. Stem of juniper shrub
12. Sump for Site 2
13. Sump for Site 3

Figure 2. Schematic of layout and equipment for intercanopy sites within a juniper community at the Sonora Station

RESULTS

Canopy Plot

Ashe juniper, with 85% canopy cover, is the dominant vegetation within Site 1. A litter layer, 7-13 cm deep, covers the soil surface throughout the entire area of Site 1. The herbaceous aerial cover of this plot was 19%, consisting mainly of Texas wintergrass and interspersed threeawn.

Surface runoff was generated during rainfall simulations in April 2003, over the juniper dominated study plot (Site 1). Three high intensity, short duration rainfall simulations were conducted in addition to one low intensity, long duration simulation. The first rainfall simulation occurred on dry soils while all the rest of the simulations occurred on wet soils. Rainfall intensity varied from 82-147 mm/hr for the high intensity storms. Surface runoff accounted for 5.2-6.9% of the water applied during these simulations (Table II). Surface runoff comprised less than 1% of the water applied to the plot during the low intensity, long duration rainfall simulation with wet soils. The low intensity, long duration rainfall simulation had a rainfall intensity of 33 mm/hr.

Shallow subsurface flow was generated in all simulations conducted over the juniper dominated site in April 2003. Less than 1% of the water applied to the plot during the first simulation, with dry soils, could be accounted for as shallow subsurface flow. Subsequent simulations on wet soils had much greater proportions of water being accounted for as shallow subsurface flow. Between 17-85% of the water applied to the study site during the last three simulations left the site as shallow subsurface flow. Shallow subsurface began 25-40 minutes after the start of rainfall simulations and flowed for hours following the simulations. Most of the shallow subsurface flow was noted to come from roots sticking out of the trench at the base of the plot. As seen in Figure 3 and Table II, shallow subsurface flow is the greatest mode of runoff generated from this site.

The rainfall simulations in April 2003, occurred before the trench was enlarged to the dimensions described previously in Figure 1. The trench was enlarged prior to conducting rainfall simulations in May 2003.

Table II. Partition of water budget for rainfall simulations over a juniper dominated site at the Sonora Station in April 2003

	mm	Liters	Percent	Time
April 2003: Run 1				
high intensity, short duration storm on dry soils				
Manual throughfall	34.15	1229.54		
Throughfall 1	17.03			
Throughfall 2	40.75			
Stemflow	2.85	166.00		
Total input[a]	37.00	1395.54	100.00	27 min.
Shallow subsurface flow	0.03	1.10	0.08	
Surface runoff	2.29	82.40	6.19	
April 2003: Run 2				
high intensity, short duration storm on wet soils				
Manual throughfall	94.63	3406.60		
Throughfall 1	4.48			
Throughfall 2	113.38			
Stemflow	5.91	344.00		
Total input[a]	100.54	3750.60	100.00	41 min.
Shallow subsurface flow	17.14	617.00	17.05	
Surface runoff	5.22	187.80	5.19	
April 2003: Run 3				
low intensity, long duration storm on wet soils				
Manual throughfall	199.44	7179.00		
Throughfall 1	10.38			
Throughfall 2	419.76			
Stemflow	30.45	1774.00		
Total input[a]	229.89	8953.00	100.00	420 min.
Shallow subsurface flow	194.53	7003.00	84.62	
Surface runoff	0.02	0.80	0.01	
April 2003: Run 4				
high intensity, short duration storm on wet soils				
Manual throughfall	152.75	5499.00		
Throughfall 1	8.16			
Throughfall 2	30.65			
Stemflow	9.73	567.00		
Total input[a]	162.48	6066.00	100.00	89 min.
Shallow subsurface flow	119.08	4287.00	73.29	
Surface runoff	11.30	406.50	6.95	

[a] Total input is equal to the summation of manual throughfall and stemflow for each rainfall simulation.

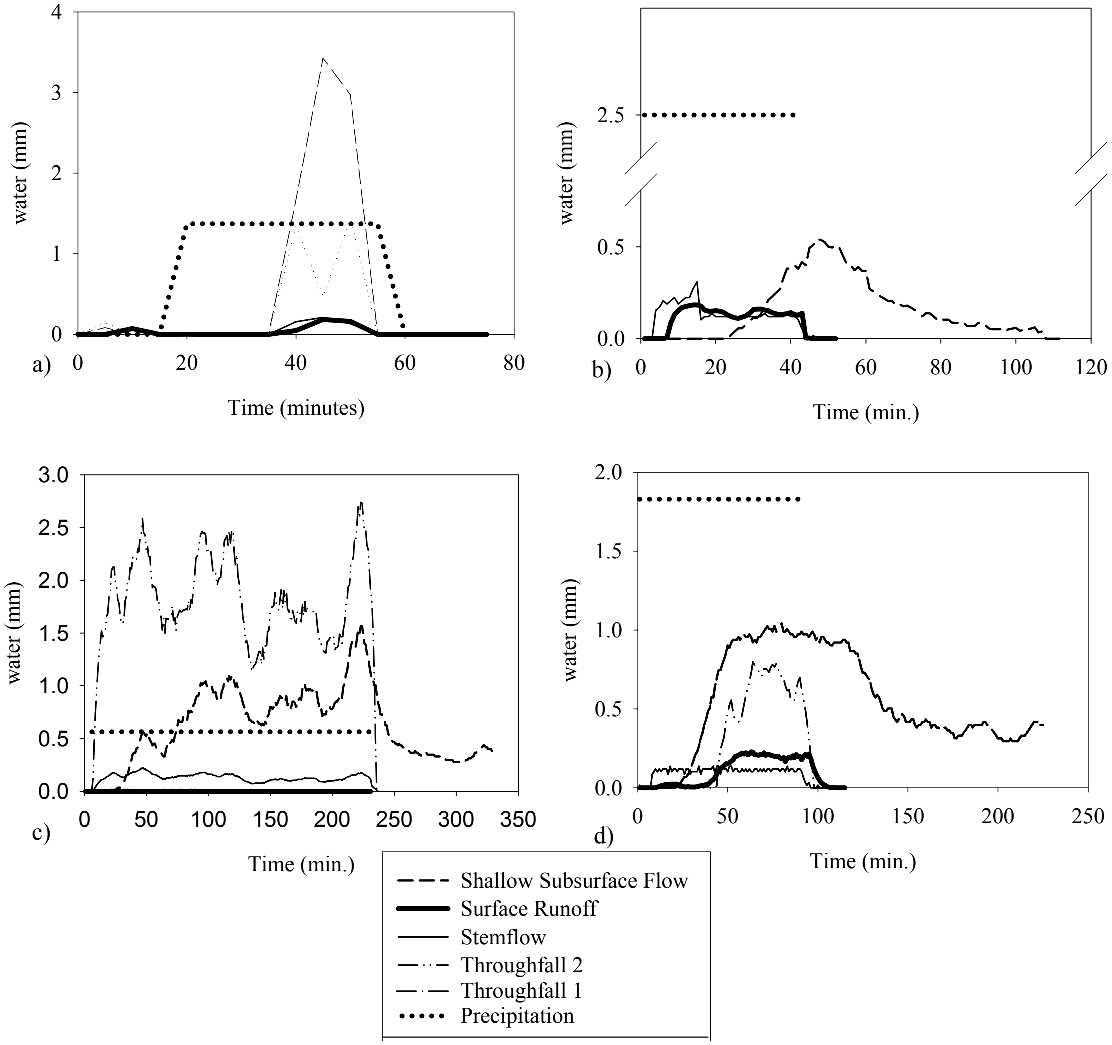


Figure 3. Hydrographs displaying the partition and flux of water for rainfall simulations on a juniper dominated site at the Sonora Station in April 2003 (a) high intensity (1.4 mm/min), short duration storm on dry soils, (b) high intensity (2.5 mm/min), short duration storm on wet soils, (c) low intensity (0.55 mm/min), long duration storm on wet soils and (d) high intensity (1.83 mm/min), short duration storm on wet soils

In May and June 2003, very little surface runoff was generated during the rainfall simulations over the juniper dominated study plot (Site 1), even for the very high rainfall intensities (Table III). Rainfall intensity for the May and June simulations ranged from 34.7-157.9 mm/hr. Of the 110.5 mm of precipitation applied to this plot during the high intensity, short duration simulation on dry soils in May 2003, only 0.91 mm could be accounted for as surface runoff. Of the 177.45 mm applied during the long duration, low intensity simulation on wet soils in May 2003, 0.02 mm of moisture was accounted for as surface runoff. Similar results were recorded for the rainfall simulations in June 2003, with respect to surface runoff (Table III).

Lateral or shallow subsurface flow was generated in all simulations conducted on the juniper dominated site. Shallow subsurface flow began 25-40 minutes after the start of rainfall simulations and flowed for hours following the simulations. For the high intensity, short storm with dry soils in May, shallow subsurface flow accounted for 25.8 mm of the 110.5 mm of water applied or 23.3% of the total rainfall. For the low intensity, long duration storm with wet soils the amount of shallow subsurface flow exceeded the amount of precipitation applied. Results from simulations in June are similar to the results obtained from the May simulations. Most of the shallow subsurface flow was noted to come from roots sticking out of the trench dug at the base of the study plot. As seen in Figure 4 and Table III, shallow subsurface flow is the greatest mode of runoff generated from this site.

Stemflow was an important percentage of water applied to the study plot during rainfall simulations. Of total precipitation applied to this plot across all simulations, 10.8% of the moisture was intercepted by the juniper canopy and diverted to the base of the shrub via stemflow. Stemflow would begin three to four minutes into simulations and would reach peak intensity within 10 minutes as shown in Figure 3. The average peak intensity of stemflow was calculated to be .2 mm/min. throughout rainfall simulations regardless of simulated rainfall intensity.

Table III. Partitioning of water budget for rainfall simulations in May and June 2003, over a juniper dominated site at the Sonora Station

	mm	Liters	Percent	Time
May 2003: Run 1				
high intensity, short duration storm on dry soils				
Manual throughfall	98.13	3532.70		
Throughfall 1	55.35			
Throughfall 2	76.96			
Stemflow	12.38	721.00		
Total input[a]	110.51	4253.70	100	42 min.
Shallow subsurface flow	25.80	924.00	23.35	
Surface runoff	0.91	27.92	0.82	
May 2003: Run 2				
low intensity, long duration storm on wet soils				
Manual throughfall	161.25	5805.00		
Throughfall 1	6.55			
Throughfall 2	8.10			
Stemflow	16.20	1686.00		
Total input[a]	177.45	7491.00	100.00	281 min.
Shallow subsurface flow	215.70	7763.00	121.56	
Surface runoff	0.02	0.63	0.01	
June 2003: Run 1				
high intensity, short duration storm on dry soils				
Manual throughfall	79.61	2866.00		
Throughfall 1	39.43			
Throughfall 2	117.10			
Stemflow	7.73	450.00		
Total input[a]	87.34	3316.00	100.00	39 min.
Shallow subsurface flow	27.78	983.00	31.81	
Surface runoff	2.54	91.60	2.91	
June 2003: Run 2				
low intensity, long duration storm on wet soils				
Manual throughfall	204.55	7363.80		
Throughfall 1	164.30			
Throughfall 2	168.30			
Stemflow	39.12	2279.00		
Total input[a]	243.67	9642.80	100.00	421 min.
Shallow subsurface flow	359.00	12926.00	147.33	
Surface runoff	0.13	4.80	0.05	

[a] Total input is equal to the summation of manual throughfall and stemflow for each rainfall simulation.

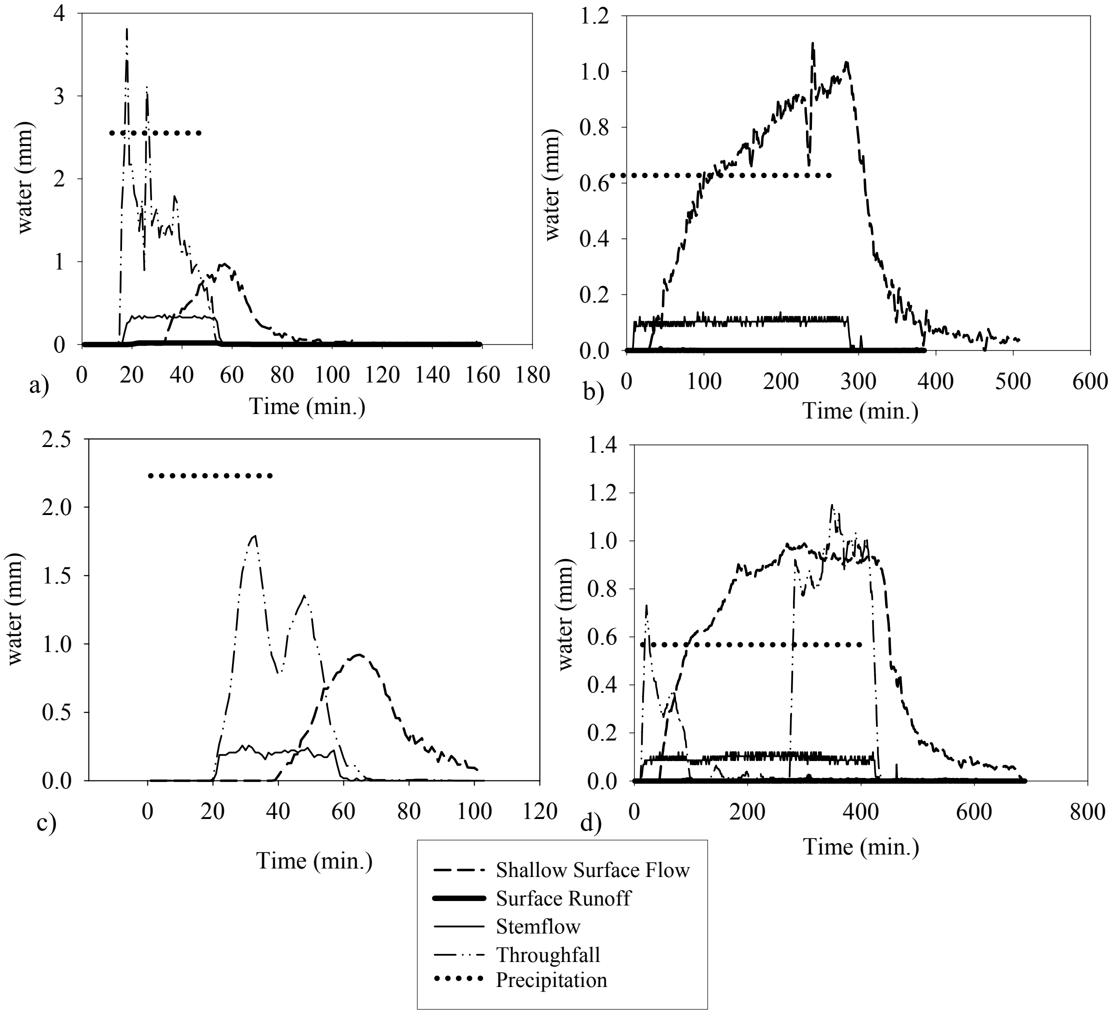


Figure 4. Hydrographs displaying partition and flux of water for rainfall simulations on a juniper dominated site at the Sonora Station in (a) May 2003, high intensity (2.6 mm/min), short duration storm on dry soil, (b) May 2003, low intensity (0.63 mm/min), long duration storm on wet soils, (c) June 2003, high intensity (2.23 mm/min), short duration storm on dry soils and (d) June 2003, low intensity (0.58 mm/min), long duration storm on wet soils

Data from the volumetric soil moisture probes indicate there was wetting throughout the entire plot, however the wetting front was not uniform despite the quantity of water applied. The responses of the soil moisture probes indicate the soils did not reach saturation during the simulations. Soil moisture content decreased almost immediately following completion of rainfall simulations. Appendix A contains the figures illustrating the responses of the Echo 10 probes to changes in soil moisture resulting from rainfall simulations. Appendix B describes how much water was potentially held by the soils following rainfall simulations. Theses values were calculated based upon the readings of the Echo 10 probes.

Table IV is a summation of all water applied to a juniper dominated site during the months of April, May, and June of 2003. Stemflow accounts for 10.8% of total water input. Shallow subsurface flow on this juniper dominated site comprises 82.6% of the water applied.

Table IV. Summation of all water applied to a juniper dominated site at the Sonora Station

	mm	Percent
Manual throughfall	1024.51	
Throughfall 1	305.68	
Throughfall 2	978.00	
Stemflow	124.37	
Total input	1148.88	100.00
Shallow subsurface flow	949.06	82.60
Surface runoff	22.43	2.00

Intercanopy Plots

One small juniper shrub, with 27% canopy cover, is rooted 5 m from the top of Site 2. Herbaceous vegetation was quantified in the same manner as for Site 1. Site 2 had 14% and Site 3 had 18% aerial cover by herbaceous vegetation. Litter was a very small component of cover on these sites.

Surface runoff was generated within five minutes of the start of simulations conducted on the intercanopy sites. Within five minutes of shutting off the rainfall simulator, surface runoff stopped. Surface runoff varied between 6.4-18.8% of precipitation applied to Site 2 for all the rainfall simulations. Surface runoff was much greater for the high intensity simulations than for the low intensity simulation. The first simulation lasted 15 minutes and 38.8 mm of moisture was applied to dry soils. The intensity of this simulation was 155.6 mm/hr. Surface runoff accounted for 5.8 mm of precipitation or 14.9% of the total moisture applied to Site 2 during the first simulation. No shallow subsurface runoff was generated during the initial simulation on this plot. Surface runoff comprised 6.4% of total precipitation applied to the plot during Run 2, which simulated a low intensity, long duration rainfall event on wet soils. Shallow subsurface flow was generated during this simulation and accounted for only 0.76% of the rainfall applied to the plot. Data obtained from the high intensity, third simulation on wet soils generated both surface runoff and shallow subsurface flow. Of the 55.8 mm of moisture put onto the plot, 10.5 mm (18.8%) was recorded as surface runoff and 4.97 mm (8.9%) was recorded as shallow subsurface flow.

The water budgets for these simulations have been partitioned and are displayed in Table V. The hydrographs for the simulations on Site 2 are displayed in Figure 5. Data was collected simultaneously on Sites 2 and 3, however, the data from Site 3 have been omitted as a result of a lack of confidence in recorded values. The stilling well, housing the float and potentiometer in the flume of Site 3 was not constructed with the appropriate dimensions and data obtained from the data logger did not correlate with hand measurements taken during the simulations.

The data from the volumetric soil moisture probe readings are similar to those obtained from the canopy plot. Soil moisture content increased as a result of rainfall simulations, but the wetting front was uneven with probes recording different soil moisture content levels. Soil moisture content would decrease shortly after the completion of rainfall simulations. Appendix A contains the figures illustrating the responses of the Echo 10 probes to changes in soil moisture resulting from rainfall simulations.

Table VI is a summation of the water budget for the simulations conducted on an intercanopy site in April of 2004. The greatest mode of runoff generation on this site is surface runoff at 12.67% of total water input. Shallow subsurface flow accounted for ≤3% of all the water applied to this site.

Table V. Partitioning of water budget for rainfall simulations on an intercanopy plot within a juniper community at the Sonora Station

	mm	Liters	Percent	Time
April 2004: Run 1				
high intensity, short duration storm on dry soils				
Total input	38.86	1457.25	100.00	15 min.
Shallow subsurface flow	0.00	0.00	0.00	
Surface runoff	5.80	224.70	14.93	
April 2004: Run 2				
low intensity, long duration storm on wet soils				
Total input	68.25	2559.40	100.00	85 min.
Shallow subsurface flow	0.52	40.00	0.76	
Surface runoff	4.35	168.58	6.37	
April 2004: Run 3				
high intensity, short duration storm on wet soils				
Total input	55.80	2092.50	100.00	35 min.
Shallow subsurface flow	4.97	379.00	8.91	
Surface runoff	10.50	407.80	18.82	

Table VI. Summation of all water applied to an intercanopy site within a juniper community at the Sonora Station

	mm	Percent
Total input	162.91	100.00
Shallow subsurface flow	5.49	3.00
Surface runoff	20.65	12.67

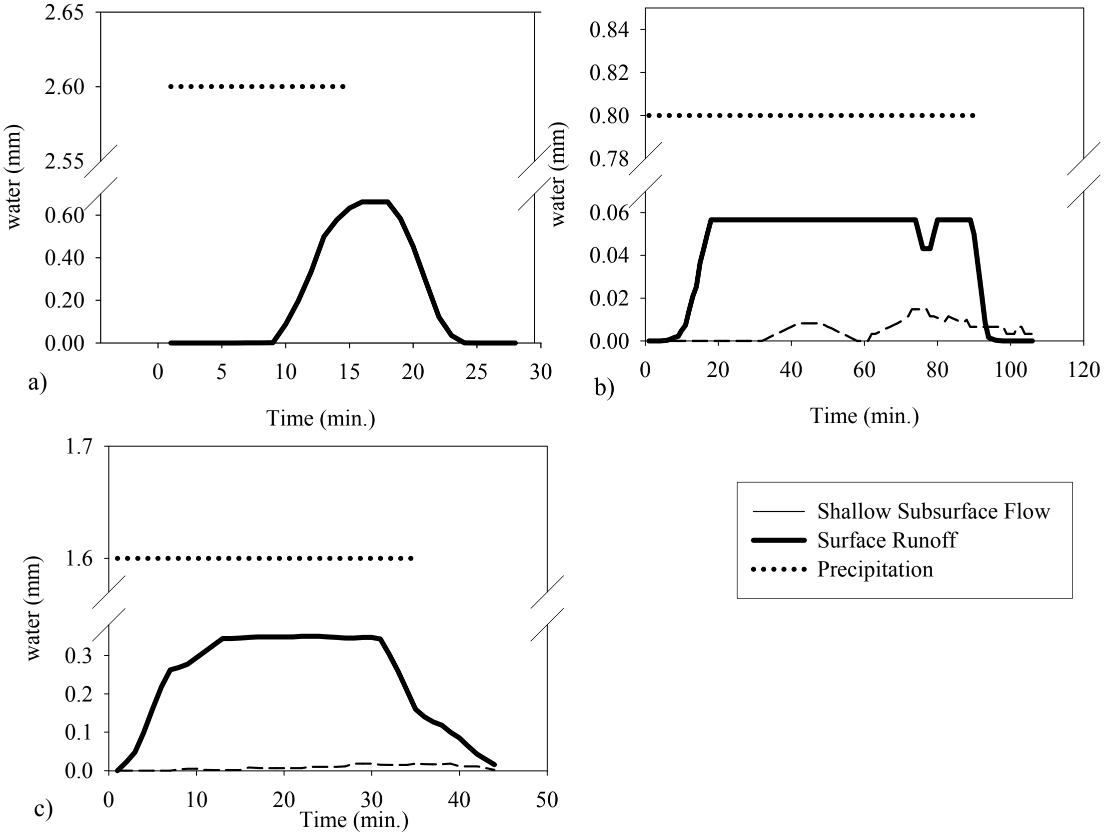


Figure 5. Hydrographs displaying partition and flux of water from rainfall simulations on an intercanopy site within a juniper community at the Sonora Station for (a) high intensity (2.6 mm/min), short duration storm with dry soils, (b) low intensity (0.8 mm/min), long duration storm on wet soils and (c) high intensity (1.6 mm/min), short duration storm with wet soils

DISCUSSION

Results obtained from the large plot rainfall simulations indicate areas occupied by juniper have greater infiltration rates than intercanopy plots. These results are consistent with earlier small plot infiltration studies (Knight *et al.,* 1984; Hester *et al.,* 1997). The presence of shrubs increases infiltration rates beneath the canopy and prevents surface runoff. As a result little surface runoff was generated from the shrub dominated plot. Most of water applied to the plot could be accounted for as shallow subsurface flow. Although shallow subsurface flow has not been considered an important hydrologic process in semiarid regions (Newman *et al.,* 1998), we found that 82.6% of the total rainfall applied to the juniper dominated site was moved off-site by shallow subsurface flow. These sites apparently have little ability to store water. In other words, excess water is shunted off the slope very quickly.

Of all the water applied to the juniper dominated site only 2% left the site as surface runoff. Most of the water that left the juniper dominated site as surface runoff was accounted for during rainfall simulations that occurred in April 2003. These simulations were conducted prior to expanding the size of the trench used to capture and quantify shallow subsurface flow. After the trench was enlarged there was a significant reduction in the amount of surface runoff as can be seen in Tables II and III. Surface runoff values from high intensity, short duration rainfall simulations in April have surface runoff values nearing 7% of the total input of water. High intensity, short durations storms in May and June have surface runoff values reaching a peak of 3% of the total water applied to the plot. These data indicate enlarging the trench at the base of the study plot inadvertently altered the hydrology of the plot. It should be noted shallow subsurface flow was still the dominate mechanism of runoff generation from this site regardless of the size of the trench and the impact the trench had on the hydrology of the site.

This study is the first to document shallow subsurface flow occurring in a Texas semiarid landscape. As noted in studies from other areas, shallow subsurface flow is driven primarily by macropore flow (Wilcox *et al.,* 1997; Newman *et al.,* 1998, 2004; Lane *et al.,* 2004). Most of the shallow subsurface flow generated from these rainfall simulations occurred along root channels. The significant amount of shallow subsurface flow along the root channels point to macropore flow as the driving factor governing shallow subsurface flow. The patchy wetting front of the soils as indicated by the Echo 10 probes point to preferential movement of water along localized subsurface pathways. As seen in Figure 6, the dynamic and responsive nature of shallow subsurface flow in relation to the intensity of throughfall supports the idea of macropore flow dominating shallow subsurface flow. As the intensity of throughfall varies during the simulation the response of shallow subsurface flow mimics that of throughfall. The correlation coefficient between shallow subsurface flow and throughfall is 0.46. Shallow subsurface flow accounts for a very substantial amount of the water applied to the juniper plot. It was by far the greatest mode of runoff generation from these experiments. The vast majority of shallow subsurface flow occurred along

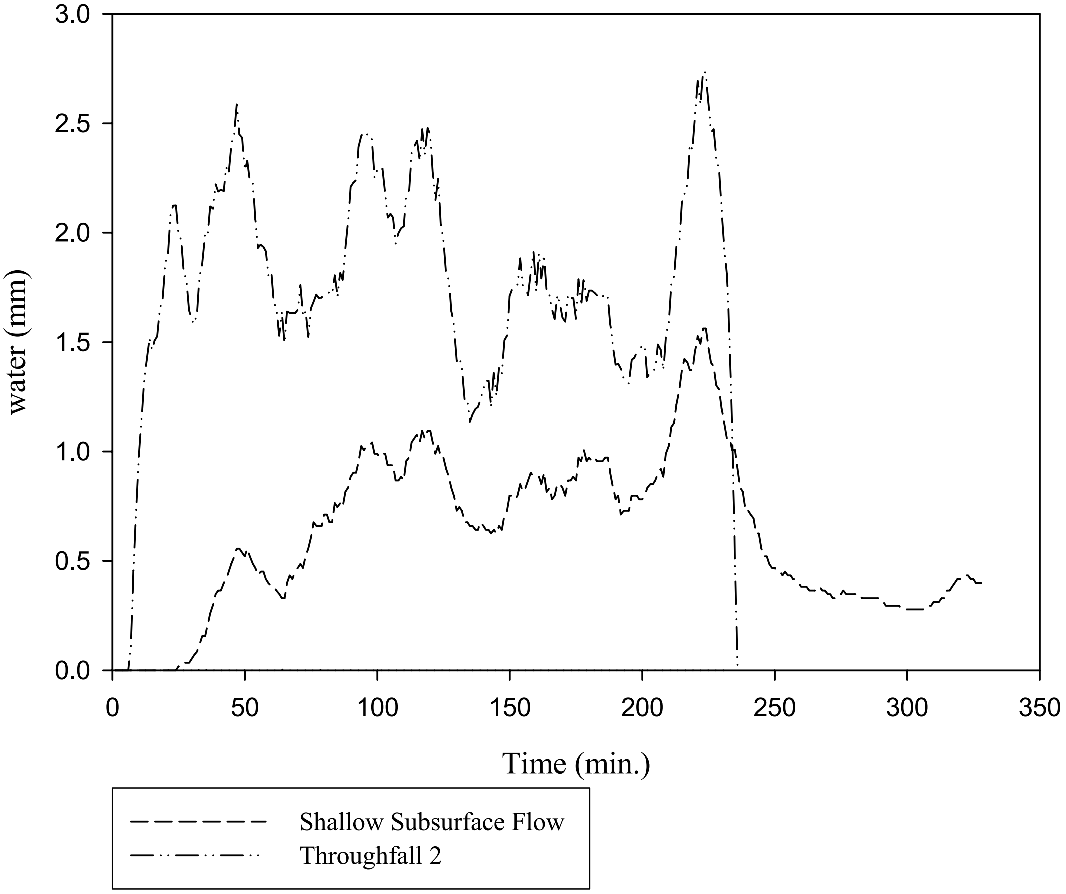


Figure 6. Illustration showing dynamic nature of shallow subsurface flow in response to throughfall on a juniper dominated site during the third simulation in April 2003, at the Sonora Station

root channels, cracks, and conduits within the soil.

We believe that most of the shallow subsurface flow observed in the trench originated within the plot boundary. Prior to simulations in June, plastic was placed around the border of the study plot to prevent water landing outside of the plot from contributing to shallow subsurface flow. If water landing outside the study plot contributed to shallow subsurface flow a decrease would have been noted when comparing June simulations to previous ones. No such decrease was observed.

The importance of stemflow has been highlighted during this experiment. The physical presence of woody species results in redistribution of water from precipitation events on rangelands (Owens and Lyons, 2004). Some intercepted water flows down the stem of the shrub or tree and is directed into the soil at the base of the shrub or tree. Once this water has infiltrated into the soil it probably flows along roots paths and contributes to runoff generation in the form of shallow subsurface flow.

Shallow subsurface flow is generated in the intercanopy spaces of shrublands as well, but to a much smaller extent. There is a significant decrease in the amount of shallow subsurface flow occurring from the intercanopy plots when compared to the canopy plot. However, as the soil becomes wetter the amount of shallow subsurface flow increases. As seen in the water budgets shown in Tables III and IV, shallow subsurface flow increases as more moisture is applied. By the third simulation, shallow subsurface flow accounted for 8.9% of total water applied to the right intercanopy plot. Shallow subsurface flow was noted to occur mainly along root channels protruding from the trench below Site 2. When compared to the juniper dominated site the intercanopy sites had very few large roots. The lack of large roots may explain the decreased level of subsurface flow recorded on Site 2.

As in other studies, surface runoff (Horton overland flow) appears to be the dominant mechanism pertaining to runoff generation from intercanopy areas of semiarid brushlands (Thurow and Carlson, 1994; Parsons *et al.,* 1996; Schlesinger *et al.,* 1999; Wilcox *et al.,* 2003). The data from these simulations indicate surface runoff comprises the greatest proportion of runoff occurring from these plots. Surface runoff would begin within minutes of the start of each simulation, indicating that Horton overland flow, not soil saturation overland flow, is the primary mechanism by which runoff occurs on the intercanopy plots. The lower the rainfall intensity, the less surface runoff generated. During the high intensity simulations, surface runoff accounted for 14.9-18.8% of total precipitation. For the low intensity rainfall simulation, 6.4% of the water could be accounted for as surface runoff. The physical presence of shrubs appears to be a determining factor in the processes involved with runoff generation on semiarid landscapes. Increased infiltration rates, stemflow, root channels, and other conduits appear to contribute the most to the generation of shallow subsurface flow. The intercanopy plots, which were for the most part devoid of large root channels and conduits, generate more runoff by Horton overland flow.

CONCLUSION

Results from this study concur with previous research indicating surface runoff is generated from the intercanopy spaces of semiarid shrublands. A large portion of shrublands are canopy covered. Experiments indicate the areas beneath shrub canopies prevent surface runoff and increase infiltration rates. This project is the first to suggest the areas beneath shrubs not only increase infiltration rates and direct water to deep soil storage but contribute to runoff generation. Runoff is generated as shallow subsurface flow beneath the shrub canopies. There is very little literature supporting this mechanism of runoff generation in semiarid regions. Most water flows beneath the soil surface, and our ability to monitor and quantify shallow subsurface flow processes are limited (Beven, 2002). Many perceive runoff on semiarid regions as being driven by Horton overland flow and have not considered other mechanisms of runoff generation (Beven, 2002). Water that infiltrates into the soil is assumed to eventually evaporate or transpire back into the atmosphere (Beven, 2002). Similar to surface runoff, shallow subsurface flow can contribute to streamflow and aquifer recharge. Of all the water applied to Site 1 during rainfall simulations 82.6% could be accounted for as shallow subsurface flow. Shallow subsurface flow comprised 3% of the moisture applied to Site 2. Additional evidence of shallow subsurface flow serving as a mechanism of runoff generation is the presence of soil pipes and pipe erosion in semiarid rangelands (Beven, 2002). This study focused on several plots with a limited number of rainfall simulations however, the results indicate shallow subsurface flow occurs and contributes to runoff generation processes in semiarid landscapes.

REFERENCES

Abrahams AD, Parsons AJ, Wainwright J. 1995. Effects of vegetation on interrill runoff and erosion, Walnut Gulch, southern Arizona. *Geomorphology* **13**: 37-48.

Agnese A, Baiamonte G, Corrao C. 2001. A simple model of hillslope response for overland flow generation. *Hydrological Processes* **15**: 3225-3238.

Beven K. 2002. Runoff generation in semi-arid areas. In *Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels*, Bull LJ, Kirkby MJ (eds). John Wiley and Sons: West Sussex, England; 57-105.

Blackburn WH. 1983. Influence of brush control on hydrologic characteristics of range watersheds, p. 73-88, Brush Management Symposium, Soc. For Range Management Meeting, Albuquerque, N.M.

Carlson DH, Thurow TL, Knight RW, Heitschmidt RK. 1990. Effect of honey mesquite on the water balance of Texas rolling plains rangeland. *Journal of Range Management* **43**: 491-496.

Dugas WA, Hicks RA, Wright P. 1998. Effect of Removal of *Juniperus ashei* on evapotraspiration and runoff in the Seco Creek Watershed. *Water Resources Research* **34**: 1499-1506.

Dugas WA, Mayeux, HS, Jr. 1991. Evaporation from rangeland with and without honey mesquite. *Journal of Range Management* **44**: 161-170.

Hennessy JT, Gibbens RP, Tromble JM, Cardenas M. 1983. Water properties of caliche. *Journal of Range Management* **36**: 723-726.

Hester JW. 1996. Influence of woody dominated rangelands on site hydrology and herbaceous production, Edwards Plateau, Texas. M.Sc. thesis, Department of Rangeland Ecology and Management, Texas A&M Univ., College Station.

Hester JW, Thurow TL, Taylor CA, Jr. 1997. Hydrologic characteristics of vegetation types as affected by prescribed burning. *Journal of Range Management* **50**: 199-204.

Hibbert AR. 1979. *Managing vegetation to increase flow in the Colorado River Basin. USDA, Forest Service*, General Tech. Report RM-66.

Hibbert AR. 1983. Water yield improvement potential by vegetation management on western rangelands. *Geomorphology* **53**: 45-73.

Hicks RA, Dugas WA. 1998. Estimating ashe juniper leaf area from tree and stem characteristics. *Journal of Range Management* **51**: 633-637.

Howes DA, Abrahams AD. 2003. Modeling runoff and runon in a desert shrubland ecosystem, Jornada Basin, New Mexico. *WaterResources Research* **33**: 2301-2314.

Huxman TE, Wilcox BP, Breshears DD, Scott RL Snyder KA, Small EE, Hultine K, Pockman WT, Jackson RB. 2005. Ecohydrological implications of woody plant encroachment. Accepted In *Ecology.*

Knight RW, Blackburn WH, Merrill LB. 1984. Characteristics of oak mottes, Edwards Plateau, Texas. *Journal of Range Management* **37**: 534-537.

Lane PNJ, Croke JC, Dignan P. 2004. Runoff generation from logged and burnt convergent hillslopes: rainfall simulation and modelling. *Hydrological Processes* **18**: 879-892

Lange J, Greenbaum N, Husary S, Ghanem M, Leibundgut C, Schick AP. 2003. Runoff generation from successive simulated rainfalls on a rocky, semi-arid, Mediterranean hillslope. *Hydrological Processes* **17**: 276-296.

Martinez-Meza E, Whitford WG. 1996. Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. *Journal of Arid Environements* **32**: 271-287.

McGinty WA, Smeins FE, Merrill LB. 1979. Influence of soil, vegetation, and grazing management on infiltration rate and sediment production of Edwards Plateau rangeland. *Journal of Range Management* **32**: 33-37.

Newman BD, Campbell AR, Wilcox BP. 1998. Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope. *Water Resources Research* **34**: 3485-3496.

Newman BD, Wilcox BP, Graham RC. 2004. Snowmelt driven macropore flow and soil saturation in a semiarid forest. *Hydrological Processes* **18**: 1035-1042.

Owens MK. 1996. The role of leaf and canopy-level gas exchange in the replacement of *Quercus virginiana* (Fagaceae) by *Juniperus ashei* (Cupressaceae) in semiarid savannas. *Am. Journal of Botany* **83**: 617-623.

Owens MK, Lyons RK. 2004. *Evaporation and interception water loss from juniper communities on the Edwards Aquifer recharge area*. Texas Agricultural Experiment Station.

Owens MK, Schliesing TG. 1995. Invasive potential of ashe juniper after mechanical disturbance. *Journal of Range Management* **48**: 503-507.

Parsons AJ, Abrahams AD, Wainwright J. 1996. Responses of interrill runoff and erosion rates to vegetation change in southern Arizona. *Geomorphology* **14**: 311-317.

Rasmussen GA, Wright HA. 1989. Succession of secondary shrubs on ashe juniper communities after dozing and prescribed burning. *Journal of Range Management* **42**: 295-298.

Richardson CW, Burnett E, Bovey RW. 1979. Hydrologic effects of brush control on Texas rangelands. *Transactions of the ASAE* **22**: 315-319.

Schlesinger WH, Abrahams AD, Parsons AJ, Wainwright J. 1999. Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: I. rainfall simulation experiments. *Biogeochemistry* **45**: 21-34.

Schott MR, Pieper RD. 1985. Influence of canopy characteristics of one-seed juniper on understory grasses. *Journal of Range Management* **38**: 328-331.

Smeins FE, Owens MK, Fuhlendorf SD. 1994. Biology and Ecology of Ashe (Blueberry) Juniper. In *Texas A&M Juniper Symposium Proceedings*, April 14, 1994, San Angelo, TX; 9-24.

Smeins FE, Taylor TW, Merrill LB. 1976. Vegetation of a 25-year exclosure on the Edwards Plateau, Texas. *Journal of Range Management* **29**: 24-29.

Taylor CA, Jr., Smeins FE. 1994. A history of land use of the Edwards Plateau and its effect on the native vegetation. In *Texas A&M Juniper Symposium Proceedings*, April 14, 1994, San Angelo, TX; 1-8.

Thurow TL, Blackburn WH, Taylor CA, Jr. 1986. Hydrologic characteristics of vegetation types as affected by livestock grazing systems, Edwards Plateau, Texas. *Journal of Range Management* **39**: 505-509.

Thurow TL, Blackburn WH, Taylor CA, Jr. 1988. Infiltration and interrill erosion responses to selected livestock grazing strategies, Edwards Plateau, Texas. *Journal of Range Management* **41**: 296-302.

Thurow TL, Blackburn WH, Warren SD, Taylor CA, Jr. 1987. Rainfall interception by midgrass, shortgrass, and live oak mottes. *Journal of Range Management* **40**: 455-460.

Thurow TL, Carlson DH. 1994. Juniper effects of rangeland watersheds. In *Texas A&M Juniper Symposium Proceedings*, April 14, 1994, San Angelo, TX; 31-43.

Thurow TL, Thurow AP, Garriga MD. 2000. Policy prospects for brush control to increase off-site water yield. *Journal of Range Management* **53**: 23-31.

Ueckert DN, Whisenant SG, Owens MK. 1994. Juniper control and management. In *Texas A&M Juniper Symposium Proceedings*, April 14, 1994, San Angelo, TX; 61-68.

Van Auken OW. 2000. Shrub invasions of North American semiarid grasslands. *Ann. Rev. Ecol. Syst.* **31**:197-215.

Wilcox BP. 2002. Shrub control and streamflow on rangelands: a process based viewpoint. *Journal of Range Management* **55**: 318-326.

Wilcox BP, Breshears DD, Allen CD. 2003. Ecohydrology of a resource-conserving semiarid woodland: effects of scale and disturbance. *Ecological Monographs* **73**: 223-239.

Wilcox BP, Newman BD, Brandes D, Davenport DW, Reid K. 1997. Runoff from a semiarid ponderosa pine hillslope in New Mexico. *Water Resources Research* **33**: 2301-2314.

Wilcox BP, Wood MK, Tromble JM. 1988. Factors influencing infiltrability of semiarid mountain slopes. *Journal of Range Management* **41**: 197-206.

Wu XB, Redeker EJ, Thurow TL. 2001. Vegetation and water yield dynamics in an Edwards Plateau watershed. *Journal of Range Management* **54**: 98-105.

APPENDIX A

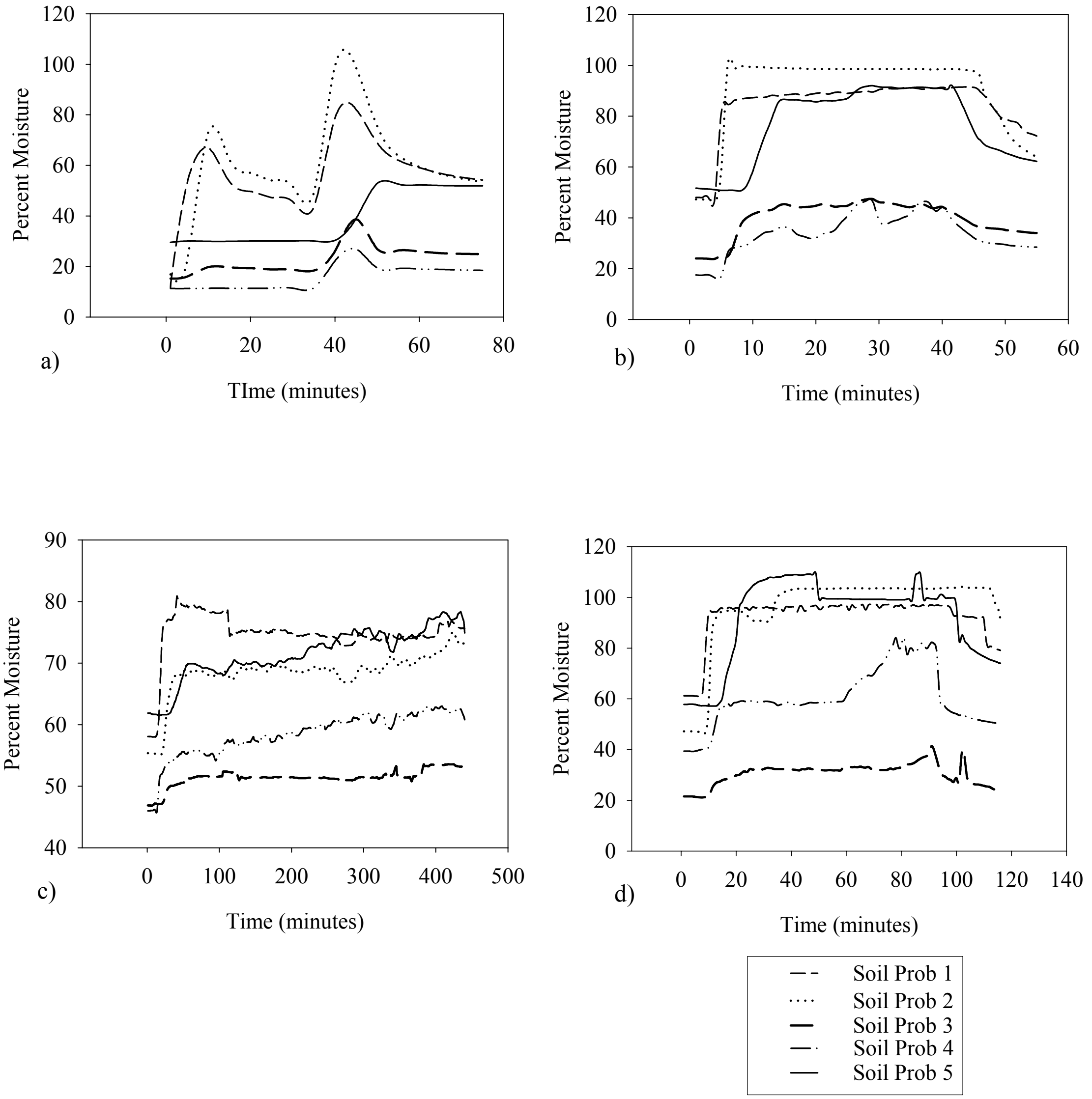


Figure A1. Response of Echo 10 soil moisture probes to simulated rainfall events on a juniper dominated plot at the Sonora Station in April 2003 for (a) high intensity, short duration storm on dry soils, (b) high intensity, short duration storm on wet soils, (c) low intensity, long duration storm on wet soils and (d) high intensity, short duration storm on wet soils

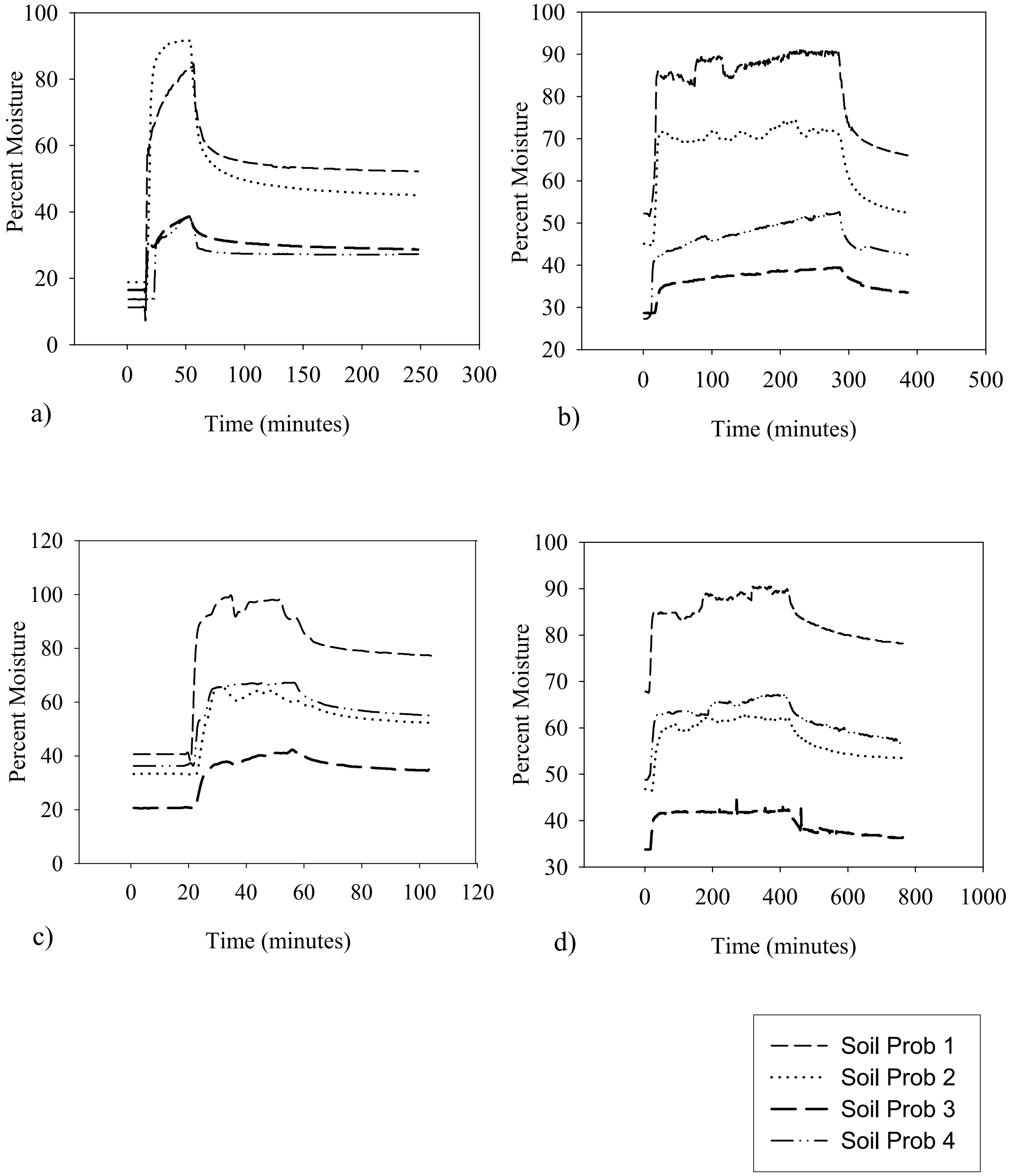


Figure A2. Response of Echo 10 soil moisture probes to simulated rainfall events on a juniper dominated plot at the Sonora Station in (a) May 2003, for high intensity, short duration storm on dry soils, (b) May 2003, for low intensity, long duration storm on wet soils, (c) June 2003, for high intensity, short duration storm on dry soils and (d) June 2003, for low intensity, long duration storm on wet soils

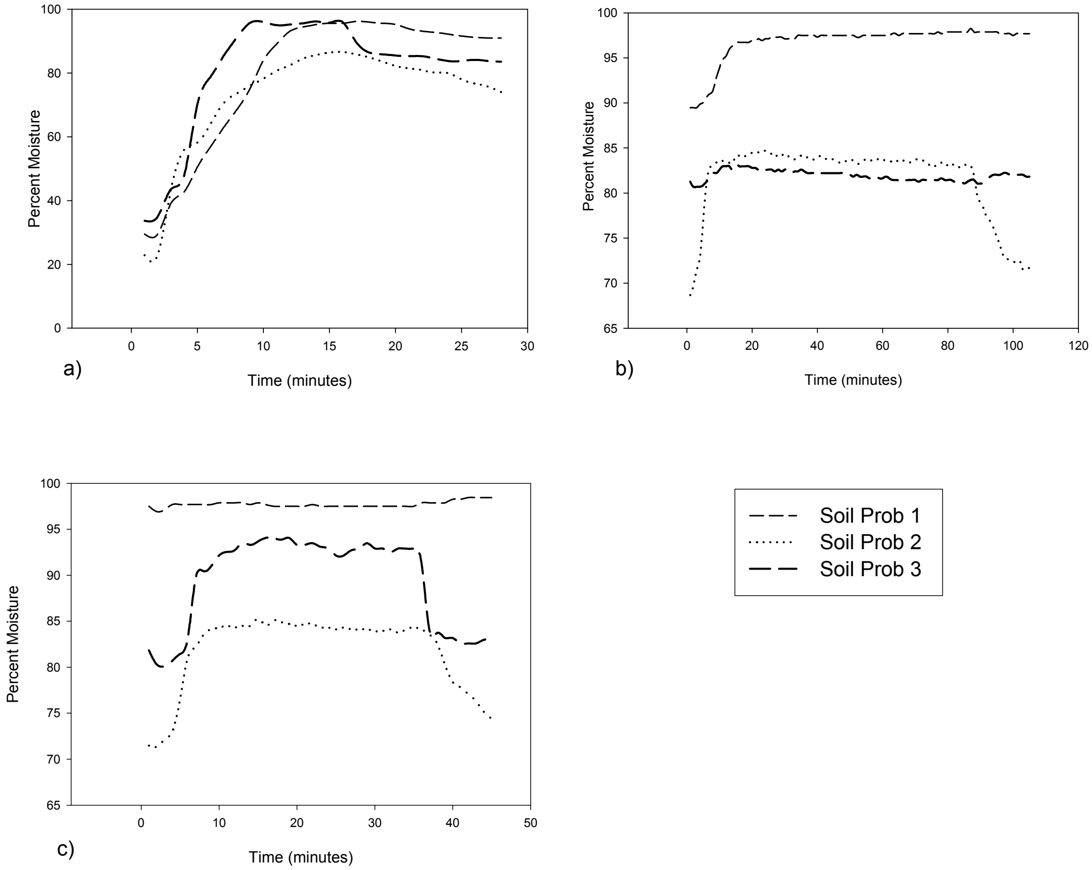


Figure A3. Response of Echo 10 soil moisture probes to simulated rainfall events on an intercanopy plot within a juniper community at the Sonora Station for (a) high intensity, short duration storm on dry soils, (b) low intensity, long duration storm on wet soils and (c) high intensity, short duration storm on wet soils

APPENDIX B

Table B1. Partition of water budget and soil moisture content for rainfall simulations over a juniper dominated site at the Sonora Station in April 2003

	mm	Liters	Percent	Time
April 2003: Run 1				
high intensity, short duration storm on dry soils				
Manual throughfall	34.15	1229.54		
Throughfall 1	17.03			
Throughfall 2	40.75			
Stemflow	2.85	166.00		
Total input[a]	37.00	1395.54	100.00	27 min.
Shallow subsurface flow	0.03	1.10	0.08	
Surface runoff	2.29	82.40	6.19	
Soil moisture content	18.5		50	
April 2003: Run 2				
high intensity, short duration storm on wet soils				
Manual throughfall	94.63	3406.60		
Throughfall 1	4.48			
Throughfall 2	113.38			
Stemflow	5.91	344.00		
Total input[a]	100.54	3750.60	100.00	41 min.
Shallow subsurface flow	17.14	617.00	17.05	
Surface runoff	5.22	187.80	5.19	
Soil moisture content	12.1		12	
April 2003: Run 3				
low intensity, long duration storm on wet soils				
Manual throughfall	199.44	7179.00		
Throughfall 1	10.38			
Throughfall 2	419.76			
Stemflow	30.45	1774.00		
Total input[a]	229.89	8953.00	100.00	420 min.
Shallow subsurface flow	194.53	7003.00	84.62	
Surface runoff	0.02	0.80	0.01	
Soil moisture content	11.3		5	
April 2003: Run 4				
high intensity, short duration storm on wet soils				
Manual throughfall	152.75	5499.00		
Throughfall 1	8.16			
Throughfall 2	30.65			
Stemflow	9.73	567.00		
Total input[a]	162.48	6066.00	100.00	89 min.
Shallow subsurface flow	119.08	4287.00	73.29	
Surface runoff	11.30	406.50	6.95	
Soil moisture content	14.5		8.9	

Table B2. Partition of water budget and soil moisture content for rainfall simulations over a juniper dominated site at the Sonora Station

	mm	Liters	Percent	Time
May 2003: Run 1				
high intensity, short duration storm on dry soils				
Manual throughfall	98.13	3532.70		
Throughfall 1	55.35			
Throughfall 2	76.96			
Stemflow	12.38	721.00		
Total input[a]	110.51	4253.70	100	42 min.
Shallow subsurface flow	25.80	924.00	23.35	
Surface runoff	0.91	27.92	0.82	
Soil moisture content	18.5		16.7	
May 2003: Run 2				
low intensity, long duration storm on wet soils				
Manual throughfall	161.25	5805.00		
Throughfall 1	6.55			
Throughfall 2	8.10			
Stemflow	16.20	1686.00		
Total input[a]	177.45	7491.00	100.00	281 min.
Shallow subsurface flow	215.70	7763.00	121.56	
Surface runoff	0.02	0.63	0.01	
Soil moisture content	8		4.5	
June 2003: Run 1				
high intensity, short duration storm on dry soils				
Manual throughfall	79.61	2866.00		
Throughfall 1	39.43			
Throughfall 2	117.10			
Stemflow	7.73	450.00		
Total input[a]	87.34	3316.00	100.00	39 min.
Shallow subsurface flow	27.78	983.00	31.81	
Surface runoff	2.54	91.60	2.91	
Soil moisture content	17.7		20	
June 2003: Run 2				
low intensity, long duration storm on wet soils				
Manual throughfall	204.55	7363.80		
Throughfall 1	164.30			
Throughfall 2	168.30			
Stemflow	39.12	2279.00		
Total input[a]	243.67	9642.80	100.00	421 min.
Shallow subsurface flow	359.00	12926.00	147.33	
Surface runoff	0.13	4.80	0.05	
Soil moisture content	4.8		2	

Table B3. Partition of water budget and soil moisture content for rainfall simulations over an intercanopy site at the Sonora Station

	mm	Liters	Percent	Time
April 2004: Run 1				
high intensity, short duration storm on dry soils				
Total input	38.86	1457.25	100.00	15 min.
Shallow subsurface flow	0.00	0.00	0.00	
Surface runoff	5.80	224.70	14.93	
Soil moisture content	43.5		112	
April 2004: Run 2				
low intensity, long duration storm on wet soils				
Total input	68.25	2559.40	100.00	85 min.
Shallow subsurface flow	0.52	40.00	0.76	
Surface runoff	4.35	168.58	6.37	
Soil moisture content	3.2		4.6	
April 2004: Run 3				
high intensity, short duration storm on wet soils				
Total input	55.80	2092.50	100.00	35 min.
Shallow subsurface flow	4.97	379.00	8.91	
Surface runoff	10.50	407.80	18.82	
Soil moisture content	0.8		1.4	

Tables B1-B3 contain estimations of the water holding capacity of the soils beneath the study sites following rainfall simulations. The values were obtained by taking into consideration the starting and ending average readings from the Echo 10 soil moisture probes, bulk density of the soil being 1.25 g/cm^3, particle density being 2.7 g/cm^3, depth of soil at 150 mm. These values were placed into Appendix B because the actual water holding capacity of the soils following rainfall simulations could not be verified.

Actual formula used is as follows

1-(Bulk density/particle density) x soil depth x percent change in soil moisture readings = mm water in soil

VITA

Joshua Russell Sorenson

Biographical:	Born in San Antonio, Texas, on December 16, 1978, the son of Richard and Carol Sorenson. Permanent address is 4241 Valley Green Circle, Riverton, Wyoming, 82501.
Education:	Graduated from Riverton High School, Riverton, Wyoming in 1997. Received Bachelor of Science in Molecular Biology at the University of Wyoming in 2002. Received Master of Science degree in Rangeland Ecology and Management at Texas A&M University in 2004.
Professional Experience:	Range Technician with the United States Forest Service on the Big Piney Ranger District of the Bridger-Teton National Forest for two seasons during 2001 and 2002. Wildland Firefighter with the Bridger-Teton Forest as part of tour of duty with the Forest Service.