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Subsurface stormflow is important in semiarid karst shrublands

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[1] In this paper we describe hillslope-scale, rainfall-simulation experiments on karst shrublands dominated by Ashe juniper. These simulations, designed to mimic flood-producing rainfall events, were carried out at two sites separated by 206 km within the Edwards Plateau of Central Texas. Five hillslope plots were instrumented—two shrub-covered (canopy) plots and three intercanopy plots measuring 12–14 m in length. We repeated the experiments on the canopy plots after removing the shrubs. For the canopy plots, both before and after shrub removal, 50% or more of the water applied exited the plots as subsurface stormflow and no overland flow occurred. For the intercanopy plots, subsurface stormflow amounted to less than 10% of the water applied and overland flow was between 10 and 50%. These experiments demonstrate the importance of subsurface stormflow in semiarid karst shrublands during flood events, and more generally highlight the fact that subsurface stormflow is important in some semiarid landscapes. **Citation:** Wilcox, B. P., P. I. Taucer, C. L. Munster, M. K. Owens, B. P. Mohanty, J. R. Sorenson, and R. Bazan (2008), Subsurface stormflow is important in semiarid karst shrublands, *Geophys. Res. Lett.*, *35*, L10403, doi:10.1029/2008GL033696.

1. Introduction

[2] Karst landscapes occupy 10–20 percent of the earth [*Palmer*, 1991]. Because extensive areas of carbonate and karst terrains exist within semiarid regions, understanding how runoff is generated within them is vital for understanding and managing water supply in these regions. To date, however, relatively little is known about runoff generation in these landscapes.

[3] In the United States, one of the largest contiguous stretches of karst is the Edwards Plateau region of central Texas. In spite of the relatively dry climate, this region boasts abundant groundwater, springs, and perennially flowing rivers—although as human population pressures increase, water is becoming more limited. At the same time, the Edwards Plateau region is prone to large flood events; it produces some of the largest unit-area flood flows in the United States [*O'Connor and Costa*, 2004].

[4] Over the past 150 or so years, the vegetation of the region has in large part undergone a conversion from grasslands to oak and juniper woodlands, a phenomenon known as *woody plant encroachment*.. This conversion is related primarily to the positive feedbacks of overgrazing and reduced fire frequency. The hydrologic implications of woody plant encroachment are not fully understood [*Huxman et al.*, 2005].

[5] The purpose of this study is to better understand runoff generation in karst hydrogeologic systems dominated by shrub vegetation and, in particular, to document the importance of subsurface stormflow. As summarized by *Weiler et al.* [2005], this type of flow "occurs when water moves laterally down a hillslope through soil layers or permeable bedrock to contribute to the storm hydrograph." Our methodology was to simulate rainfall on canopy and intercanopy hillslopes 12–14 m long, to determine (1) how runoff is generated in these landscapes; (2) whether runoff generation is affected by the removal of woody vegetation; and (3) whether there are significant differences between canopy and intercanopy areas.

2. Setting and Study Area

[6] The Edwards Plateau region in West Central Texas consists of around 100,000 km^2 in the southern part of the Great Plains province. The climate is semiarid to subhumid and exhibits a strong precipitation gradient. The region encompasses two major landforms: the Texas Hill Country and the Edwards Plateau proper. Both of these landforms are underlain by Cretaceous limestones and dolomites [*Woodruff and Wilding*, 2008]. Soils in the region typically have a dark, organic-matter-rich A horizon up to 30 cm thick. Depending on the weathering characteristics of the parent material, this horizon can lie (1) over partially weathered *in-situ* materials (caliche) or (2) directly on hard bedrock [*Wilcox et al.*, 2007].

[7] Our experiments in this region were carried out at two study sites (Figure 1): the Honey Creek Study Area on the east side, in the Texas Hill Country (29°50′N, 98°29′W); and the Sonora Research Station on the west side, on the Edwards Plateau itself (31°N, 100°W). Although separated by 206 km, the sites are similar in many respects. Precipitation at Honey Creek averages around 740 mm annually, higher than at Sonora, where average annual precipitation is around 550 mm. At both sites the dominant woody vegetation is Ashe juniper (*Juniperus ashei Buccholz*) and live oak (*Quercus virginiana Mill.*).

[8] Soils are similar in that they were derived from limestone parent materials and have dark, highly organic, and rocky A horizons. At Sonora, the A horizon is underlain by a weathered caliche (Bk) layer to a depth of about 1 m. At Honey Creek, the A horizon directly overlies indurated limestone. However, the soil stratigraphy under the canopy plot at Honey Creek is more complex: the A horizon is

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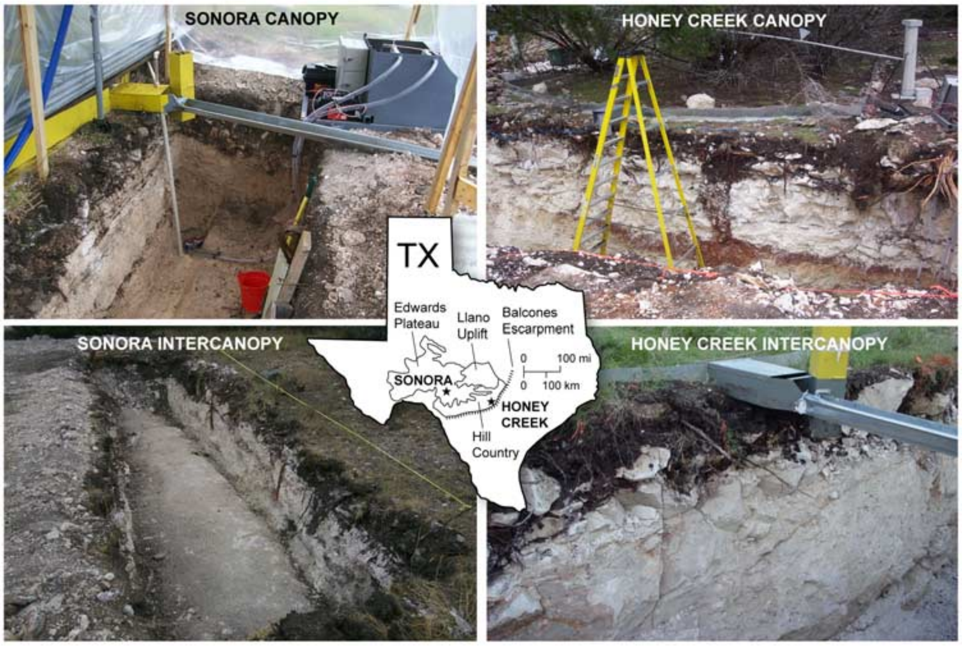

Figure 1. Location map and photographs of the trenches associated with each hillslope plot.

underlain by an R/A horizon composed of partially fractured limestone, some of the fractures being filled by A material; this layer is then underlain by a weathered Bk horizon.

3. Methods

[9] At each site, we conducted large-scale rainfall simulation experiments on hillslope plots representing mature Ashe juniper woodland conditions (canopy) and more open (intercanopy) conditions. The plots—two canopy (one at Honey Creek and one at Sonora) and three intercanopy (one at Honey Creek and two at Sonora)—each measured 12–14 m in length (see Figure 1). Trees in the canopy locations were 8–10 m in height. The intercanopy plots were composed mostly of grasses and forbs. To monitor subsurface stormflow, a trench was constructed at the base of each plot (Figure 1). Specifics for each of the plots, including plot and trench dimensions, are given in Table 1.

[10] The rainfall simulator (fully described in *Munster et al.*, 2006) consists of six telescoping masts having a maximum extension of 11 m. Each mast is topped with a manifold that feeds four sprinkler heads. The simulator applies water at rates ranging from 2.5 to 25 cm/hr. The median raindrop size varies slightly with application rate but is around 2 mm [*Munster et al.*, 2006]. Each simulation, designed to represent the relatively infrequent (but nevertheless very important) flood-producing rainfall, consisted of two or three runs of different intensities and durations. Since the intercanopy plots at Sonora were separated by only about 1 m, we were able to apply rainfall to these plots simultaneously.

[11] Each hillslope plot was instrumented for measuring throughfall, surface runoff, and subsurface stormflow during the rainfall simulation experiments. In addition, for the canopy plots we measured stemflow on selected trees, following the methodology of *Owens et al.* [2006]. Throughfall was measured by an array of 140-mm-capacity rain gauges arranged in a grid pattern (1-m intervals) within each plot. Surface runoff was continually monitored with a 15.25-cm H-flume.

[12] The trench bottoms, all of which were indurated limestone, were sloped to drain into a sump located at one or both ends. As subsurface stormflow collected in the sump, it was pumped to a tipping-bucket gauge array having a 1-L data resolution.

[13] For all the plots (except the canopy plot at Sonora), we installed plastic sheeting around the boundaries, allowing us to assume a subsurface contributing area equivalent to that of the surface area. For the Sonora canopy plot,

Table 1. Specifics for Each of the Hillslope Plots

	Honey Creek		Sonora		
	Canopy	Intercanopy	Canopy	Intercanopy Right	Intercanopy Left
Surface Area, m	7 × 14	7 × 14	3 × 12	3.1 × 12.5	3.05 × 13
Subsurface Area, m	7 × 14	7 × 14	5.2 × 12	3.1 × 12.5	3.05 × 13
Trench length, m	10	10	5.2	14	14
Trench depth, m	2.5	2.5	1.5	1	1
Woody Plant Cover, %	100	0	85	27	0
Herbaceous Cover, %	5	95	20	14	18

Table 2a. Honey Creek Canopy Plots: Rainfall and Runoff for the Simulation Experiments Before and After Tree Removal[a]

Date	Duration, min	Input, mm	Intensity, mm/min	SSSF, mm	SSSF, %
		Before Tree Removal			
12/5/2003	60	124	2.1	20	16
	60	83	1.4	31	37
Total	**120**	**207**		**51**	**25**
12/11/2003	45	75	1.7	12	16
	60	67	1.1	30	45
	60	12	0.2	31	258
Total	**165**	**154**		**73**	**47**
12/18/2003	45	68	1.5	17	25
	60	53	0.9	30	57
	60	12	0.2	19	158
Total	**165**	**133**		**66**	**50**
10/26/2004	60	64	1.1	20	31
	120	28	0.2	23	82
	45	53	1.2	40	75
Total	**225**	**145**		**83**	**57**
6/1/2005	60	48	0.8	4	8
	120	25	0.2	11	44
	45	54	1.2	37	69
Total	**225**	**127**		**52**	**41**
6/9/2005	60	53	0.9	23	43
	120	26	0.2	20	77
	45	53	1.2	50	94
Total	**225**	**132**		**93**	**70**
		After Tree Removal			
6/14/2005	60	67	1.1	16	24
	120	39	0.3	23	59
	45	66	1.5	43	65
Total	**225**	**172**		**82**	**48**
6/15/2005	60	65	1.1	12	18
	120	35	0.3	29	83
	45	69	1.5	27	39
Total	**225**	**169**		**68**	**40**
6/28/2005	60	63	1.1	24	38
	120	35	0.3	21	60
	45	63	1.4	23	37
Total	**225**	**161**		**68**	**42**

[a] Surface runoff is not included because little or none occurred. Input = water reaching the surface as throughfall; SSSF = subsurface stormflow.

plastic sheeting was installed only for the June 2003 set of simulations. For this plot, therefore, we assumed the contributing area to be equivalent to the length of the trench times the plot length (5 × 12 m).

[14] After completing the simulations on the canopy plots, we cut and removed the juniper and then carried out additional rainfall simulation experiments. At Honey Creek, the experiments took place the same year that the trees were removed. At Sonora, experiments were conducted one year and two years following tree removal. In all, 12 sets of experiments were done at Honey Creek and 8 sets at Sonora.

4. Results

4.1. Canopy Plots Before Tree Removal

[15] Before removal of the juniper, six sets of simulations were conducted on the canopy plot at Honey Creek and two at Sonora. The results were generally consistent both within and between the sites. At both, infiltration rates in the canopy plots were very high—there was no surface runoff, even at application rates as high as 80 mm/hr at Honey Creek and 190 mm/hr at Sonora (Tables 2a and 2b). Subsurface stormflow was important at both sites, amounting to 40%–80% of the total water applied (Tables 2a and 2b). Flow occurred within 20–40 minutes of the initial application of rainfall (first run) and just a few minutes following onset of the second and third runs. Under the wet conditions produced by the initial high-intensity application, subsurface stormflow as a percentage of the total water applied increased. For some simulations—especially at Sonora—it was roughly equivalent to the amount of rainfall applied (Figure 2).

[16] At both Honey Creek and Sonora, the bulk of the flow entered the trench as preferential flow. At Honey Creek most of the subsurface stormflow traveled through discrete conduit and fracture features within the R/A horizon. Contrary to our expectations, there was little subsurface stormflow at the interface of the A and R/A horizons. Only small amounts entered as matrix flow through root-filled clay pockets within the R/A horizon, and little or none exited from the weathered caliche horizon below the R/A. At Sonora, the preferential flow was concentrated within the Bk horizon but coincided with zones of high root concentration.

4.2. Canopy Plots After Tree Removal

[17] At both sites infiltration rates remained very high and surface runoff was minimal after tree removal. Subsurface stormflow was roughly similar in location, magnitude, and timing as before tree removal (Tables 2a and 2b). At Honey Creek, the amount of subsurface stormflow captured in the trench was lower as a percentage of the application amount than before tree removal. One possible explanation is that stemflow amounts feeding subsurface flowpaths were reduced by removal of juniper trees.

4.3. Intercanopy Plots

[18] Results for the intercanopy plots were similar in that, unlike the canopy plots, surface runoff did occur on all three

Table 2b. Sonora Canopy Plots: Rainfall and Runoff for the Simulation Experiments Before and After Tree Removal[a]

Date	Duration, min	Input, mm	Intensity, mm/min	SSSF, mm	SSSF, %
		Before Tree Removal			
5/21/2003	42	110	2.6	15	14
	281	178	0.6	124	70
Total	**323**	**288**		**139**	**48**
6/2/2003	39	87	2.2	16	18
	421	244	0.6	211	86
	460	**331**		**227**	**69**
		After Tree Removal			
7/28/2004	45	158	3.5	34	22
	363	304	0.8	219	72
	105	159	1.5	148	93
Total	**513**	**621**		**401**	**65**
8/16/2005	38	171	4.5	44	26
	353	351	1.0	316	90
	103	268	2.6	135	50
Total	**494**	**790**		**495**	**63**

[a] Surface runoff is not included because little or none occurred. Input = water reaching the surface as throughfall; SSSF = subsurface stormflow.

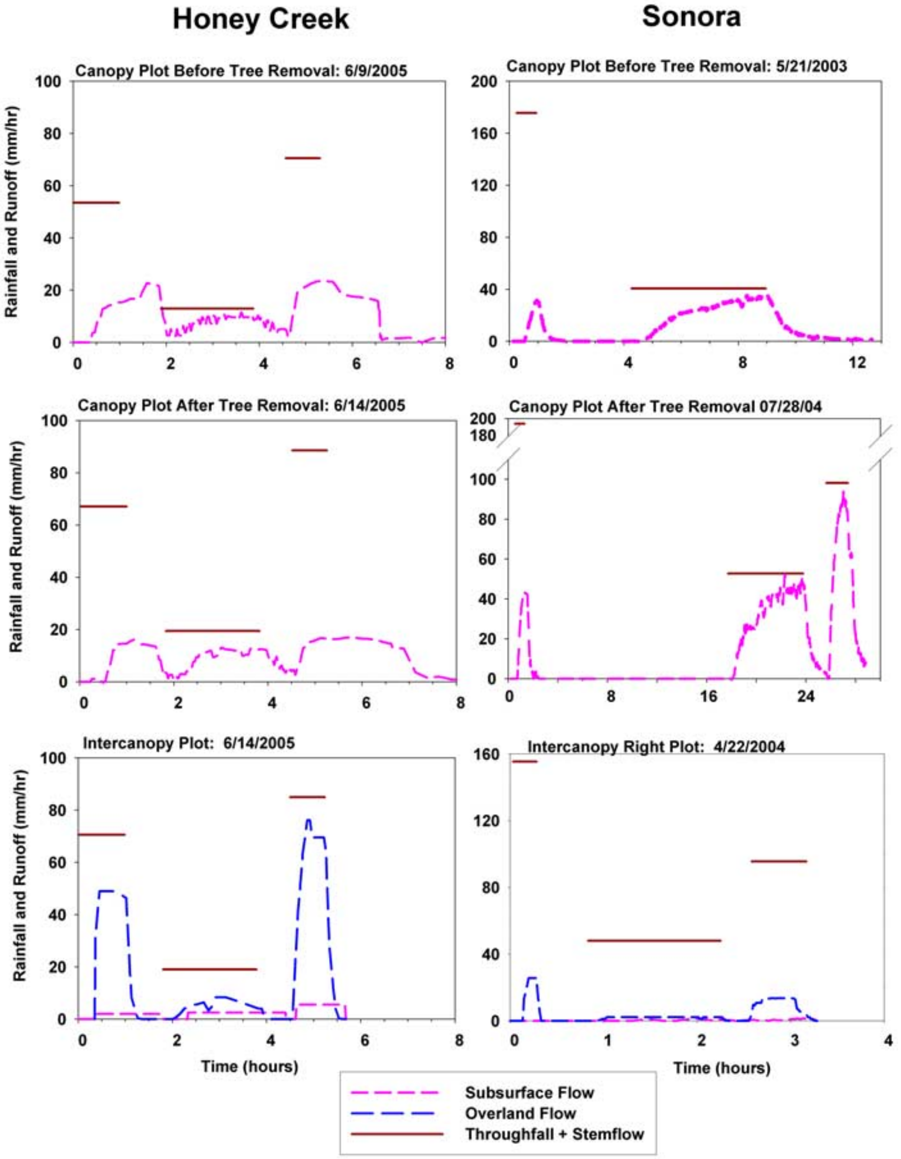

Figure 2. Hydrographs for selected simulation experiments at each location, for the canopy plot before shrub removal; the canopy plot after shrub removal; and the intercanopy plots.

intercanopy plots (Table 3); it was especially prevalent at the Honey Creek site, where soils are shallow. When rainfall simulations were conducted on two consecutive days (August 10 and 11) at Honey Creek, the measured amounts of both surface runoff and subsurface stormflow were much greater under the wet conditions of the second day (Table 3). For the plots at Sonora, where soils are deeper than at Honey Creek, surface runoff occurred as well, but made up only around 10% of the water budget. At both sites, surface runoff began within minutes after rainfall (Figure 2).

[19] Subsurface stormflow occurred on each of the intercanopy plots, but was much less important than for the canopy plots. At both sites it made up between 5% and 10% of the water applied. At Sonora it occurred as preferential flow along root channels in the Bk (caliche) horizon and at the interface of the A and Bk horizons. At Honey Creek, it occurred exclusively at the A and R/A horizons.

5. Discussion and Conclusions

[20] Although the Honey Creek and Sonora sites are separated by more than 200 km, results for the two were quite similar. We found that for large rainfall events runoff generation is spatially variable, occurring as a mosaic of overland and subsurface flow. Differences were associated with vegetation cover—the canopy areas being zones of very high infiltration and characterized by subsurface stormflow, and the intercanopy areas exhibiting more surface flow (with smaller amounts of subsurface stormflow under conditions of very high rainfall). Most significant, removal of the juniper had little effect on runoff processes. Subsurface stormflow remained the dominant form of runoff for the plots from which the trees had been removed—in the

Table 3. Rainfall and Runoff for the Simulation Experiments on the Intercanopy Plots[a]

Date	Duration, min	Input, mm	Intensity, mm/min	Surface Runoff, mm	Surface Runoff, %	SSSF, mm	SSSF, %
Honey Creek Intercanopy							
7/6/2004	60	58	1.0	9	16	2	3
	120	31	0.3	2	6	5	16
	45	60	1.3	32	53	4	7
Total	**225**	**149**		**43**	**29**	**11**	**7**
8/10/2004	60	68	1.1	11	16	1	1
	120	28	0.2	2	7	1	4
	45	61	1.4	39	64	3	5
Total	**225**	**157**		**52**	**33**	**5**	**3**
8/11/2004	60	71	1.2	34	48	3	4
	120	38	0.3	11	29	5	13
	45	64	1.4	48	75	6	9
Total	**225**	**173**		**93**	**54**	**14**	**8**
Sonora Intercanopy Right							
6/11/2003	39	103	2.6	13	13	0	0
	426	240	0.6	6	3	26[b]	11
	64	111	1.7	26	24	13[b]	12
Total	**529**	**454**		**45**	**10**	**39**	**9**
4/22/2004	15	39	2.6	6	15	0	0
	85	68	0.8	4	6	1	1
	35	56	1.6	11	20	5	9
Total	**135**	**163**		**21**	**13**	**6**	4
Sonora Intercanopy Left							
6/11/2003	39	88	2.2	22	25	0	0
	426	251	0.6	1	0	16	7
	64	80	1.3	10	13	7	9
Total	**529**	**419**		**33**	**8**	**24**	**6**
4/22/2004	15	22	1.5	NA	NA	0	0
	85	54	0.6	NA	NA	0	0
	35	37	1.1	NA	NA	0	0
Total	**135**	**113**		NA	NA	**0**	0

[a] Input = water reaching the surface as throughfall; SSSF = subsurface stormflow. SSSF was adjusted downward by 50% on the basis of visual estimate of the leakage quantity. NA means not available because of equipment malfunction.

[b] On this date there was leakage into the trench from the surface.

case of the Sonora plot, for as much as two years following removal.

[21] Because these findings are based on only five hillslope plots at two sites, a strict generalization cannot be made that subsurface flow characterizes all tree canopy locations and overland flow is restricted to intercanopy locations. These findings, however, do lend strong support to the idea that subsurface stormflow (1) is an important mechanism of runoff generation in these landscapes and (2) is highly variable, depending on the nature of the vegetation cover, the underlying soils, and the parent material.

[22] The most remarkable finding of these experiments was the magnitude and nature of subsurface stormflow in this region. Conduit flow is to be expected in karst settings; however, to our knowledge, subsurface stormflow has not been documented before on karst hillslopes in semiarid climates. It has been documented for semiarid forests [*Wilcox et al.*, 1997], but is not generally considered an important process in dryland regions [*Dunne*, 1978]. More recently, some have suggested that subsurface stormflow in semiarid settings may be underestimated and should be investigated in more detail and at more locations [*Beven*, 2002; *Newman et al.*, 2006].

[23] It has been commonly believed that in the Edwards Plateau region, soils are uniformly shallow and have low water-holding capacity, and they therefore generate large amounts of overland flow during flooding events. Obviously, overland flow does occur; but as demonstrated by this study, it is not uniform spatially or temporally nor is it the only mechanism of runoff generation. Other recent work has shown that far from being uniformly shallow, soils in the region can be surprisingly deep and possess good water-holding and infiltration capacities [*Wilcox et al.*, 2007; *Woodruff and Wilding*, 2008]. And some results suggested, on the basis of hydrography analysis, that subsurface stormflow may be an important contributor to streamflow and groundwater recharge [*Wilcox et al.*, 2005].

[24] These rainfall simulation experiments have made clear that for flood-producing events, runoff generation is quite spatially variable—occurring as overland flow in some areas and as subsurface stormflow in others. The type of runoff will be dictated by the character of the underlying soils, the parent material, and the vegetation cover. What is not yet certain concerns the interplay among these factors. For example, to what extent (if any) is subsurface flow controlled by the presence or absence of woody plants?

[25] We found that the organic-rich soils under the canopies had exceedingly high infiltration capacities, which is consistent with observations from other studies in the Edwards Plateau region [*Hester et al.*, 1997] and studies in other shrublands [*Dunkerley*, 2000; *Joffre and Rambal*, 1993; *Roundy et al.*, 1978; *Seyfried*, 1991]. A number of factors are responsible for these high infiltration capacities, including greater inputs of leaf litter, trapping of eolian dusts, and activity of roots.

[26] The dominance of subsurface stormflow in the canopy areas is also related to the presence of woody plants, as suggested by other studies as well: shrub-linked preferential flow along root channels has been documented for a number of drylands, including the Mojave Desert scrubland [*Devitt and Smith*, 2002], the Chihuahuan desert [*Martinez-Meza and Whitford*, 1996], the Australian mallee vegetation [*Nulsen et al.*, 1986], and ponderosa pine forests [*Newman et al.*, 2004]. The canopy-plot trenches at both Honey Creek and Sonora exhibited preferential-flow pathways associated with roots; at Sonora, root macropores served as the exclusive paths for subsurface stormflow. Tracer testing at Honey Creek suggests that flow conduits may be connected to juniper roots and that fractures may be structurally enhanced by root action [*Dasgupta et al.*, 2006]. The intercanopy plots, which had little or no root mass below the soil layer, produced a correspondingly small amount of subsurface flow compared with that from the canopy plots.

[27] In addition to the clear effect of vegetation on hydrology, soil type and parent material to a large extent dictate where subsurface flow may occur. Subsurface flow will be minimal where soils are shallow and underlain by massive, impermeable limestone, such as those of the intercanopy plot at Honey Creek (Figure 1).

[28] Moreover, it is likely that woody plants preferentially become established in the locations with deeper soils and/or fractured parent material because of water availability. Preferential establishment of juniper vegetation on permeable zones then further enhances both infiltration and lateral macropore flow through the effects of litter addition and root growth. The resulting patchwork of high-infiltration and lower-infiltration areas creates zones of overland flow and of subsurface flow.

[29] The interaction of these patches at the hillslope and landscape scales probably depends on numerous additional factors, including slope, relative coverage of woody plants vs. grass, and land management practices. While woody plant encroachment may be associated with land degradation and routing of runoff off the hillslope via interconnected interspaces [*Wilcox et al.*, 2003], in other cases vegetation patches, including woody plants, may act as sinks for water by harvesting run-on from intercanopy areas. It seems likely that the canopy patches may act as important sinks for capturing overland flow and thus potentially contribute to streamflow via subsurface stormflow and groundwater recharge.

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