Rainfall, Soil Moisture, and Runoff Dynamics in New Mexico Piñón-Juniper Woodland Watersheds

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Abstract*—Clearing trees in piñón-juniper woodlands may increase grass cover and infiltration, leading to reduced surface runoff and erosion. This study was conducted to evaluate piñón-juniper hydrology conditions during baseline data collection in a paired watershed study. We instrumented six 1.0 to 1.3 ha experimental watersheds near Santa Fe, NM to collect rainfall, soil moisture, and runoff data. Volumetric water content reflectometers (VWCRs) were used to measure soil moisture on wooded hillslopes, on grass hillslopes, and in valley bottoms. Time domain reflectometry (TDR) probes were installed in two watersheds to measure soil wetting at hillslope, gully headcut and channel locations. Spatial dynamics of rainfall and runoff interactions were evaluated for 9 rainfall events. Runoff was present at all watersheds in 3 of the 9 rainfall events. Rainfall intensity of 5mm/15min was generally the minimum precipitation required to generate channel runoff. During high intensity rain storms, greater soil moisture was observed at valley bottoms when compared to grass hillslopes and wooded hillslopes. At the watershed scale, total runoff as a proportion of precipitation was relatively low. Wetting depth measured with TDR probes was consistent with increases in soil moisture measured with VWCRs. In general, the wetting depth was greater at the channel, followed by the gully headcut and then by the hillslope. Results to date from the baseline data collection period suggest that larger storms that wet the entire watersheds produce most annual runoff, so clearing trees may increase grass cover, but may have little effect on annual runoff.*

Keywords*: New Mexico, piñón-juniper, baseline data, rainfall, soil moisture, runoff, wetting depth, TDR*

Introduction

Piñón-juniper (PJ) woodlands cover a large portion of semi-desert U.S. ecosystems, extending from Texas to California and occupying an area of approximately 24.7 million ha (Burns and Honkala 1990). In New Mexico, PJ woodlands are the most abundant type of forest and cover nearly 53 percent of the total forested area of the state (O'Brien 2003). Temporal variations in precipitation are important for runoff generation in piñón-juniper woodlands of northern New Mexico. Wilcox (1994) reported two typical precipitation seasons that produce runoff in a steep mountainous area of this region: a mid-summer season, with convective storms generating most of the runoff; and a mid-to-late winter season, with snow melt producing some runoff. Amount and intensity of precipitation is also important for the generation of runoff. Reid and others (1999) reported that convective storms characterized by high-intensity short-duration precipitation events generated most of the runoff and that frontal storms also produced considerable runoff in a 26-month study done in north-central New Mexico. Soil moisture dynamics in piñón-juniper woodlands, especially in the shallow soil layer, are important in

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determining water availability for different plant species. Breshears and others (1997) found that both piñón and juniper trees can extract water from the top 30 cm of intercanopy locations and compete with forage species for water.

Piñón-juniper tree control by mechanical removal, treatment with fire, or herbicide, may increase forage response and soil water infiltration and consequently reduce surface runoff and erosion. In order to characterize hydrology effects of PJ control, it is important to understand and evaluate watershed conditions prior to treatment. This study is part of a research effort to evaluate watershed response to piñón-juniper control in northern New Mexico. This study was conducted to collect baseline data and evaluate hydrology conditions before tree clearing planned in 2009. We formulated two study questions:

1. How does channel runoff respond to different precipitation amounts and intensities?
2. What is the soil moisture response to rainfall on wooded hillslopes, on grass hillslopes, and in valley bottoms of the watersheds?

Study Site

The research site is located at the New Mexico State University-Santa Fe Ranch (NMSU-SFR), 16 km northwest of Santa Fe, NM. The vegetation of the area is represented by piñón-juniper woodland on the hillslopes and grassland in the valleys. Oneseed juniper (*Juniperus monosperma* Engelm.) is the dominant tree species, followed by piñón pine (*Pinus edulis* Engelm.). The dominant species in the understory is blue grama (*Bouteloua gracilis.* Willd. ex Kunth), followed by New Mexico feathergrass (*Stipa neomexicana*), sideoats grama (*Bouteloua curtipendula.* Michx), and purple threeawn (*Aristida purpurea.* Nutt). Piñón-juniper woodlands are generally between 1370 and 2440 m. In New Mexico, these woodlands are found in elevation that range from 1520 m to 2130 m (Burns and Honkala 1990). Elevation of the watersheds at the NMSU-SFR study site ranges from 1939 m in the valley bottoms to 1977 m on the ridge tops. Slopes range from 2% to 5% in the valley bottoms and 20% to 50% on the hillslopes. Average annual precipitation is 387 mm. Most of this precipitation falls during the monsoon season from May to October. The average low annual temperature is 4.4 °C and the average high annual temperature is 26.7 °C. The soil type is classified as part of The Santa Fe Group (Tsf) and is mostly characterized by sediments from fluvial deposits of sand, silt, clay and pebbles with basaltic and sedimentary inclusions (Scholle 2003, Till and others 2003).

Methods

Six watersheds (WS-1, WS-2, WS-3, WS-4, WS-5, and WS-6) of 1.0 to 1.3 ha were instrumented to collect precipitation, runoff, and soil moisture data starting in April of 2003 (fig. 1). WS-2 and WS-3 were equipped with Time Domain Reflectometry (TDR) technology to measure soil wetting depth.

Precipitation measurements were taken with four tipping-bucket rain gauges with datalogger enclosed (HOBO rain gauge, manufactured by Onsetcomp). These rain gauges were installed at mid-slope elevation in four watersheds (WS-2, WS-3, WS-5, and WS-6) to collect precipitation data. The rain gauge at WS-2 was installed in April of 2003 and the remaining three were installed between June and July of the same year. The WS-2 rain gauge was used to represent adjacent WS-1, and the WS-3 rain gauge was used to represent adjacent WS-4 (fig. 1).

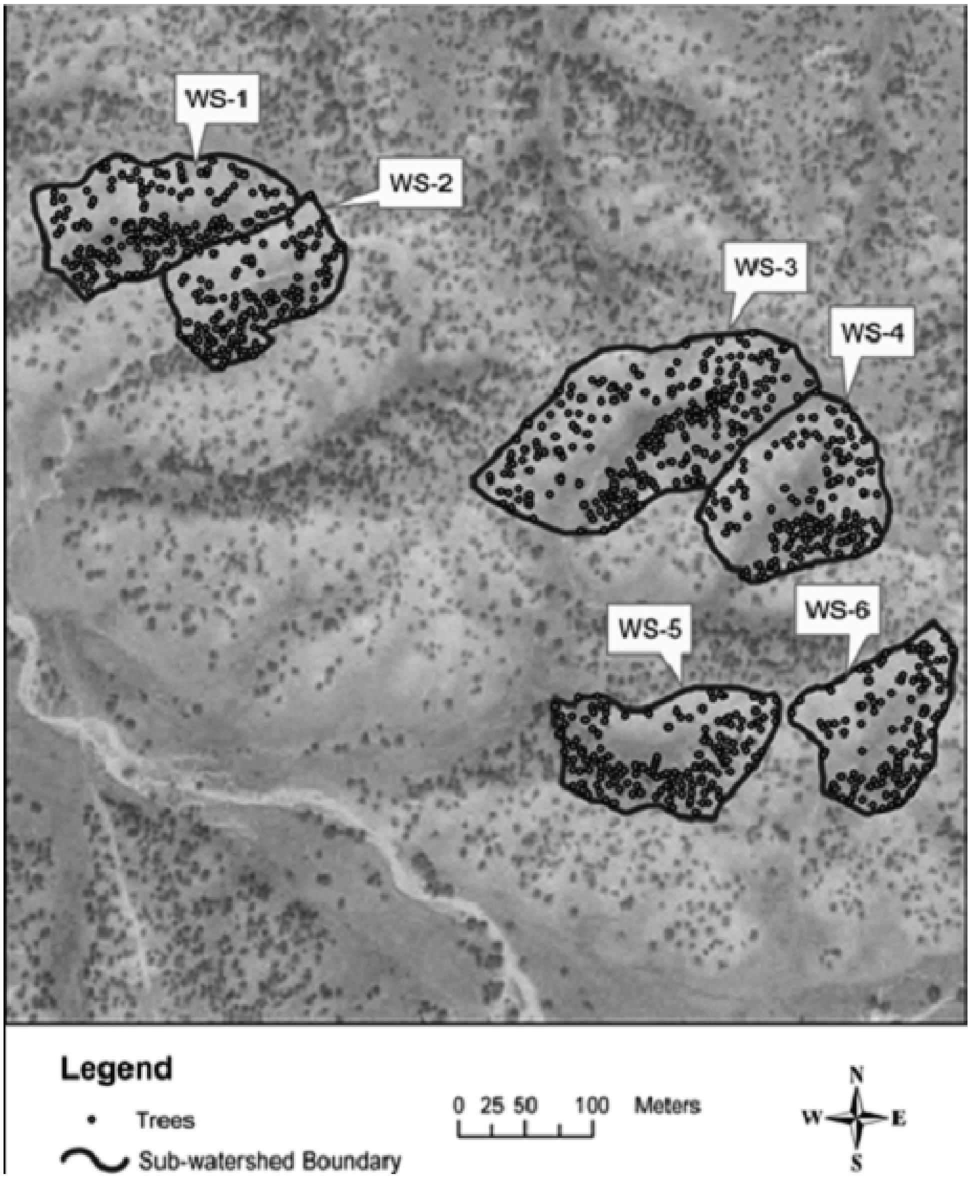

Figure 1—Watersheds of the NMSU-Santa Fe Ranch.

Runoff data were collected at the outlets of the watersheds. Type H flumes equipped with pressure transducers were installed at the outlets to measure water stage. Total amount of runoff per rainfall event was calculated with the low flow discharge equation for type H flumes with floor sloping of 0.003 to 0.03 (Brakensiek and others 1979).

Soil moisture data were collected using six volumetric water content reflectometers (VWCRs) in each watershed. The VWCRs were installed under canopy and in the intercanopy of wooded hillslopes, grass hillslopes, and valley bottoms. The VWCRs were inserted horizontally at 10 cm depth and attached to dataloggers. Soil volumetric water content data were collected every hour. Maximum values of increase in soil moisture measured by all six VWCRs after precipitation events that produced runoff in each watershed were added and divided by the total number of precipitation events to obtain average increase in soil water content for the two-year study period.

Soil wetting depth was calculated using data collected with TDR sensors. A total of sixteen 15 cm-long experimental sensors were installed at WS-2 and WS-3 to collect the TDR trace signals. The TDR sensors were installed vertically, with the tip exposed, at gully headcut, channel bed, channel bank, ridge, and hillslope. Two rain gauges attached to dataloggers were installed in the valley bottoms of WS-2 and WS-3 to activate the TDR systems. During rainfall events, the TDR systems were triggered by the automated rain gauges and data were continuously collected during the precipitation event and until 15 minutes after rainfall stopped in order to capture the total expected time needed for rainfall to either infiltrate or run off. Under dry conditions, TDR data were collected twice a day, at noon and at midnight. TDR data were entered into a physically based multisection model developed by Tidwell and Brainard (2005) to calculate the soil wetting depth. The model uses the S_{11} scatter function and Debeye parameters for dielectric dispersion and loss is used to analyze the TDR traces.

Results

Precipitation

We present precipitation data for nine rainfall events that generated runoff. Two occurred in 2003 and the remaining seven happened in 2004 (table 1). Rainfall was temporally and spatially variable among watersheds. During the two-year study, we observed that precipitation at the study site was characterized by scattered convective storms during the months of May to September and by frontal storms during October and November. Also, it is noteworthy that precipitation varied considerably from one watershed to the other, with differences up to 3.4 mm inter-watershed differences measured in one single rain storm. The year of 2003 was drier than 2004. For example, precipitation recorded at WS-2 from April to December of 2003 was 215.6 mm, and for the same period in 2004 it was 308.6 mm.

Table 1—Runoff response to precipitation events during a two-year study period at the NMSU-Santa Fe Ranch, NM.

	Watersheds and Areas											
	WS-1 1.35 ha		WS-2 1.00 ha		WS-3 1.14 ha		WS-4 1.34 ha		WS-5 1.21 ha		WS-6 1.06 ha	
Date	Rain	Runoff	Rain	Runoff	Rain	Runoff	Rain	Runoff	Rain	Runoff	Rain	Runoff
	(mm)											
5/26/03	14.0	0.175	14.0	0.172	14.0	-	14.0	-	14.0	-	14.0	-
10/4/03	6.0	0.051	6.0	*	5.8	*	5.8	*	5.2	0.025	5.6	*
6/19/04	11.8	-	11.8	0.007	12.4	0.041	12.4	0.004	13.6	-	12.4	0.005
7/12/04	24.6	0.180	24.6	0.019	22.2	0.010	22.2	0.044	24.2	0.977	23.6	0.010
8/18/04	6.6	-	6.6	0.036	5.8	-	5.8	0.005	5.6	-	5.6	0.00002
8/21/04	6.2	-	6.2	0.020	6.8	0.013	6.8	-	6.0	-	6.0	-
10/5/04	12.4	0.953	12.4	0.022	11.3	0.136	10.3	0.229	9.3	0.136	9.0	0.006
10/11/04a	7.6	0.372	7.6	0.027	8.4	0.127	7.6	0.056	7.6	0.184	7.0	*
10/11/04b	17.2	1.534	17.2	0.016	14.2	0.145	13.0	0.402	11.0	0.088	9.0	0.006
Total	**106.4**	**3.3**	**106.4**	**0.3**	**100.9**	**0.5**	**97.9**	**0.7**	**96.5**	**1.4**	**92.2**	**0.03**

- No data
* No runoff

Runoff

The difference in precipitation between years was also reflected in the amount of runoff generated. In 2003, runoff data were collected at two watersheds during a convective, high-intensity short-duration rain storm on 26 May. Also in 2003, runoff data were collected at two watersheds during a low-intensity long-duration frontal storm on 4 October. In 2004 there was more precipitation and runoff than in 2003. A total of seven storms produced runoff in at least two of the watersheds. The highest runoff value of 1.534 mm was calculated from a frontal storm at WS-1 in 11 October 2004, and the lowest runoff value of 0.00002 mm was calculated from a low-intensity rain storm at WS-6 in 18 August 2004. The total amount of single event runoff produced per watershed during the two-year study was relatively low. WS-6 presented the lowest amount of total runoff with 0.03 mm and WS-6 had the highest value with 3.3 mm (table 1).

Soil Moisture

Average increase in soil volumetric water content (VWC) ranged widely depending on the point of measurement, which was dictated by the soil moisture sensor location in the watershed. Calculations of average soil VWC were based on soil moisture increases measured after precipitation events that produced some runoff in the two-year study period. The lowest average value of 0.01 (one percent) was observed in the intercanopy of grass hillslope at WS-6. The highest average value of 0.18 (eighteen percent) was observed in the intercanopy of the valley bottom at WS-4 (table 2).

Table 2—Average soil moisture increase after precipitation events during a two-year study period at the NMSU-Santa Fe Ranch, NM.

	Valley bottom Vol water content (cm^3/cm^3)		Grass hillslope Vol water content (cm^3/cm^3)		Wooded hillslope Vol water content (cm^3/cm^3)	
Watershed	**Under canopy**	**Interspace**	**Under canopy**	**Interspace**	**Under canopy**	**Interspace**
WS-1	0.03	0.06	0.06	0.04	0.02	0.05
WS-2	0.10	0.02	0.12	0.08	0.04	0.09
WS-3	0.07	0.04	0.03	0.03	0.06	0.04
WS-4	0.16	0.18	0.05	0.10	0.04	0.02
WS-5	0.05	0.07	0.05	0.05	0.08	0.08
WS-6	0.01	0.06	0.04	0.01	0.04	0.04
Average	**0.07**	**0.07**	**0.06**	**0.05**	**0.05**	**0.05**

Depth to Wetting Front

Data from TDR sensors in WS-3 were used to calculate soil-wetting depth. Figure 2 shows soil wetting depth calculated using data collected with one TDR sensor and soil volumetric water content data from one VWCR. Both, the TDR sensor and the VWCR are installed within 3 m distance of each other in WS-3. In general, the soil wetting depth measured with the TDR sensor followed the same wetting-drying pattern than soil moisture content measured with the VWCR.

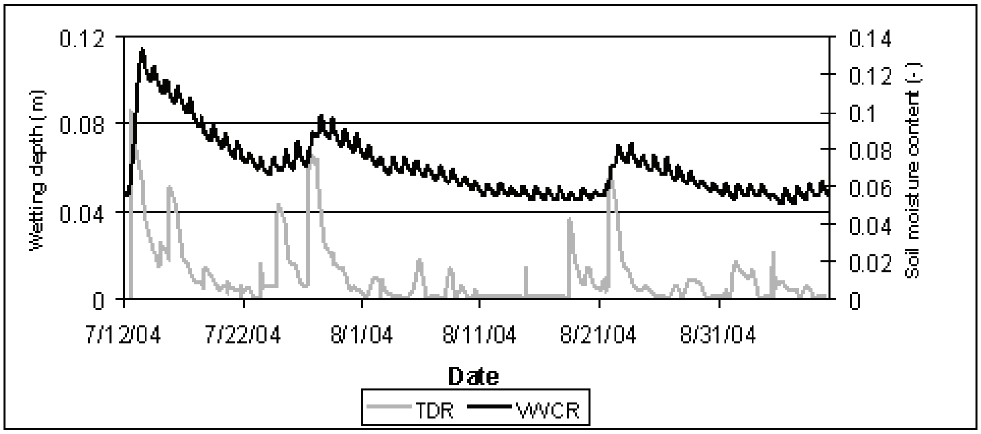

Figure 2—Volumetric water content reflectometer (VWCR) soil moisture and site-adjacent time domain reflectometry sensor (TDR) wetting depth response during the summer of 2004.

Discussion

Precipitation data collected during the two-year study indicated a clear pattern, which showed differences in the spatial distribution of precipitation at the watersheds. The lowest cumulative precipitation occurred in WS-6 and the highest cumulative precipitation occurred in WS-2. Precipitation amount and intensity play an important role in the generation of runoff. We were able to identify the temporal distribution of precipitation that produced runoff in the watersheds. In contrast to results reported by Wilcox (1994) where he stated that runoff in PJ woodlands in northern New Mexico is typically present in mid summer (intense thunderstorms) and mid to late winter (snow melting), we found that runoff at the NMSU-SFR watersheds was present during the summer season when runoff was generated by high intensity convective storms. Runoff was also produced during early to mid fall, when runoff was produced by frontal storms. Rainfall intensity greater than 5 mm/15 min appears to be the minimum amount of precipitation needed before runoff occurred at the watersheds outlet.

It was observed that frontal storms with low-intensity precipitation events, which occurred in the month of October in 2003 and 2004, lasted longer than convective storms with high-intensity precipitation events in May to August of both years. These precipitation events during frontal storms lasted several hours until the soil got wetted and overland flow started to occur. Thus, antecedent soil moisture was important for runoff response at the watersheds. Also, it was noted that sediment movement was greater during these frontal storms than during convective precipitation events, probably due to the moisture regime of the soil.

In general, across all watersheds, greater average soil moisture was observed in the valley bottoms than on the grass hillslopes and wooded hillslopes. However, there were small differences in soil moisture increases between under canopy and intercanopy locations. At the single watershed level, WS-4 presented higher soil moisture in the valley bottom, followed by grass hillslope, and then by wooded hillslope. This difference by location was probably due to the topography of the watershed that includes a greater valley area and less steep hillslopes.

The new application of TDR technology worked well and seems to be a promising tool to accurately calculate soil-wetting depth in real time. In contrast to data obtained with the VWCR, where an average water content value of the soil in contact with the probe waveguides is obtained, the use of this model allowed us to calculate to 1 mm precision the soil water flux in the upper 15 cm of the soil. Also, it was noted that in general the wetting depth was greater at the channel, followed by the gully headcut and then by the hillslope.

Some obstacles and limitations of the study and study site in particular are worth noting. The study site is located on federal land, and it is exposed to the inherent risks of open public access. To protect from vandalism, most of the equipment is inside solid material enclosures. This is the case of the type H flumes that are enclosed in cages built with concrete and steel screen. In some high intensity rain storms, the screen starts accumulating debris, and if not cleaned right after the storm, chances are that accumulated debris will trap sediment, creating a dam and restricting free water flow. For example, it was observed that after a high intensity rainfall in 11 October 2004, the screen that protects the flume got clogged and acted as a dam, accumulating sediment in the upstream arroyo and impeding free water flow through the flume. Thus, for a rain storm that occurred at the same location two days later, data collected was not considered reliable and it was discarded.

Dealing with electronic equipment in remote locations to measure real time natural phenomena is always a challenge. The study site is located 480 km from the investigator offices, and there is to date no remote communication with the sensors installed in the watersheds. Thus, the long distance between the study site and the headquarters and the lack of a telecommunication system that would alert us in real time to precipitation events, made it difficult to perform maintenance needed after each precipitation event. Also, TDR data collected from WS-2 were not considered reliable due to high variability in the TDR signal, probably due to a faulty multiplexer rely or a poor connection that introduced some noise in the signal.

Conclusions

Channel runoff responded differently to different precipitation amount and intensities. Runoff was produced by rainfall events with intensities greater than 5 mm/15 min. Runoff is affected by antecedent soil moisture. Most of the runoff was produced by convective storms during the summer. Some runoff was produced by frontal storms during the fall. Total amount of runoff produced per watershed during the two-year study was relatively low. Soil moisture response to rainfall was higher in the watershed valley bottoms than in grass hillslopes, and wooded hillslopes. The use of TDR technology to measure wetting depth is a potential tool to determine threshold precipitation for runoff generation.

Management Implications

Based on analysis of rainfall, runoff, soil moisture, and channel flow, we feel confident that the main runoff generating mechanism at the NMSU-SFR study site is infiltration excess runoff. This is similar to that observed by Wilcox (2002), who states that overland flow is important and may be the dominant mechanism of runoff in the majority of juniper woodlands. This infiltration excess runoff appeared to occur even during longer-duration frontal storms. Results to date from the baseline data collection period suggest that larger storms that wet the entire watersheds produce most annual runoff, so clearing trees may increase grass cover, but may have little effect on annual runoff. Detailed characterization of actual effects of tree clearing will be improved with continued measurements during baseline data collection and after planned tree clearing in 2009.

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