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Runoff and erosion in intercanopy zones of pinyon-juniper woodlands

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Abstract

In semiarid pinyon-juniper environments, the principal mechanisms of redistribution of water, sediments, nutrients, and contaminants are runoff and erosion. To study the phenomena underlying these mechanisms, we established six 30-m² plots, in intercanopy zones, for monitoring over a 2-yr period (1991-1993). Two of the plots were severely disturbed; 4 were undisturbed.

We measured the most runoff from these plots during mid summer (generated by intense thunderstorms) and late winter (from snowmelt and/or rain-on-snow). Runoff accounted for 10 to 28% of the water budget over the 2-yr period—a higher proportion than that observed in most other pinyon-juniper woodlands, which is probably explained by the smaller scale as well as the higher elevation of our study area. Runoff accounted for 16% of the summer water budget the first year, with above-average precipitation (and thereby higher soil moisture content) and 3% the second year, when precipitation was about average. Winter runoff was substantial both years as measured on the small scale of our study (no winter runoff was observed in the nearby stream channel). Interestingly, even though precipitation was lower the first winter, runoff was higher. This may be because snowmelt set in about 20 days earlier that year—while the soils were still thoroughly frozen, inhibiting infiltration.

Differences between disturbed and undisturbed plots were most evident in the summer: both runoff and erosion were substantially higher from the disturbed plots.

On the basis of our observations during this study, we suggest that the following hypotheses proposed about runoff and erosion in other semiarid landscapes are also true of pinyon-juniper woodlands: (1) Runoff amounts vary with scale: runoff decreases as the size of the contributing area increases and provides more opportunities for infiltration. (2) The infiltration capacity of soils is dynamic; it is closely tied to soil moisture content and/or soil frost conditions and is a major determinant of runoff amounts. (3) Soil erodibility follows an annual cycle; it is highest at the end of the freeze-thaw period of late winter and lowest at the end of the summer rainy season, when soils have been compacted by repeated rainfall.

Key Words: range hydrology, streamflow generation, water budget, sediment budget

In semiarid ecosystems, the relationship between the total quantity and the importance of runoff presents a fascinating paradox (Graf 1990): runoff is quite sporadic and generally makes up a small portion of the water budget, yet it is a primary mechanism by which these lands are shaped. Processes such as chemical and nutrient cycling, erosion, and contaminant transport are closely tied to runoff. In addition, runoff may be a sensitive indicator of ecosystem change, as suggested by Dahm and Molles (1992), who examined historical runoff in New Mexico for clues to climate change.

In spite of its importance, however, runoff is a poorly understood phenomenon in that our predictive capabilities are mediocre at best (Hromadka and Whitley 1989), especially in arid and semiarid landscapes (Yair and Lavee 1985). A process-based understanding of runoff (i.e., one capable of prediction) is needed for effective evaluation and resolution of the myriad environmental problems that characterize semiarid landscapes (National Research Council 1991). This kind of understanding requires not only careful application of theoretical concepts, but also long-term, continuous, and detailed monitoring of these environments on different spatial and temporal scales (as well as ongoing refining of the underlying concepts on the basis of data obtained).

The study described in this paper is a pilot study designed to provide basic information about runoff and erosion in a particular semiarid ecosystem, the pinyon-juniper woodlands of New Mexico. The insights gained will be a valuable addition to our knowledge base for

- developing and testing theories that will improve our ability to predict how erosion and runoff will behave, and what effects they will have, in semiarid intercanopy zones;
- estimating parameters for runoff-prediction models and providing data for validation of those models; and
- guiding future studies aimed at developing a process-based understanding of runoff in this ecosystem.

Past Hydrological Research in Pinyon-Juniper Woodlands

Most of the watershed- and hillslope-scale hydrologic studies in pinyon-juniper woodland environments were conducted in the 1960s and 70s (Table 1). The management objectives of the day did not call for a process-based understanding of runoff and erosion; rather, the impetus for most of these studies was to test the hypothesis that removing the pinyon-juniper overstory would increase both water yield and forage production.

The best-documented of the watershed-scale studies was done at

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Table 1. Watershed- and hillslope-scale hydrologic studies in pinyon-juniper environments.

Location	Number of sites	Size	Years active	Study purpose	Precipi--tation	Runoff		Dominant runoff season/event	References
		(ha)			(mm)	(mm[a])	(%)		
Watershed studies									
Beaver Creek (AZ) (Watersheds 1, 2, 3)	3	51-146	22	Evaluate effect of P-J control (cabling, hand-slashing, burning, herbicide)	458	27	6	Winter (85%) (rain-on-snow, prolonged rain, snowmelt)	Clary et al. 1974; Baker 1982
Beaver Creek (AZ) (Watersheds 4, 5, 6)	3	24-140	22	Evaluate effect of P-J control (cabling, hand-slashing, burning, herbicide)	526	121	23	Winter (97%) (rain-on-snow, prolonged rain, snowmelt)	Clary et al. 1974; Baker 1982
Carrizzo Creek (AZ)	1	61,382	12	Evaluate effect of P-J control (chaining, hand-slashing, burning)	457	18	4	Winter (90%)	Collings and Myrick 1966
Corduroy Creek (AZ)	1	55,166	12	Evaluate effect of P-J control (chaining, hand-slashing, burning)	457	24	5	Winter (93%)	Collings and Myrick 1966
Mexican Springs (NM)	9	1391-3437	6-20 2-6	SCS[b] characterization of P-J environment	283	13	5	Summer	Dortignac 1960
Sante Fe (NM)	3	31-319	10	SCS[b] characterization of P-J environment	327	7	2	Summer	Dortignac 1960
Hillslope studies									
Beaverhead (NM)	20	0.04	2	Evaluate impact of fuelwood cutting and burning	325	28	8	Runoff data collected only during the summer	Wood 1991
Baird (TX)	6	0.02-0.19	2	Evaluate impact of burning of juniper	613	23	4	Summer and winter	Wright et al. 1976
Milford and Blanding (UT)		0.04	3	Evaluate effect of P-J control (chaining, win-rowing; chained debris left in place)	246	3	1	Summer (high-intensity thunderstorms)	Gifford 1975a

[a]= Data are for untreated (control) areas except where no control data were available.
[b]= SCS = Soil Conservation Service

Beaver Creek, Ariz. (Clary et al. 1974; Baker 1982; Baker 1984). It was initiated following a severe drought in the 1950s, when several researchers began optimistically forecasting water-yield improvements from clearing of pinyon-juniper cover (Barr 1956). Several treatments, including herbicide application and mechanical removal, were applied to small watersheds dominated by Utah juniper (1,585- to 1,680-m elevations) and alligator juniper (1,889- to 1,950-m elevations). Water yields increased slightly in the herbicide-treated areas, but not in the areas where trees were removed mechanically. Baker (1984) suggested that this was because the trees killed by herbicide not only had ceased to draw water from the soil, but were still providing shade, both of which had the effect of reducing evapotranspiration. Later, when the dead trees were removed, water yield diminished.

The hydrologic impact of pinyon-juniper removal was also examined in Arizona on a much larger scale (Collings and Myrick 1966). Like Beaver Creek, these studies showed that there was little if any increase in water yield from such removal. At Beaver Creek, dramatic increases in runoff were seen at the higher elevations, where evapotranspiration is lower (as shown in Table 1, runoff was about 5 times higher from the alligator-juniper watersheds than from the Utah-juniper watersheds).

Dortignac (1960) compared the early Beaver Creek findings with those of some little-known watershed work conducted in New Mexico (Table 1) and concluded that the runoff regimes of the Arizona and New Mexico watersheds were different—that whereas in New Mexico most of the runoff is generated by intense summer thunderstorms and is of short duration, in Arizona it is generally a winter phenomenon, produced by frontal rain storms, rain-on-snow, and/or snowmelt.

The effects of clearing of pinyon and juniper on surface runoff and erosion has also been examined in several hillslope-scale studies. Wood (1991) and Gifford (1975a) found that runoff was greater if slash and debris were removed. When these were left in place, runoff was lower—presumably because the increased surface storage capacity allows more time for water to infiltrate. Wright et al. (1976) found that in central Texas, burning of juniper increased runoff on steeper slopes for a period of 15 to 30 months (until regrowth took hold) but produced little change on smaller-gradient slopes.

A number of rainfall simulation studies have been conducted on pinyon-juniper woodlands. Some of the earlier studies compared infiltration and erosion patterns within different plant communities (Smith and Leopold 1942, Blackburn and Skau 1974, Blackburn 1975); others evaluated the effects on hydrologic events of pinyon-juniper control strategies (Williams et al. 1969, Gifford et al. 1970, Williams et al. 1972, Roundy et al. 1978). More recent rainfall simulation studies in pinyon-juniper woodlands have focused on the development of parameter values for hydrologic and erosion models (Ward 1986, Ward and Bolin 1989a, Ward and Bolin 1989b, Ward and Bolton 1991).

As Hawkins observed (1986), pinyon-juniper woodlands exist in diverse climatic, edaphic, topographic, and geologic settings. For this reason, there is no unique hydrologic behavior for the areas characterized by this plant community. Very generally, we can say that in pinyon-juniper woodlands, evapotranspiration is the dominant mechanism of water loss. Runoff typically accounts for less than 10% of the water budget (the high-elevation pinyon-juniper regions are probably an exception—for example, the Arizona alligator-juniper watershed studies, where runoff was around 20%—Table 1). Attempts to increase runoff by removing the overstory cover, in the hope of reducing evapotranspiration, have not been successful. Increases in runoff have been achieved when soils were disturbed and/or compacted to the point that infiltration capacity was reduced—but such artificial means are generally not desirable: they lead to ecosystem degradation both by aggravating soil erosion and by diminishing the quantities of water available for plants.

We can also say that in pinyon-juniper woodlands streamflow is usually ephemeral; it is generated by intense summer thunderstorms, prolonged frontal storms, or melting snow, but the underlying mechanism by which water reaches stream channels has been little studied. It is probably mostly Hortonian overland flow rather than subsurface flow. A possible exception to this is the sustained winter streamflow, lasting several months, seen in the higher-elevation pinyon-juniper woodlands of Arizona (Clary et al. 1974 and Baker 1982), which may be the result of subsurface flow (the mechanisms of runoff generation at these sites was not explicitly discussed).

Finally, groundwater recharge is generally believed to be very small to nonexistent in pinyon-juniper woodlands, because of the high rates of evapotranspiration (Dortignac 1960, Gifford 1975b).

Current and Future Research

Over the last decade, there has been a dramatic shift of focus of hydrological investigations in pinyon-juniper woodlands. The traditional resource issues of increasing water yield and grazing capacity through vegetation manipulation have given way to issues of ecosystem sustainability, the effects of climate change, soil and water contamination, and impacts on riparian areas. Recognizing that the then-current understanding of pinyon-juniper hydrology was inadequate, Schmidt (1986) called for a comprehensive network of watershed studies in pinyon-juniper woodlands across the United States. These would employ a much more detailed investigative methodology, aimed at acquiring a process-based understanding of hydrological events.

Carrying out this type of study is especially challenging in semiarid environments (Pilgrim et al. 1988). One major problem has been the difficulty of maintaining and monitoring equipment in remote locations (but recent advances in data acquisition technology have greatly ameliorated this problem). Another problem is that development of a suitable hydrologic record could take decades, because runoff events are usually infrequent and of short duration, making important events easy to miss. Despite the challenges they present, studies of this kind are the only means for significantly advancing our understanding of water dynamics in semiarid ecosystems.

Study Area Setting

The study area lies within the Los Alamos National Laboratory's Environmental Research Park on the Pajarito Plateau of north-central New Mexico (Fig. 1). Formed by a series of violent volcanic eruptions beginning some 1.4 million years ago (Crowe et al. 1978), the plateau ranges in elevation from 1,910 to 2,730 m. To the west, it butts up against the Jemez Mountains. To the east, a parallel drainage network has created a series of finger-like mesas separated by deep canyons, through which intermittent and ephemeral streams flow to the Rio Grande. Average annual precipitation varies with elevation from about 330 to 460 mm, of which about 45% occurs in July, August, and September (Bowen 1990).

The 111-km^2 Environmental Research Park includes extensive tracts of pinyon-juniper woodlands and ponderosa pine forests (Allen 1989). Juniper coverage decreases and pinyon increases with elevation (Padien and Lajtha 1992).

Our study area, at an elevation of 2,141 m, is near the upper limit for pinyon-juniper on the Pajarito Plateau (Barnes 1986). Soils at the site are described by Nyhan et al. (1978) as Hackroy series (Alfisols of the subgroup Lithic Aridic Haplustalf and family Clayey, mixed, mesic). These are shallow soils that have developed on the volcanic tuff parent material and are characterized by a loam or sandy-clay-loam surface texture with a strong clay or clay-loam argillic horizon at a depth of about 10 cm.

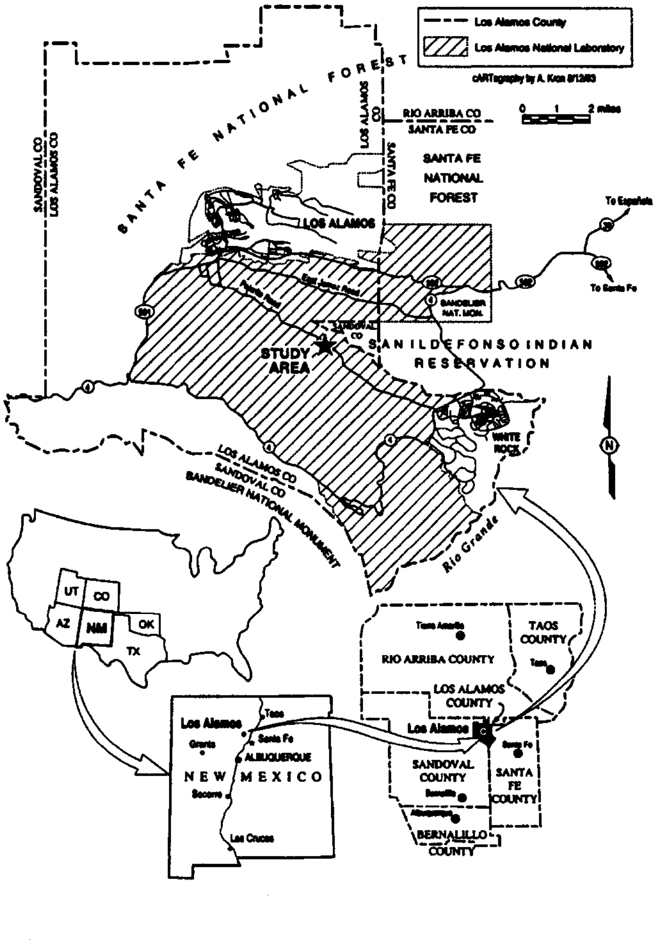

Fig. 1. Location of study area.

Experimental Design and Methodology

Naturally occurring runoff and erosion were monitored for 2 years in intercanopy zones of a pinyon-juniper woodland. (Intercanopy zones were selected for study because they are assumed to be the major source areas for runoff.)

Plot Description

We established 6 plots for monitoring, each measuring 3.04 x 10.64 m. Four of these plots (C, D, E, and F) had been used earlier for rainfall simulation studies associated with the development of the WEPP soil erosion model (Simanton and Renard 1992). All vegetation (including root crowns), cryptogamic crust, litter, and rock cover had been removed from 2 of these (C and F) in 1987; there has been regrowth, but grass cover—and especially cryptogamic crust cover—is much more sparse and bare ground is more extensive than on the other plots (Plot F recovered the least and has the most bare ground). Vegetation on plots A, B, D, and E was left undisturbed. The dominant grass species on all the plots is blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.], and common semi-shrubs and forbs are bitterweed [*Hymenoxys Richardsonii* (Hook.) Cockll.], fringed sagebrush (*Artemisia frigida* Willd.), Navajo tea [*Thelesperma filifolium* (Hook.) Gray] and Indian paintbrush (*Castilleja integra* Gray). Although grazing by domestic livestock had a profound effect on the original composition of the vegetation in this region, such grazing has been prohibited for the past 50 years.

All 6 plots were modified in July 1991 to collect naturally occurring runoff. A metal gutter was installed across the width of each plot at the downslope end. Two collection tanks, a primary and an overflow, having a combined capacity of about 600 liters, were placed 20 to 30 m downslope, and each was calibrated such that the water volume can be estimated from the depth. A drainline connected to a hole in the bottom of the gutter carries the runoff to the tanks, which are kept covered with plywood to prevent evaporation. (The degree of slope and the extent of basal cover of each plot are given in Table 2.) Basal cover was determined from point measurements taken every 5 cm along 5 transects running the width of each plot (at intervals of 2 m).

Throughout the study, the plots were inspected regularly for signs of leakage under the collection plate, and soil was added at the juncture if needed. (Such leakage is most pronounced in late winter, when frequent thawing and refreezing increases the likelihood of separation of the collection plate from the soil.)

Runoff and Sediment Collection

Runoff and erosion data were collected from July 1991 to March 1993. Runoff volume was measured for each event, including snowmelt. Because only plots A and B were completely operational during the first 2 runoff events of 1991, volumes for those events for the other 4 plots were estimated using a regression relationship (Plot B runoff vs that of plots C through F for the next 6 runoff events). The coefficient of determination (R^2) was found to range from 0.70 to 0.88.

We were unable to collect any winter runoff from Plot C because of recurrent freezing of the drainline. In the case of Plot E— and possibly F as well—leakage problems during the second winter (1992-93) lowered the amount of runoff water collected in the tanks.

To calculate rates of erosion, we collected sediment samples from each plot for each summer runoff event (except, for the first event, no samples were obtained; and for the second, samples were obtained from plots A and B only). Because sediment concentrations are much less variable during the winter, samples were taken only for selected events, on the basis of which a mean concentration was calculated for each plot. These sediment concentration values were generally based on 3 samples from each plot, but in some cases only 1 or 2 samples were collected.

Precipitation Collection

Summer precipitation was measured on a daily basis using on-site volumetric precipitation collectors. These gauges are not suitable for measuring snowfall, for which we used a heated, tipping-bucket rain gauge located about 3 km southeast of the site.

Results and Discussion

Runoff

A monthly summary of runoff from April 1991 to March 1993, averaged across all the plots, is presented in Figure 2 (although no data were collected until July 1991, we were able to extend the record back to April because on-site observation confirmed that no runoff had occurred in the interim). These data show clearly that runoff in pinyon-juniper woodlands in northern New Mexico typically has 2 "seasons": mid summer and mid to late winter. Summer runoff is generated from intense thundershowers, and winter runoff is produced by snowmelt augmented by frozen soil conditions and, at times, rain-on-snow. Runoff and precipitation amounts for the 2 seasons are compared in Table 3. Figure 3, which compares the frequency of summer and winter runoff events with the amount of runoff, shows that (1) large runoff events were much less frequent than small runoff events, and (2) the largest runoff events occurred during the summer months. During the 2-yr study period, runoff accounted for 10 to18% of the water budget for undisturbed plots and up to 28% for disturbed plots (Table 3), which is a higher proportion than at most of the pinyon-juniper sites studied to date (see Table 1). The most likely explanations are the small scale of our study (as will be discussed

Table 2. Plot slope and basal cover conditions.

Plot	Slope	Degree of disturbance	Basal cover: Grass	Shrub	Forb	Cryptogamic crust, moss	Litter	Bare ground	Other*
	(%)		%						
A	4.4	Negligible	12.3	2.7	0.3	51.6	20.5	12.0	0.6
B	4.8	Negligible	8.1	1.0	1.4	43.7	16.3	26.8	2.8
C	4.4	Severe	5.4	6.5	2.2	29.1	10.1	46.8	0.0
D	5.2	Negligible	22.7	1.4	1.7	50.2	17.9	6.2	0.0
E	5.3	Negligible	10.8	3.1	1.0	53.9	18.0	13.2	0.0
F	5.7	Severe	4.4	4.1	1.0	26.6	2.4	61.1	0.3

*= includes rock, lichen, and cactus

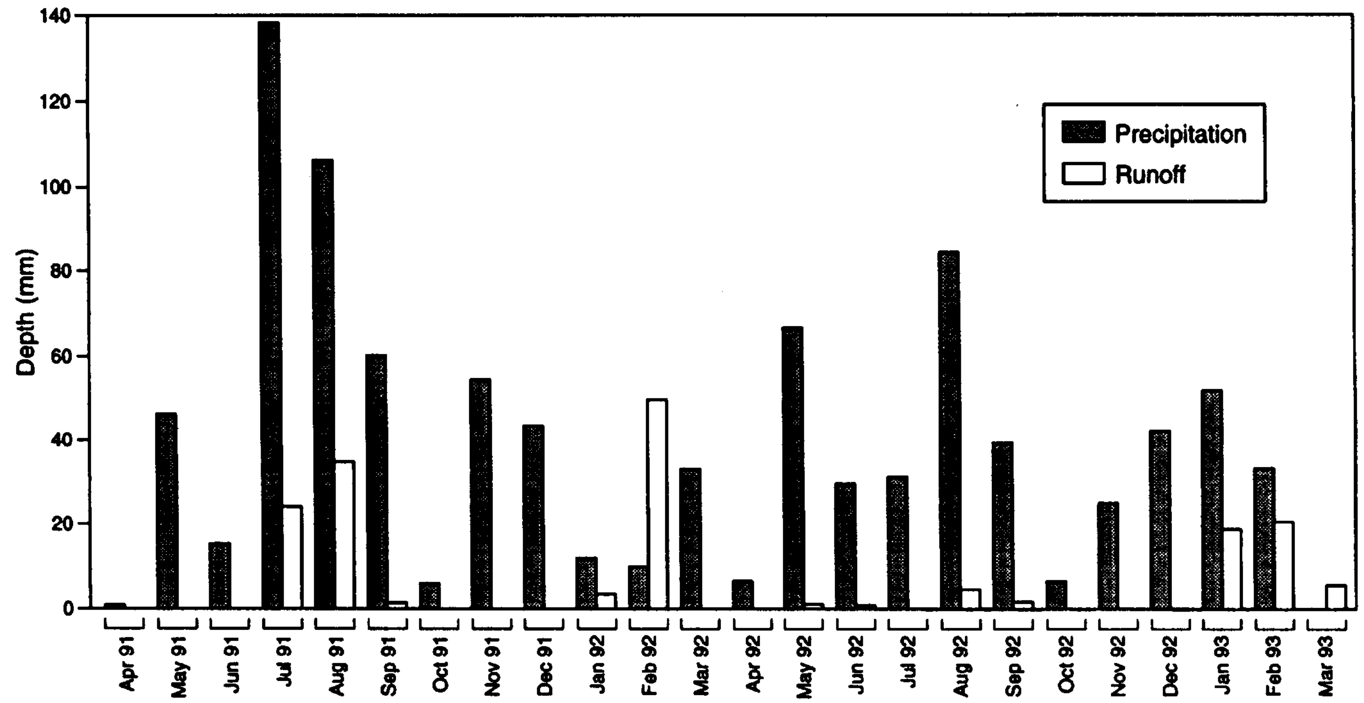

Fig. 2. Monthly precipitation vs runoff (totals averaged for all plots) April 1991-March 1993.

later) and the high elevation of the study area, which is near the limit for pinyon and juniper (as was seen in the Beaver Creek studies, runoff increased dramatically at the higher elevations).

Summer Runoff

The amount of runoff collected the first summer (1991) represented a significant portion of the summer water budget—in contrast with the second summer (1992), when runoff was almost negligible (Table 3). Long-term precipitation data (1911-1992) collected at a Los Alamos site about 300 m higher than our study site indicate that summer 1991 was wetter than average, whereas summer 1992 precipitation was about average (Fig. 4). We conclude from this that

Table 3. Runoff and precipitation by season.

Season	Precipitation (mm)		Plot runoff A	B	C	D	E	F	Average
Summer									
1991	365	Total (mm)	26.9	50.0	86.1	42.2	60.9	87.7	59.9
		(%)	7.4	13.7	23.6	11.6	16.7	24.0	16.2
1992	247	Total (mm)	2.1	1.1	7.4	2.5	1.8	24.6	7.0
		(%)	0.8	0.4	3.0	1.0	0.7	10.0	2.8
Winter									
1991-92	118	Total (mm)	47.8	25.6	*	41.8	71.8	74.0	52.2
		(%)	40.5	21.7	*	35.4	60.9	62.7	44.2
1992-93	151	Total(mm)	31.7	18.0	*	60.4	32.5	74.5	43.4
		(%)	21.0	11.9	*	40.1	21.6	49.4	28.8
Totals									
Apr 91-Feb 93	929	Total (mm)	108.5	94.7		146.9	167.0	260.8	
		(%)	11.7	10.2		15.8	18.0	28.1	

*= Plot C was not operational during the winter.

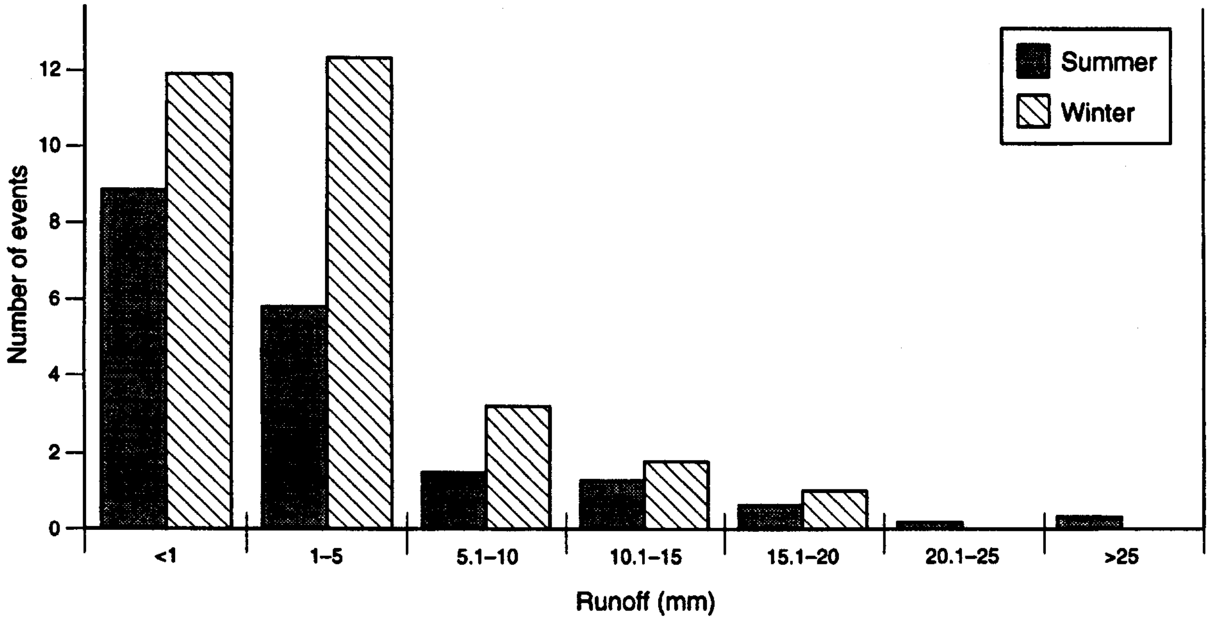

Fig. 3. Frequency distribution of summer and winter runoff events (averaged across all plots) April 1991-March 1993.

summer runoff in 1991 was higher than average. Figure 5 shows the relationship between precipitation and runoff amounts during the summer of 1991 for Plot F, where the greatest amount of runoff was measured. Note that from about mid July to mid August, when thundershowers were very frequent, runoff amounts were much higher with respect to precipitation amounts than during previous drier periods, and some runoff was generated during almost every precipitation event. The likely explanation for this is that as soil moisture increases, soil infiltration capacity decreases—a phenomenon well documented in the rangeland hydrology literature (e.g., Wilcox et al. 1988). Soil moisture data collected during the summer of 1991 from a woodland area adjacent to the study site shows that soil moisture increased from around 15% in May to about 35% in early August (Barnes et al.1992).

Figure 6 compares cumulative precipitation with cumulative runoff by plot for both summers, 1991 and 1992. The very different patterns of precipitation are evident: not only was there less precipitation overall in 1992 than 1991, it was also more spread out. The other

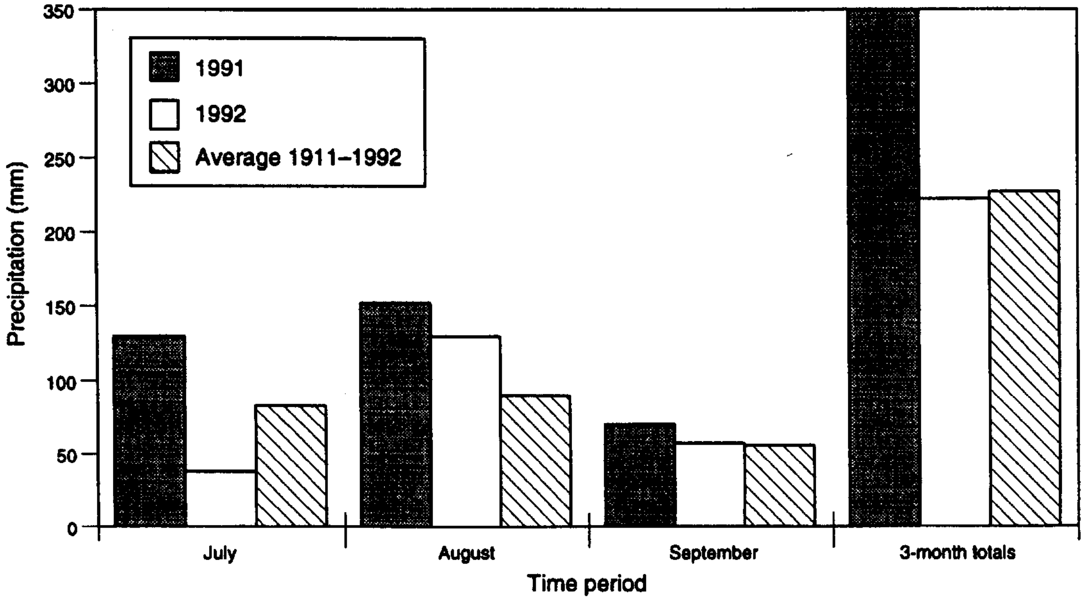

Fig. 4. Comparison of 1991, 1992, and average (1991-1992) summer precipitation amounts.

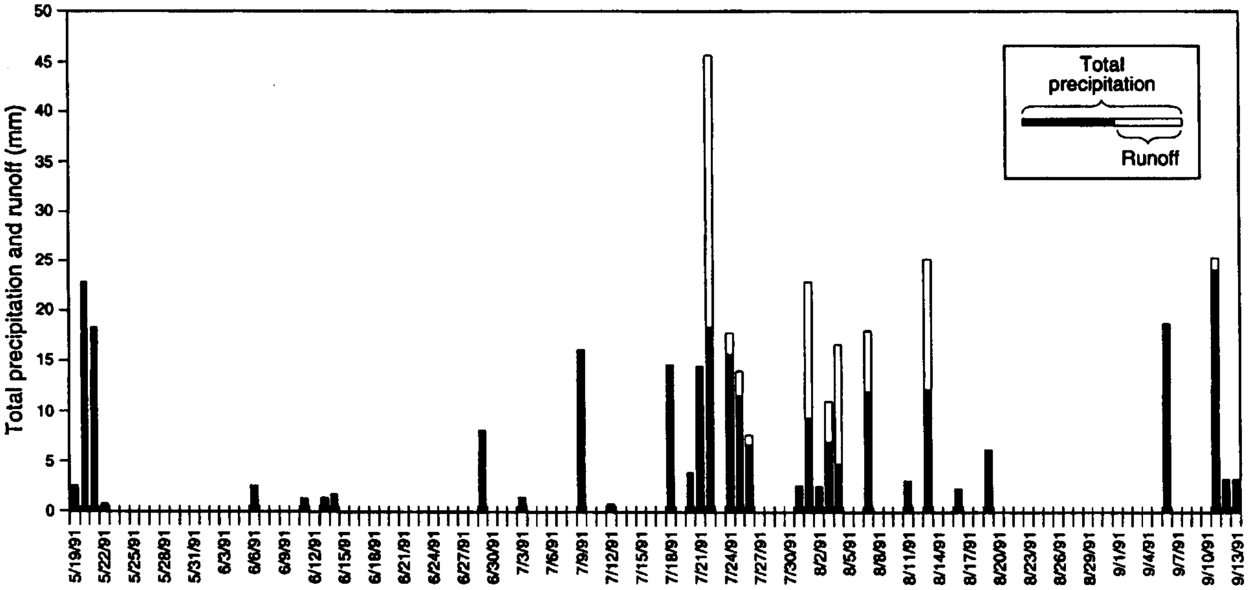

Fig. 5. Precipitation-runoff relationship for Plot F, summer 1991.

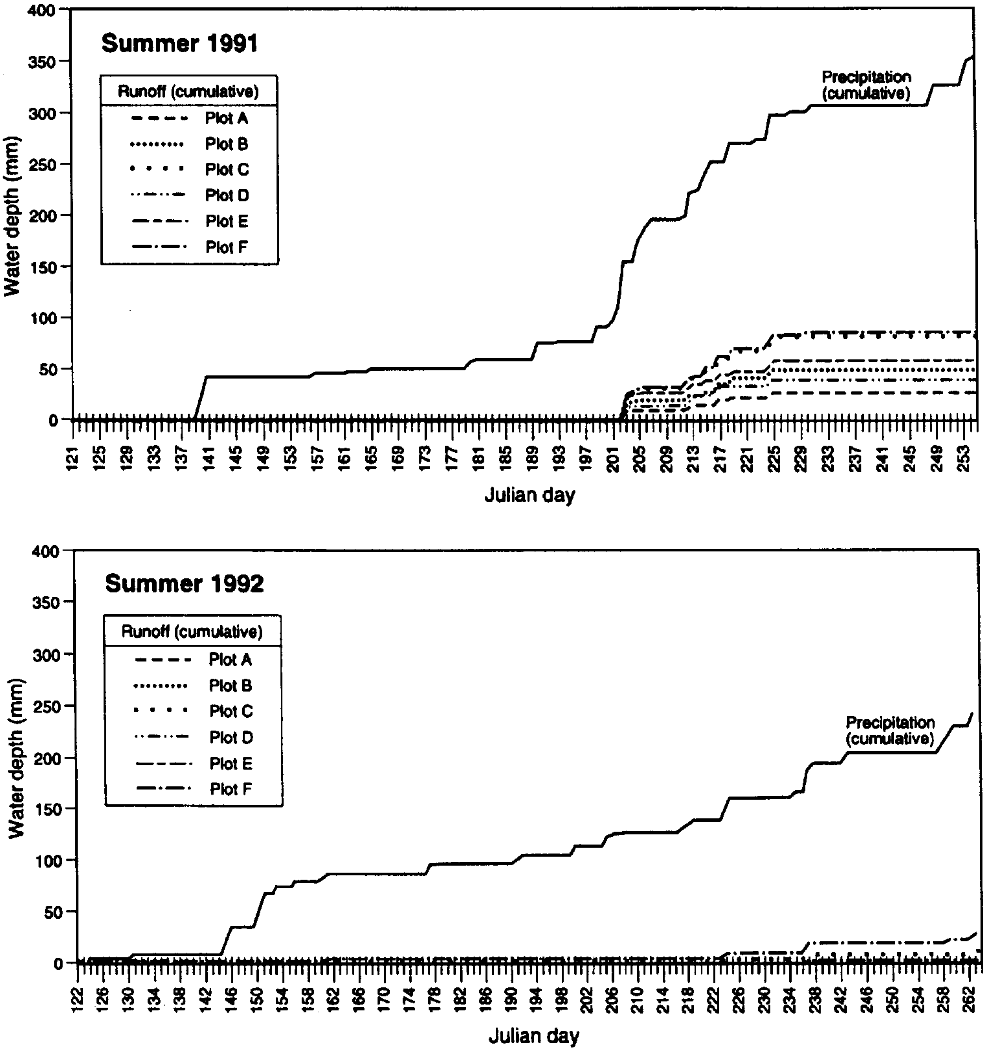

Fig. 6. Cumulative summer precipitation vs runoff, 1991 and 1992.

major observation was the difference in runoff between the undisturbed and the disturbed plots. Runoff amounts for both summer seasons were substantially higher for plots C and F than for the other plots (see also Table 3). It was especially high for plot F, where there was less regrowth of vegetation (Table 2).

Winter Runoff

Runoff measured during the 2 winter seasons (1991-92 and 1992-93) was appreciable, averaging more than 52 mm for winter 1991-92 and nearly 43.5 mm for winter 1992-93 (Fig. 2, Table 3). Even though the amount measured during the second winter was probably somewhat underestimated because of leakage problems at plots E and F—especially E—the overall results show higher runoff the first winter. This is particularly clear in the case of plots A and B, where we are reasonably certain there was no leakage. The only plot where more runoff was measured the second winter was Plot D. What is especially interesting is that the winter with the higher runoff was also the winter with the lower precipitation (Table 3); as a percentage of the winter water budget, runoff accounted for more than 44% the first winter vs less than 29% the second winter.

A more comprehensive picture of winter runoff patterns is presented in Figure 7, where cumulative runoff for each plot is compared with cumulative precipitation. This figure shows, first, that during the winter of 1991-92, most of the runoff came from snowmelt in the absence of precipitation; during the following winter, most of the runoff was produced by rain-on-snow events (as seen in the figure, at least 3 such events were recorded, on Julian days 7, 39, and 50). Second, general snowmelt began about 20 days earlier the first win-

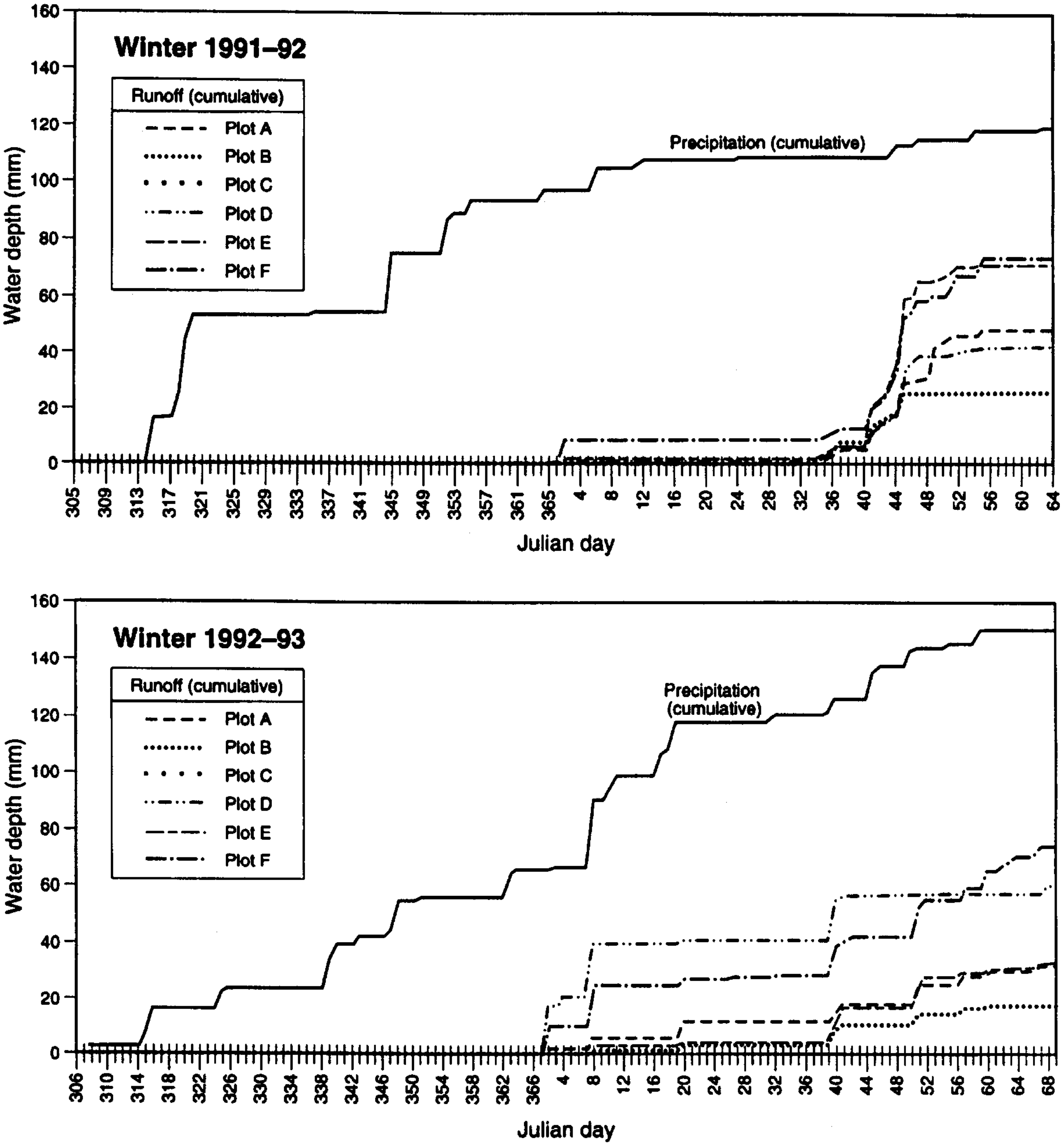

Fig. 7. Cumulative winter precipitation vs runoff, 1991-92 and 1992-93.

ter than it did the second. In early February of 1992, we began to observe a daily thawing and refreezing of the upper 5-10 cm of soil (which, when thawed, was completely saturated). Below that depth, the soils remained frozen through the period of active runoff. The second winter, snowmelt did not begin until late February, by which time the soil was probably more deeply thawed. No definite pattern of nightly refreezing was apparent.

On the basis of these observations, we theorize that soil frost dynamics in combination with the timing of general snowmelt could explain the higher amounts of runoff (despite lower precipitation) during the winter of 1991-92. Although no specific data were collected to support this idea, the earlier snowmelt in concert with frozen soils, which would inhibit infiltration, almost certainly contributed to the increased runoff measured the first winter. On the other hand, the later snowmelt combined with more deeply thawed soils the second winter would have encouraged more infiltration of water into the soil.

With respect to the effects of plot disturbance on winter runoff, the results of our study are not decisive because 1 of the disturbed plots (Plot C) malfunctioned both winters. Winter runoff was greatest from other plots that were not disturbed (Table 3).

Our study also yields some data relevant to another discussion. Dortignac had concluded, on the basis of data from earlier watershed investigations, that in the pinyon-juniper woodlands of northern New Mexico runoff is mainly a summer phenomenon. The large amounts of winter runoff we measured contrast sharply with that earlier data, and we believe the difference is explained by effects of scale: whereas Dortignac's conclusions were based on data collected from watersheds of 30 to 3,000 ha and focused on measurement of runoff in the stream channel, our study used plots many orders of magnitude smaller. Even during the periods of most active winter runoff, we found no water in the stream channel several hundred meters downslope of the plots. Apparently it was being absorbed en route, into "sink" or recharge areas such as pinyon-juniper canopy spaces, snow drifts, and/or alluvial-flood-plain sediments.

In other words, winter runoff appears to be locally important as a mechanism of redistribution of water, but these effects can be seen only at the smaller scales. Amerman and McGuinness (1967) were among the first to note the effects of scale on measured runoff and cautioned against "scaling up" plot data to predict hydrologic behavior at larger scales. Other researchers have also observed that the generation of runoff in arid and semiarid environments can vary greatly with scale. In the southwestern United States this phenomenon is usually attributed to channel transmission losses, primarily on the basis of work conducted at the Walnut Gulch Experimental Watershed in Arizona (Renard 1970). More recent work in Israel (Yair and Lavee 1985) has demonstrated that scale-related differences in measured runoff are also a function of differences in the infiltration capacity of hillslope soils. Because of these differences, some areas (lower-infiltration) function as *source areas* for runoff while others (higher-infiltration) serve as *sinks* for runoff.

Our observations indicate that redistribution of water by runoff is occurring in pinyon-juniper communities. Ecological investigators have suggested that this phenomenon is a major determinant of vegetation patterns in semiarid environments, and hydrological/ecological interactions is an area of active research (Yair and Danin 1980; Moorhead et al. 1989; Schlesinger et al. 1989; Cornet et al. 1992).

Erosion

The extent of erosion varied considerably, both by season and by plot (Table 4). Over the 2-year study, most of the erosion resulted from a few large events the first summer. (Other studies have also found that erosion was produced mainly by large runoff events—e.g., Hjelmfelt et al. 1986). Another finding, that sediment concentrations tended to decrease as the summer runoff season advanced—which we observed the first summer, when there were a large number of precipitation events—is similarly reflected in other studies. For example, Yair et al. (1980) observed that in arid regions of the northern Negev, sediment concentrations decreased progressively with repeated runoff events. In pinyon-juniper areas, it is possible that fine particles loosened by the freeze-thaw cycle of the previous winter are washed away early, and the remaining surface soil then becomes compacted. Schumm and Lusby (1963) demonstrated for the Mancos Shale that seasonal variations in soil erodibility and infiltration capacity were tied to variations in frost dynamics and the force of rainfall. This is probably equally true of pinyon-juniper woodlands and other semiarid environments.

Erosion rates were very high from the most disturbed plot, Plot F (Table 4), which had much more bare ground than the other plots. However, 1 undisturbed plot (E) also showed a quite high erosion rate. The reason for this is not obvious.

Finally, we noted that even when runoff was higher during the winter than the summer, snowmelt runoff produced very little erosion. This is consistent with the finding of Ellison (1948) that erosion is much lower in the absence of rainfall impact on the soil surface.

Table 4. Erosion of plots by season.

	Sediment			
Plot	Summer 1991	Summer 1992	Winter 1991-92	Winter 1992-93
	-kg/ha			
A	313	13	53	56
B	560	5	10	32
C	1089	42	*	*
D	280	5	67	107
E	2868	25	79	57
F	10831	255	118	131
Average	2656	58	65	77

*= Plot C was not operational during the winter.

Conclusions

The measurements made during our study support the following conclusions about runoff and erosion in intercanopy areas of pinyon-juniper woodlands in northern New Mexico.

Runoff takes place during 2 times of the year: mid summer (generated by thunderstorms) and mid to late winter (generated by snowmelt). At least on smaller scales, runoff can make up a substantial part of the winter water budget. During the 2-yr study period, runoff accounted for between 10 and 18% of the water budget for undisturbed sites (up to 28% for disturbed sites). This is higher than has been observed for many other pinyon-juniper studies (Table 1), which is probably explained partially by the high elevation of our site and partially by the small scale of our study.

Erosion from intercanopy pinyon-juniper sites having little bare ground is minimal, and increases as the extent of bare ground increases. Most of the erosion is produced by large summer thunderstorms. Erosion is slight during the winter, even when runoff is high, because of the absence of raindrop impact.

Both runoff and erosion are greater on disturbed sites during the summer. The effect of disturbance (extent of bare ground) is less pronounced during the winter.

Observations made during the course of this study suggest that the following hypotheses proposed for other semiarid landscapes are applicable to pinyon-juniper woodlands as well.

Hypothesis 1: *Runoff amounts vary with scale: runoff decreases as the size of the contributing area increases (and provides more opportunities for infiltration).* Other investigators have noted that in semiarid regions runoff varies with scale—because of either transmission losses in the stream channel or differences in soil infiltration capacities. We believe that in the pinyon-juniper communities of New Mexico, effects of scale are especially pronounced during the winter because runoff is generated from discrete points in the landscape (snowmelt will vary depending on topographic position). Our study allowed us to observe that winter runoff can be substantial locally, but that the water travels little distance before being absorbed into "sink" areas.

Hypothesis 2: *The infiltration capacity of soils is dynamic; it is closely tied to soil moisture content and/or soil frost conditions and is a major determinant of runoff amounts.* Rainfall simulation studies, such as those of Thurow et al. (1988), have demonstrated the dynamic nature of infiltration capacity. We believe that at our site, the two most important factors affecting soil infiltration capacity are soil moisture changes during the summer and soil freezing during the winter. The impact of soil frost on runoff in other semiarid environments is well recognized (for example, the sagebrush steppe—Johnson and McArthur 1973, Seyfried et al.1990); but the phenomenon has been little studied in pinyon-juniper landscapes.

Hypothesis 3: *Soil erodibility follows an annual cycle. It is highest at the end of the freeze-thaw period of late winter and lowest at the end of the summer rainy season, when soils have been compacted by repeated rainfall.* Our observations suggest that this hypothesis, proposed by Schumm and Lusby (1963) for the Mancos Shale areas in western Colorado, also applies to pinyon-juniper woodlands. During the first summer of our study, when runoff was frequent, sediment concentrations tended to decrease as the summer advanced.

These conclusions and hypotheses have important implications, among them that surface runoff is an important mechanism for the redistribution of water, sediments, nutrients, and contaminants in pinyon-juniper woodlands, especially on a local scale. In these environments, it may be said that runoff is often a small-scale phenomenon, and that on the small scale, it can make up a large portion of the total water budget. Adequate prediction of surface runoff in these environments will require models that appropriately simulate both the spatial (Hypothesis 1) and the temporal (Hypotheses 2 and 3) variability of these environments—one of the major challenges currently facing hydrological researchers.

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