
3 **Runoff and Erosion from a Rapidly Eroding Pinyon–Juniper Hillslope**

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1 **INTRODUCTION**

Pinyon–Juniper woodlands are extensive in the western United States, covering around 24 million ha. Although the range of these woodlands has fluctuated considerably over the last 12 000 years, largely in response to climate change, their expansion and increase in density during the last 100 years has been unprecedented (Miller and Wigand 1994). A number of explanations for this expansion have been put forward, including overgrazing, fire control, climate change, and higher concentrations of carbon dioxide.

An important ramification of the spread and the increase in density of pinyon–juniper woodlands is a decline in understorey vegetation. These trees—juniper in particular—have widely spread lateral root systems and are able to out-compete many of the herbaceous species for the limited water and nutrient resources (Johnsen 1962; Gottfried *et al.* 1995). A diminished understorey often results in a dramatic acceleration of soil erosion, especially in the more xeric locations, such as south-facing slopes and areas where soils are shallow (Miller and Wigand 1994). Accelerated erosion in pinyon–juniper woodlands represents a threat to the long-term stability and productivity of these regions. But despite widespread recognition of this threat, there have been few, if any, sustained efforts to study the phenomenon and the runoff dynamics associated with it. Schmidt (1987) noted that “other than the water yield studies at Corduroy Creek and Beaver Creek in Arizona, most of the remaining work has been conducted as small plot studies in Utah and Nevada.” Recognizing that an adequate understanding of runoff and erosion processes cannot be obtained without more long-term, catchment-scale studies, he makes a forceful plea for such work.

Because our ability to find effective solutions to many environmental problems depends on understanding how erosion processes behave and the factors that control those processes, we have initiated a number of hillslope- and catchment-scale hydrologic studies on the Pajarito Plateau in northern New Mexico (Wilcox and

Breshears 1995), one of which focuses on a rapidly eroding pinyon-juniper catchment (1 ha) within Bandelier National Monument. The vegetation in this area has changed markedly over the past century, from an open forest dominated by ponderosa pine (*Pinus ponderosa*) to a woodland entirely composed of pinyon (*Pinus edulis*) and one-seed juniper (*Juniperus monosperma*). Since July of 1993, we have been gathering data on the hydrology, geomorphology, ecology and soils of the site. These data indicate greatly accelerated erosion of the intercanopy soils. We hypothesize that this accelerated erosion was triggered by a reduction in ground cover resulting from the combined and interrelated effects of overgrazing, increase in the density of pinyon and juniper, and a severe drought in the 1950s.

The long-term objectives of the study are to (1) estimate water and sediment budgets for rapidly eroding semi-arid woodlands; (2) determine the effect of 20th century vegetation change on erosion processes; (3) develop a conceptual and quantitative understanding of the relationships between runoff and erosion; and (4) determine what effect scale has on runoff and erosion in rapidly eroding semi-arid woodlands. Given the current scarcity of data, this information will prove valuable for evaluating runoff and erosion models for these ecosystems. Although we recognize that these long-term objectives have not been fully attained less than three years into the study, our results to date have proved most interesting and have added significantly to our knowledge of runoff and erosion dynamics in these important woodlands.

2 STUDY AREA

The subject catchment is located in northern New Mexico, within Bandelier National Monument (Figure 3.1). The elevation of the area ranges from 1969 to 1990 m; average annual precipitation for this elevation on the Pajarito Plateau is around 360 mm (Bowen 1990). Soils on the site developed on tuff residua (although there have probably been small inputs of material from aeolian sources) and pumice. An open ponderosa pine forest dominated the site until the late 1800s, when livestock grazing and an associated reduction in fire frequency (both from fire suppression and reduced ground fuel) allowed pinyon and juniper to markedly increase in density (Allen 1996). The growing pinyon-juniper population probably caused a further decline in herbaceous cover, which reached a critical point with the severe drought of the 1950s, that also killed all the ponderosa pine. A large feral burrow population was present in the area from 1940 to 1980 and further stressed the herbaceous cover. These events apparently triggered the current episode of accelerated erosion. Today, fallen ponderosa pine logs are scattered across the area, but there are no live ponderosa trees. Clumps of pinyon and juniper trees provide canopy cover over about half the catchment. Slope of the catchment is around 5%. Ground surfaces in intercanopy patches are mostly bare soil or rock, while those beneath the canopy are mostly needle litter. In addition to the extensive patches of bare soil and the scant vegetation coverage, evidence of accelerated erosion includes numerous hillslope channels, soil pedestals, and exposed subsoils. Although channelling is extensive, the proximity of bedrock to the soil surface prevents the formation of gullies or deeply

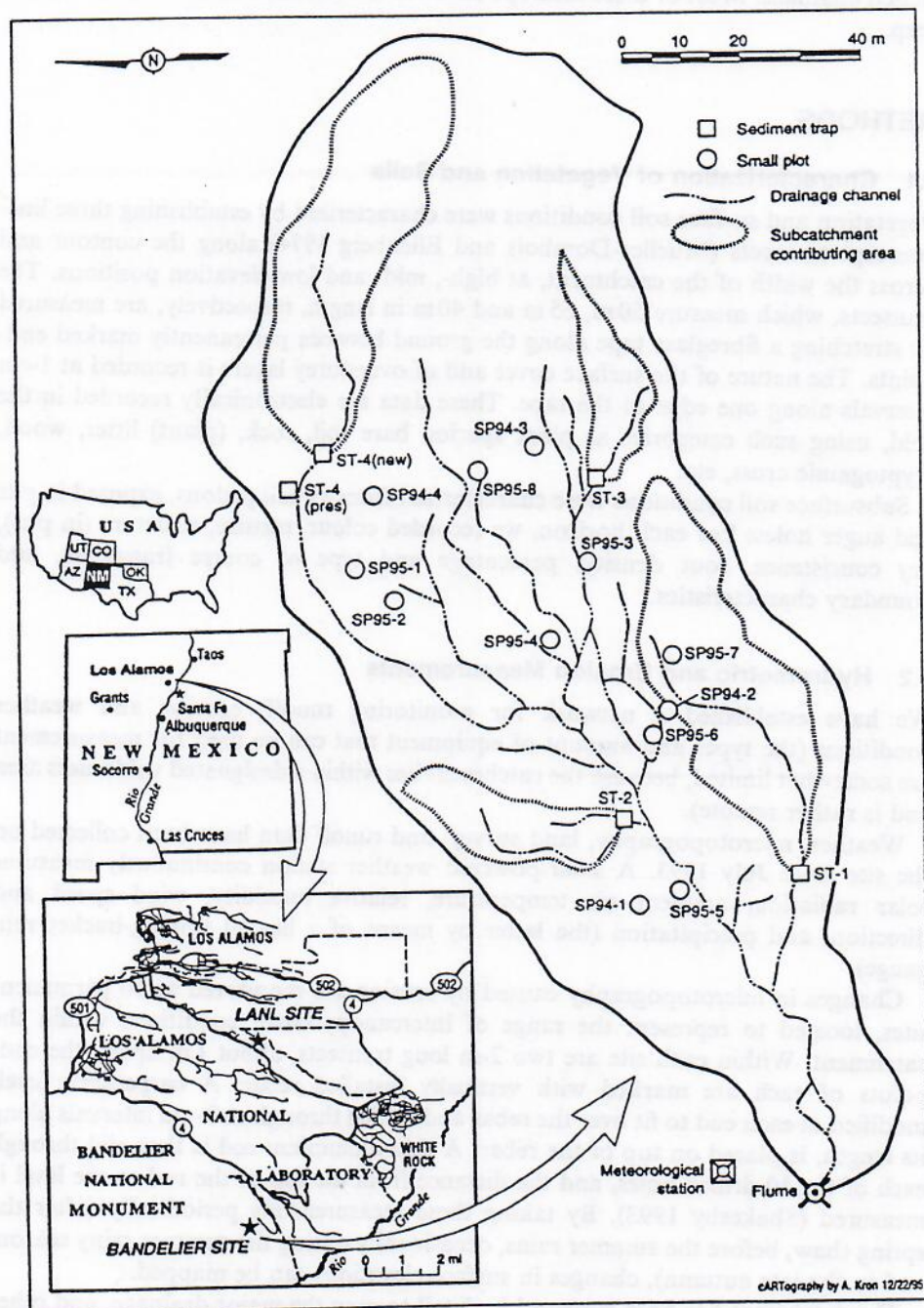


Figure 3.1 Location of study area, including details of Bandelier site

incised channels. Most of these hillslope channels are less than 30 cm wide and 10 cm deep.

METHODS

3.1 Characterization of Vegetation and Soils

Vegetation and surface soil conditions were characterized by establishing three line-intercept transects (Mueller-Dombois and Ellenberg 1974) along the contour and across the width of the catchment, at high-, mid- and low-elevation positions. The transects, which measure 50 m, 65 m and 40 m in length, respectively, are measured by stretching a fibreglass tape along the ground between permanently marked end-points. The nature of the surface cover and of overstorey layers is recorded at 1-cm intervals along one edge of the tape. These data are electronically recorded in the field, using such categories as plant species, bare soil, rock, (plant) litter, wood, cryptogamic crust, etc.

Subsurface soil conditions were characterized from 19 soil pedons, exposed in pits and auger holes. For each horizon, we recorded colour, texture, structure (in pits), dry consistence, root density, percentage and type of coarse fragments, and boundary characteristics.

3.2 Hydrometric and Erosion Measurements

We have established a network for monitoring runoff, erosion and weather conditions (the types and amount of equipment that can be used for measurement are somewhat limited, because the catchment lies within a designated wilderness area and is rather remote).

Weather, microtopography, land survey, and runoff data have been collected on the site since July 1993. A solar-powered weather station continuously measures solar radiation, ambient air temperature, relative humidity, wind speed and direction, and precipitation (the latter by means of a heated tipping-bucket rain gauge).

Changes in microtopography caused by erosion are monitored at 10 permanent sites, located to represent the range of intercanopy cover conditions within the catchment. Within each site are two 2-m long transects, about 1 m apart; the end-points of each are marked with vertically installed rebar. A carpenter's level, modified at each end to fit over the rebar and drilled through at 8-cm intervals along its length, is placed on top of the rebar. A thin aluminium rod is then slid through each of the 10 drilled holes, and the distance from the top of the rod to the level is measured (Shakesby 1993). By taking these measurements periodically (after the spring thaw, before the summer rains, occasionally during the summer rainy season, and in the late autumn), changes in surface elevations can be mapped.

The catchment has been surveyed in detail to map the major drainage, and other topographic features.

Individual runoff events from the catchment are measured by means of a flume installed in a bedrock-floored segment of the main channel, above the point at which

the channel drops into a canyon. Following the design of Replogle *et al.* (1990), the flume is constructed from a 4-m-long piece of 38-cm PVC pipe; the floor of the pipe has a flat concrete sill that forces the flow to critical depth (Froude number = 1.0) as it exits the pipe. Water height in the flume is measured by a pressure transducer located in an adjacent stilling well. Because of the high sediment and debris load from this catchment, however, there have been some problems in measuring runoff, especially for the larger events. The pipe connecting the flume and the stilling well becomes clogged with sediment when runoff is receding, with the result that for the last one-half to one-third of the hydrograph recession limb, the flow must be estimated. In addition, for the largest runoff events, debris may accumulate in front of the flume, forcing water around it (this has happened on at least one occasion).

Concurrent with installation of the flume, a pit was excavated immediately upstream to capture sediment being transported in the channel. However, with its 0.4-m³ capacity, the pit was found to be too small to trap all the sediment leaving the catchment when discharge was moderate or high. Because it was not practical to enlarge the pit, which was already dug into bedrock, in 1995 we installed four additional sediment traps, each at the base of a tributary channel within the catchment (Figure 3.1). The traps are lined with wood and have a storage capacity of 1 m³. The four contributing areas (subcatchments) range from 300 to 1100 m².

In 1995 we also completed a network of 12 small (1 m²) runoff plots; each is equipped, along its downstream end, with a gutter that catches the runoff and channels it into a bucket set into the ground. After each runoff event, the volume of runoff is recorded; two litres of the water (if available) is then reserved for measurement of sediment concentration. Ten of the plots were established in the intercanopy areas having tuff residua soils, one was established under a tree canopy, and one was established in an intercanopy area having high-pumice soil.

4 RESULTS

4.1 Vegetation

Our vegetation characterizations indicate that about 45% of the catchment has a canopy of small pinyon and juniper trees. Canopy understoreys (93%) are dominated by litter (needles, dead wood), whereas intercanopy areas are mostly bare ground (66%), with about 30% litter and only 2.2% basal cover by herbaceous plants. The most important herbaceous species is blue grama (*Bouteloua gracilis*), which makes up about 1% of basal cover. Cryptogams account for less than 1% of basal cover—another striking piece of evidence of accelerated erosion (in nearby stable woodlands we have measured cryptogamic cover as high as 50% (Wilcox 1994)).

4.2 Soils

Most of the soils in the catchment (dominantly Lithic and Typic Haplustalfs) are shallow, having an average depth of 35 cm. Some soils, consisting of a buried B horizon under a 50- to 75-cm layer of locally reworked pumice, are considerably

deeper. The buried portions of these soils, which average 69 cm in thickness, are presumably the largely uneroded lateral equivalent of surface soils in the non-pumice areas. Assuming that to be the case, we can infer that the surface soils in the non-pumice areas have lost roughly 34 cm to erosion (in addition to any overlying pumice). The timing of the loss cannot be determined on the basis of the pumice alone, which was initially deposited some 50 000 to 60 000 years ago (Reneau *et al.* 1996) and may have been locally reworked more recently. There is growing evidence, however, for multiple periods of erosion on the Pajarito Plateau over the past 10 000 years (Longmire *et al.* 1995).

At the same time, we do find clues to recent erosion rates in the morphology of soils upslope and downslope of fallen ponderosa pine trees (the trees, which based on examination of sequential aerial photographs, fell in the 1960s, have acted as natural sediment traps). Four of five pedons immediately upslope of these trees include buried A and B horizons, overlain by an average of 12 cm of recent sediment. For the 30-year period since the trees fell, this represents an average sediment deposition rate of about 4 mm per year. Downslope of the fallen trees, slopes are steeper and the reddish B horizons are commonly exposed in broad patches. In contrast to their upslope (buried) counterparts, these soils have been stripped of much of their A horizon (an average of 12 cm), probably in the same 30-year period that saw deposition behind the fallen trees. Thus, we have a rough estimate based on soil morphology of about 4 mm per year of erosion.

4.3 Runoff

4.3.1 Catchment scale runoff

A summary of catchment-scale runoff and the precipitation that generated it is presented in Table 3.1. Since July 1993, when the first measurements were taken, 19 runoff events have been recorded—all but one generated by intense summer thunderstorms. The highest rainfall intensity recorded at the site was on 29 June 1995: 2.7 mm/min (such intensities are maintained only for a few minutes at a time). The debris transported by this event blocked the flume, diverting runoff around it (for this reason, the runoff volume shown in Table 3.2 for this event was estimated from the small plot data). Runoff at this site is typical of that of many semi-arid landscapes, in that it is of short duration and peak flow occurs within minutes of the onset of runoff (Figure 3.2(a)).

In terms of volume, the largest runoff event was actually produced by a fall frontal storm, which dropped 55 mm of precipitation in two days. Runoff began after the first 24 hours, during which about 15 mm of rain fell, and continued unabated for a 6-h period (Figure 3.2(b)); another 30 mm of rain fell during that time, but with rainfall intensity never exceeding 0.25 mm/min.

Because of below-freezing temperatures, the flume is not operational in the winter and spring. However, we did observe evidence (pools of water in the channel, traces of sediment in the flume) of small amounts of spring runoff on one occasion, probably from snowmelt while the soils were still frozen.

Water budget calculations are given in Table 3.2. We have assumed that at our site, as in other semi-arid areas, groundwater recharge makes up an insignificant

Table 3.1 Catchment-scale runoff (July 1993–September 1995)

Date	Precipitation (mm)	Peak precipitation (mm/min)	Catchment runoff (mm)	Peak flow (l/s)
<i>1993</i>				
28 July 93	36	1.8	7	3660
6 Aug. 93	9	0.8	1	960
20 Aug. 93	5	0.5	<1	480
26 Aug. 93	23	0.5	4	780
27 Aug. 93	24	2.0	12	5160
28 Aug. 93	11	0.8	3	600
6 Sept. 93	19	2.0	6	3480
13 Sept. 93	4	2.0	<1	570
<i>1994</i>				
2 Aug. 94	6	1.0	2	1800
21 Aug. 94	4	1.5	1	2220
5 Sept. 94	10	0.8	5	2340
15 Oct. 94	54	0.5	20	1560
<i>1995</i>				
29 May 95	14	1.0	4	4070
29 June 95	26	2.7	>10 ^a	
17 July 95	14	0.5	1	720
18 July 95	5	0.2	<1	375
13 Aug. 95	10	1.0	2	1540
18 Sept. 95	9	1.0	2	1340
29 Sept. 95	3	0.8	1	1470

^aFlume clogged with debris; runoff volume estimated from small-plot data.

portion of the water budget and that any water not accounted for as surface runoff is lost to evapotranspiration. Precipitation during the period of observation has been higher than the average projected for this elevation on the basis of long-term measurements in the area (Bowen 1990). Annual precipitation was especially high in water years 1995 (October 1994–September 1995), mainly as a result of heavy rainfall during October and November 1994. As a fraction of the water budget for the two complete years of observation, the contribution of runoff has been small (2% in WY 94 and 7% in WY 95). It does, however, contribute a much higher percentage of the budget for the summer rainy season (Table 3.2).

4.3.2 Small plot runoff

For the third summer rainy season (summer of 1995), we have data from the small plots as well as from the catchment (Table 3.3). Runoff from these plots was recorded for a total of 11 events (those on 17 and 18 July were treated as a single event), including five for which small amounts of runoff were measured in at least some of the plots, but none was measured for the catchment. There was considerable variability in runoff amounts from plot to plot; intercanopy tuff residua plots produced the most, and the amounts from these plots were also highly

Table 3.2 Annual and summer precipitation and runoff for the period of observation

Water year	Total precipitation (mm)	Summer precipitation (mm)	Yearly runoff (mm)	Summer runoff (mm)	Total runoff (%)	Summer runoff (%)
1993		195 ^a	35	35		18
1994	384	131 ^b	8	8	2	6
1995	549	123 ^b	41	21	7	17

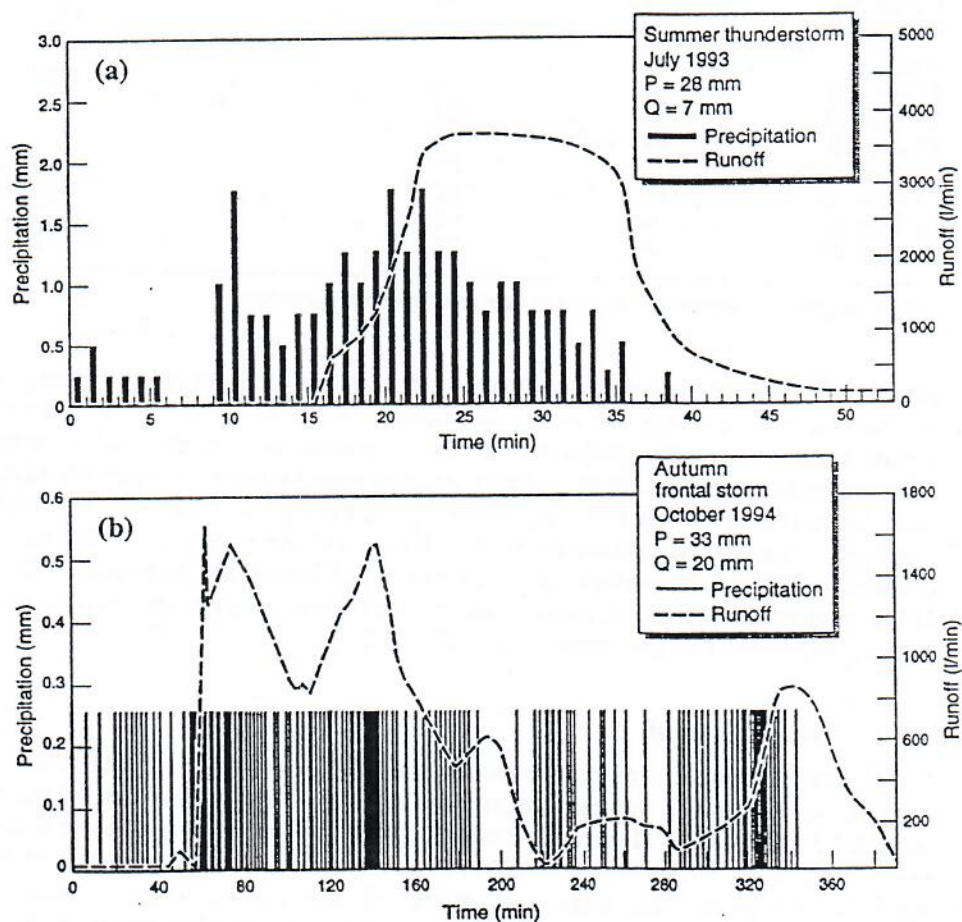
^a26 July–31 Sept.^b1 July–30 Sept.**Figure 3.2** Rainfall and runoff for (a) a summer thunderstorm and (b) an autumn frontal storm

Table 3.3 Summary of small plot runoff in the summer of 1995

Plot no.	Plot description	Event day											
		29 May	26 June	29 June	30 June	16 July	17,18-July	5 Aug.	13 Aug.	10 Sept.	17 Sept.	29 Sept.	
		Total precipitation (mm)											
		42	6	35	4	10	31	8	14	17.5	8.5	12.5	
		Runoff (mm)											
		Total											
95-5	Intercanopy - tuff residua	2.0	0.0	20.0	1.3	0.8	12.5	0.1	3.0	3.0	4.5	3.0	50.2
95-3	Intercanopy - tuff residua	4.5	0.0	20.0	0.7	0.0	10.0	0.6	4.0	1.0	4.0	4.0	48.8
95-7	Intercanopy - tuff residua	3.5	0.0	25.0	0.8	0.0	7.3	0.1	4.0	1.0	4.0	2.0	47.7
95-2	Intercanopy - tuff residua	8.0	0.2	22.0	0.0	0.0	4.5	0.1	3.5	0.1	3.0	2.5	43.9
95-8	Intercanopy - tuff residua	10.0	0.0	24.0	0.0	0.0	1.5	0.0	2.5	0.1	2.8	2.0	42.9
95-4	Intercanopy - tuff residua	5.0	0.2	20.0	0.0	0.0	3.8	0.0	2.0	0.0	1.1	2.0	34.1
94-4	Intercanopy - tuff residua	6.5	0.0	20.0	0.1	0.0	2.0	0.0	2.0	0.0	1.2	1.2	33.0
95-1	Intercanopy - tuff residua	2.0	0.1	15.0	0.0	0.0	1.0	0.0	1.0	0.0	2.5	2.0	23.6
94-3	Intercanopy - tuff residua	^a	0.0	19.0	0.0	0.0	0.6	0.0	0.3	0.0	0.5	1.0	21.4
94-2	Intercanopy - tuff residua	2.0	0.0	12.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	14.3
95-6	Canopy	0.5	0.0	5.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	5.6
94-1	Interspace - pumice soil	0.0	0.0	3.5	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	3.7
Weighted average (mm)													
2.18	0.02	10.73	0.12	0.03	1.78	0.04	0.91	0.21	0.96	0.79	17.6		

^aPlot malfunction.

variable, ranging from 14 to 50 mm. The tuff residua plot that produced only 14 mm, No. 94-2, differs from the others in that cryptogamic cover is still partially intact. Very little runoff came from either the canopy plot or the pumice-soil plot; the little that was measured came mostly from the large storm of 29 June.

Using the small plot data, we computed a "weighted average" for runoff from the catchment. Each plot was assigned to one of three categories on the basis of cover type (canopy, intercanopy with pumice soil, and intercanopy with tuff residua soil) and weighted according to the percentage of the catchment each cover type was estimated to represent. The canopy plot was weighted 50%, the pumice-soil plot 10%, and the tuff residua plots (using an average of the ten) 40%. The results of this computation for each runoff event were then compared with runoff measured at the flume (Figure 3.3). Although the match is quite good, catchment-scale runoff is generally slightly higher, suggesting that we are not sufficiently weighting the high-runoff-producing areas. The most important implication, however, is that little runoff is being stored on the catchment (otherwise plot-scale runoff would be greater than catchment-scale runoff).

4.4 Erosion

4.4.1 Microtopography Measurements

Microtopographic measurements have been made regularly since July 1993; since that time, surface elevations have changed in a consistent and predictable pattern, in response to (1) soil erosion during the summer rains, (2) frost heaving in the early spring, and (3) raindrop compaction in the spring and summer. We have found that over a period of one year, surface changes due to frost heaving and those due to raindrop compaction are roughly equal. Between July 1993 and September 1995, the average change in elevation of the 400 measured points at the 20 sites is -6.7 mm, most or all of which we attribute to soil erosion. Three representative micro-

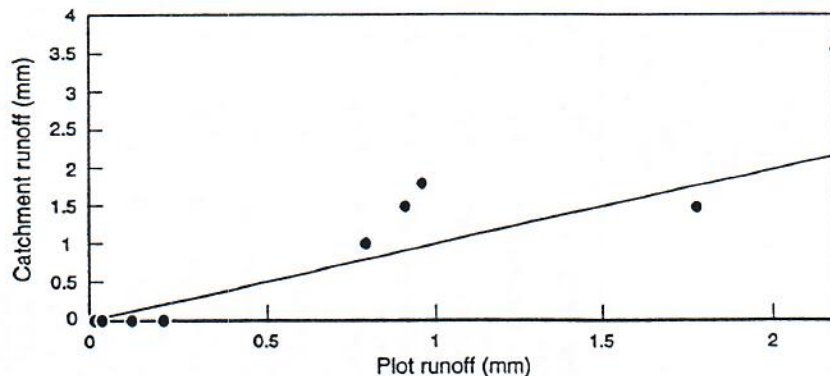


Figure 3.3 Runoff amounts calculated from weighted averages of small-plot data compared with those measured at the catchment outlet. The line represents a perfect fit

topographic profiles are shown in Figure 3.4: a rapidly eroding section from which as much as 7 cm of soil has been lost in a 26-month period (Figure 3.4(a)); a deposition zone in which up to 8 cm of sediment has accumulated, underscoring the dynamic changes occurring on the hillslope (Figure 3.4(b)); and a location at which there is still some cryptogamic cover and at which erosion has been comparatively small, showing the stabilizing effect of this cover (Figure 3.4(c)).

An estimate of erosion in t/ha is given by the following expression:

$$E = (B_d)(H)(10) \quad (3.1)$$

where E is erosion (t/ha), B_d is soil bulk density (g/cm^3), and H is net change in surface elevation.

Assuming an average loss in surface elevation of 6.7 mm for half of the catchment (the intercanopy areas) and a bulk density of 1.4 g/cm^3 , we estimate total erosion from the catchment at about 47 t/ha or 15 600 kg/ha year.

4.4.2 Small Plot Erosion

Erosion data collected from the small plot network in 1995 are shown in Table 3.4. By far, most of the erosion was produced by the largest storm, that of 29 July. The plots show dramatic differences in extent of erosion. For example, erosion was two orders of magnitude greater from many of the intercanopy plots on tuff residua than from either the canopy plot or the pumice-soil plot.

4.4.3 Subcatchment and Catchment Erosion

Estimates of erosion during 1995 for the catchment as a whole and for the four subcatchments are given in Table 3.5. We note trends similar to those observed from the small plots, namely, that most of the erosion was produced by the single largest event; however, erosion at the subcatchment scale is an order of magnitude greater than that at the plot scale, reflecting the influence of channel erosion. As already noted, there are numerous small channels across the catchment. In fact, in many locations, the hillslope has the appearance of a braided stream channel. In addition, there was considerable variability in erosion among the subcatchments; for example, erosion from subcatchment 2 was four times greater than that from subcatchment 1 (large portions of which consist of pumice soil).

As previously noted, because the sediment trap at the catchment outlet was too small for larger amounts of sediment, no measurements are available for the first two events of the year, both of which overtopped the trap. For the four smaller storms, erosion was greater at the subcatchment scale than at the catchment scale, indicating storage of sediment on the hillslope (at least for the smaller events); and indeed, we observe accumulations of sediment in many areas in the catchment hillslopes and channels. We hypothesize that during larger events, these sediment storage sites are evacuated—and, thus, that over a period of a year or two, the net quantities of sediment leaving the catchment are probably roughly the same as those leaving the subcatchments.

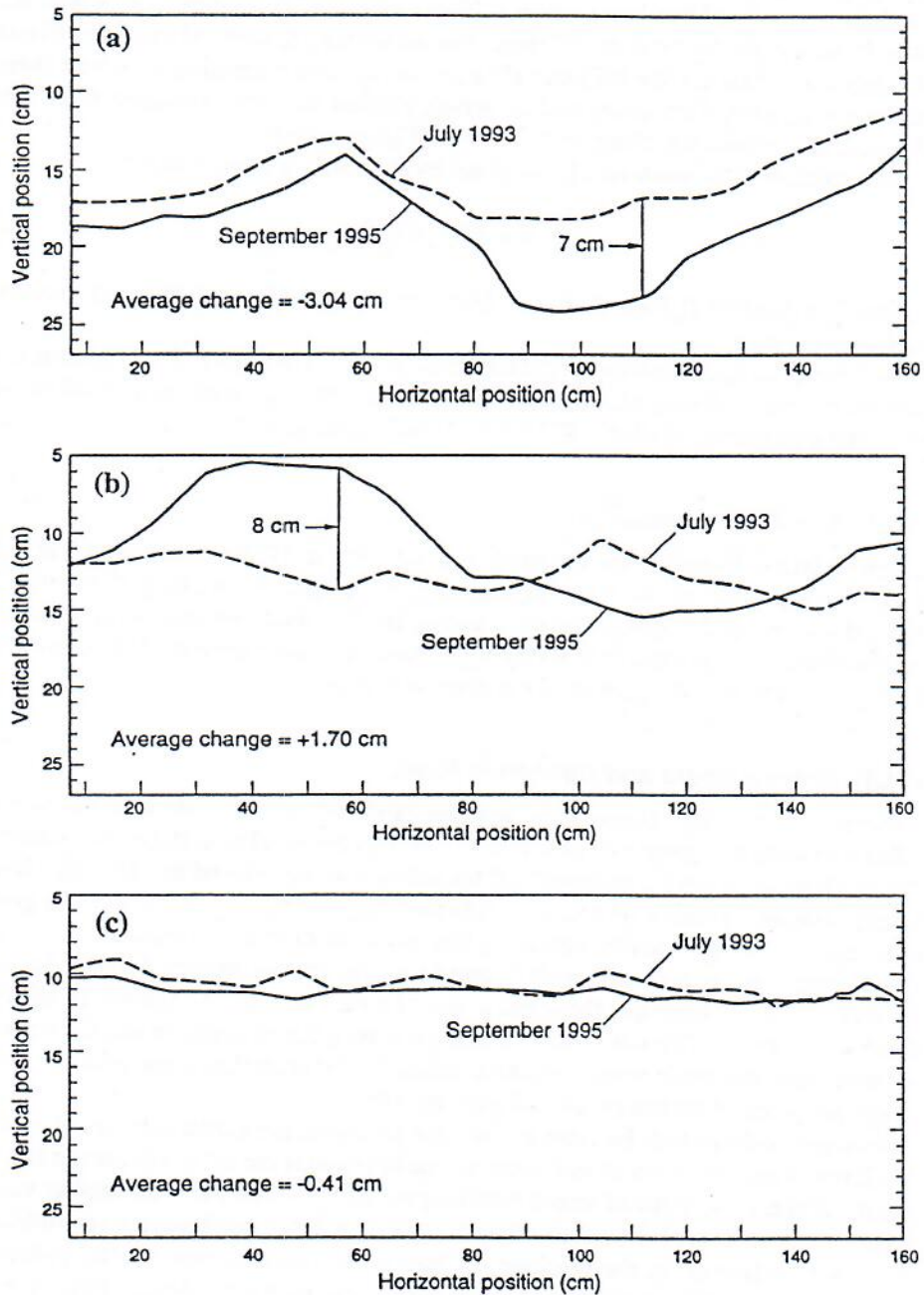


Figure 3.4 Microtopographic changes at three locations within the catchment representative of (a) an eroding surface; (b) a depositional surface; and (c) a relatively stable surface

Table 3.4 Summary of small plot erosion in the summer of 1995

Table 3.4 Summary of small plot erosion in the summer of 1955

Plot no.	Plot description	Event date											Total	
		Erosion (g/m ²)												
		29 May	26 June	29 June	30 June	16 July	18 July	15 Aug.	13 Aug.	10 Sept.	17 Sept.	29 Sept.		
95-5	Intercanopy tuff residua	13	0	179	1	2	8	0	15	3	12	10	244	
95-3	Intercanopy tuff residua	32	0	393	7	0	17	15	65	2	37	167	736	
95-7	Intercanopy tuff residua	12	0	224	2	0	3	0	46	3	26	15	330	
95-2	Intercanopy tuff residua	34	1	167	0	0	2	0	14	0	102	23	344	
95-8	Intercanopy tuff residua	88	0	250	0	0	3	0	57	0	22	68	488	
95-4	Intercanopy tuff residua	24	0	93	0	0	2	0	4	0	1	12	136	
94-4	Intercanopy tuff residua	43	0	257	0	0	2	0	54	0	4	38	398	
95-1	Intercanopy tuff residua	6	0	84	0	0	0	0	4	0	5	15	114	
94-3	Intercanopy tuff residua	a	0	173	0	0	0	0	3	0	1	6	185	
94-2	Intercanopy tuff residua	2	0	32	0	0	0	0	0	0	0	0	34	
95-6	Canopy	1	0	5	0	0	0	0	0	0	0	0	6	
94-1	Intercanopy pumice soil	0	0	3	0	0	0	0	0	0	0	0	3	
Weighted average														
		12	0	77	0	0	1	1	10	0	8	14	124	

^aPlot malfunction.

Table 3.5 Subcatchment- and catchment-scale sediment yields

		Event date						
		29 May	29 June	18 July	13 Aug.	17 Sept.	29 Sept.	
		Catchment runoff (mm)						
		3.6	>10	1.5	1.5	1.8	1	
	Area (m ²)	Erosion (g/m ²)						Total ^b
Subcatchment 1	1046	65	239	10	15	0	14.93	279
Subcatchment 2	308	^a	921	15	77	0	101.44	1114
Subcatchment 3	308	294	468	152	25	16.7	25.36	687
Subcatchment 4	1107	^a	493	56	28	31.75	14.11	623
Subcatchment average		180	530	59	36	12	39	855
Catchment	10 000	>40	>40	19.5	22.6	17.18	14.06	

^aTrap not yet installed.^bTotalled for last three events only.

5 DISCUSSION AND CONCLUSIONS

The expansion of pinyon-juniper woodlands during the last century is unprecedented and incontrovertible (Miller and Wigand 1994). Although it is widely believed that this expansion has led to increased soil erosion, this belief remains controversial, being based mostly on anecdotal information (Gottfried *et al.* 1995; Allen 1999). The effect of pinyon-juniper expansion on the soil resource has not been studied systematically, and the work that has been done consists mainly of small plot studies using artificial rainfall. While this work has added to our knowledge, an adequate understanding of erosion processes in pinyon-juniper woodlands will come only through larger-scale studies (in terms of both time and space). The small catchment study described here is a step in that direction, and although longer-term observations will be required to fully address our objectives, the insights gained from these first 26 months are important. In regard to the project objectives, we can say the following.

5.1 Objective 1: Estimate Water and Sediment Budgets for Rapidly Eroding Semi-arid Woodlands

In semi-arid environments, measurements must be taken over many years to develop representative "averages" for water budget components. The estimates we have made so far are based on the assumption that contribution to groundwater is zero (any water that does not run off will be evapotranspired). Our results to date indicate that runoff accounts for less than 10%—and perhaps closer to 5%—of the water budget of the catchment, which is consistent with data from other semi-arid

environments. In the summer rainy season, however, runoff makes up perhaps 15–20% of the water budget. For many of the intercanopy areas the runoff percentage during this time may be as high as 40%.

To estimate erosion from the catchment, we are directly measuring erosion at a number of scales: plot (1 m^2), subcatchment ($300\text{--}1100\text{ m}^2$), and catchment ($10\,000\text{ m}^2$). In addition, by monitoring the surface microtopography and documenting soil morphological changes, we have some indirect measures of erosion. The estimates based on soil morphology are probably the crudest, but they represent the longest time periods and are remarkably close to those given by the microtopographic measurements: the soil morphology data indicate an average soil loss in the intercanopy zones of about 4 mm/year for the past 3 years. Assuming 50% loss in the intercanopy area, these data suggest an average erosion rate for the catchment of $10\,000\text{--}20\,000\text{ kg/ha}$. Our direct measurement of erosion at the subcatchment scale (which is comparable to the scale represented by the indirect measurements) in 1995 was about 9000 kg/ha .

At these rates—50 to 100 times higher than in more stable pinyon-juniper woodlands (Wilcox 1994)—the soil resource cannot be sustained. We estimate very roughly that the intercanopy soil will be mostly stripped from this catchment in about a century.

5.2 Objective 2: Determine the Effect of 20th Century Vegetation Change on Erosion Processes

Vegetation in our study catchment has changed markedly over the past century. An open stand of ponderosa pine, with only a scattering of pinyon and juniper trees, characterized this site until the onset of domestic livestock grazing in the late 1800s. The grazing apparently suppressed the surface fires, which previously burned through such low elevation pine stands at roughly 15-year return intervals (Allen 1989), by reducing the herbaceous ground cover through which the fires propagated (Gottfried *et al.* 1995). Livestock grazing continued until 1932, after which feral burros similarly affected the system until about 1980. With fire eliminated and herbaceous competition reduced, pinyon and especially juniper tree establishment increased markedly. As the density of pinyon and juniper trees increased, herbaceous ground cover was likely further reduced. When the severe drought occurred in the 1950s, there was inadequate water available to sustain all the woody vegetation which had developed since the fires ceased. As a result, every ponderosa pine in this catchment died, leaving more drought-tolerant pinyon and juniper. It seems likely that the drought also caused additional declines in herbaceous ground cover. Reduced cover of vegetation and litter led to increased surface runoff. We hypothesize that these vegetation changes, caused by this history of human land-use practices and climatic variability, have led to the current episode of accelerated soil erosion.

The information gathered to date at our site, particularly the soil characterization information, supports our hypothesis that the current cycle of erosion was triggered by the 1950s drought. We know that the surface was stable at one time, because we find moderately well-developed argillic horizons, which in semi-arid environments

require time periods of the order of 10 000 years to develop (Birkeland 1984). That the current period of instability began around the time of the ponderosa pine die-off is suggested by the presence of mostly intact soils upslope of fallen ponderosa pine logs (which act as sediment traps), whereas the soils downslope of the logs are highly eroded. Physical rather than biological processes now dominate the barren, little-vegetated intercanopy areas.

5.3 Objective 3. Develop a Conceptual and Quantitative Understanding of the Relationships between Runoff and Erosion

Although many more years of observation will be required to fully achieve this objective, our results to date are quite enlightening and generally strengthen those from studies in other semi-arid environments. For example, we have clear evidence that in these regions intense thunderstorms produce the most erosion per unit of runoff; gentle rains, even though prolonged and able to generate large amounts of runoff, result in comparatively little erosion. Our results to date are the beginning of a quantitative database for evaluating runoff/erosion models in semi-arid landscapes.

5.4 Objective 4: Determine what Effect Scale has on Runoff and Erosion in Rapidly Eroding Semi-arid Woodlands

Our results with respect to this issue are contrary to those obtained for more stable pinyon-juniper woodlands, where runoff and erosion clearly diminish as scale increases from small plot to hillslope (Wilcox 1994). Most interesting is that at this site, not only does runoff not diminish with scale (i.e. there is little if any storage of water on the hillslope), but erosion actually increased from the plot to the subcatchment scale. We hypothesize that the hillslope channels themselves—or areas very near the channels—are sources of sediment.

In conclusion, understanding the many factors that play a role in accelerated erosion in semi-arid ecosystems—and related feedback mechanisms—is obviously key to the ability to manage and sustain these ecosystems. Only through long-term, detailed gathering of relevant data, from a multitude of sites, can such an understanding be gained. This study is contributing to the development of such an understanding.

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