Conf-9411157--1

LA-UR- 94-3833

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Submitted to: Semiarid Hydrology Conference
Tucson, AZ
November 1-3, 1994

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FRIJOLITO WATERSHED: INTEGRATED INVESTIGATIONS OF A RAPIDLY ERODING PINYON-JUNIPER HILLSLOPE

By

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Abstract: The dramatic acceleration of erosion associated with the expansion of pinyon-juniper woodlands over the past 100 years has been widely recognized, but few process-based studies of this phenomenon have been undertaken. In an attempt to identify the underlying causes, and the factors that affect erosion processes, we have initiated an interdisciplinary study of a rapidly eroding pinyon-juniper woodland in northern New Mexico. Since July 1993, we have collected data on runoff, erosion, and weather conditions from a 1-ha catchment study area and have conducted surveys of topography, soils, and vegetation. Our preliminary results indicate that although runoff makes up less than 10% of the annual water budget, runoff events – which are frequent in the summer – are capable of moving large amounts of sediment. We estimate that between July 1993 and October 1994, between 25,000 and 50,000 kg of sediment has eroded and been transported from the catchment. The information gained from such studies is essential to our ability to formulate effective strategies for managing these rapidly eroding woodlands.

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This work was supported by the Environmental Restoration Project, Los Alamos National Laboratory. We thank Marvin Gard, Kevin Reid, Shannon Smith, Randy Johnson, Nicole Gotti and John Hogan for assistance in the field. Technical editing was provided by Vivi Hriscu.

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 during the last 100 years has been unprecedented. A number of explanations for this expansion have been put forward, including overgrazing, reduced fire frequency, climate change, and higher concentrations of carbon dioxide (Miller and Wigland 1994).

An important ramification of the spread and the increase in density of pinyon-juniper woodlands is a decline in understory vegetation, often causing a dramatic acceleration of soil erosion. Erosion is especially pronounced in the more xeric locations – for example, south-facing slopes and areas where soils are shallow (Miller and Wigland 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.

Recognizing that our ability to find effective solutions depends on understanding how erosion processes behave and the factors that control those processes, we have been investigating a rapidly eroding pinyon-juniper hillslope site in northern New Mexico. The study area is a small (1-ha) catchment in the Bandelier National Monument. Over a 16-month period, we have been gathering data on the hydrology, geomorphology, ecology, and soils of the site. In this paper, we describe the hydrology and erosion studies that are under way and present our results to date.

STUDY AREA

General Setting

Bandelier National Monument is located on the Pajarito Plateau in northern New Mexico. The plateau has a semiarid, temperate mountain climate. Average annual precipitation varies with elevation, from about 330 to 460 mm, of which about 45% occurs in July, August, and September. Most summer precipitation occurs as intense afternoon and evening thunderstorms (Bowen 1990). In winter, precipitation occurs mostly as snow.

The parent material for most soils is the Bandelier Tuff, an extensive ash flow constituting the uppermost geologic unit on the plateau. The El Cajete pumice (from the latest volcanic eruption, some 50,000 years ago) and wind-blown sands also provide material for soil development. The major vegetation zones of the Pajarito Plateau are juniper grassland (1600 - 1900 m), pinyon-juniper woodland (1900 - 2100 m), ponderosa pine forest (2100 - 2300 m), and mixed conifer forest (2300 - 2900 m) (Allen 1989).

Site Description

The watershed, or catchment, is located in Bandelier National Monument, west of the headquarters, on the southwest side of a gently sloping hillslope near the Frijolito ruins. Soils on the site developed on tuff residua and volcanic pumice, and the dominant vegetation (until a severe drought in the 1950s) was mixed ponderosa pine. Today, fallen ponderosa pine logs are scattered across the area, but there are no live trees. Pinyon and juniper trees, more or less evenly spaced across the site, cover about half the catchment. The surface is mostly bare ground or rock in intercanopy zones and litter in canopy zones. Understory vegetation, including cryptogamic crust, makes up about 2% of the basal cover. Evidence of accelerated erosion includes numerous hillslope channels, soil pedestals, extensive patches of bare ground, and the scant cryptogamic coverage. Although channels are extensive, the shallow bedrock contact limits channel incision.

METHODS

Weather and runoff data have been collected on the site since July 24, 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).

Individual runoff events 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.

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-m^3 capacity, the pit was found to be too small to trap all the sediment leaving the catchment when discharge was moderate or high. In July 1994, four additional sediment traps were installed, each at the base of a tributary channel. Each trap is lined with wood and has a storage capacity of 1 m^3. At the same time, four small (1 m^2) runoff plots were established within intercanopy zones. One of these is in an area of high-pumice soil and is devoid of vegetation; the other three are in areas of tuff-derived soils and have good vegetation cover, compared with many other intercanopy areas within the catchment. Along the downstream end of each plot is 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 liters of the water (if available) is then reserved for measurement of sediment concentration.

Changes in microtopography from erosion and frost heaving are monitored at 10 permanent sites, located to represent the range of intercanopy cover conditions within the catchment. Each site comprises two transects (about a meter apart), the endpoints of which consist of rebar 2 m apart. 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 aluminum rod is then slid through each of the 20 drilled holes, and the distance from the top of the rod to the level is measured to determine ground elevation (Shakesby 1993). These measurements are made after the spring thaw, before the summer rains, occasionally during the summer rainy season, and in the late fall. Additional measurements are periodically made.

RESULTS AND DISCUSSION

The preliminary results presented here are based on runoff and erosion data collected between July 1993 and October 1994.

Runoff

During the first 16 months of observation, precipitation amounted to 640 mm, but most of that precipitation produced no runoff. A total of 65 mm of runoff was measured from the catchment. Most of that (45 mm) was generated during the two summer, by brief, intense thunderstorms. We documented a single runoff event from a prolonged frontal storm; and no runoff during the one winter of observation.

Considerably more runoff was produced the first summer (1993) than the second (Table 1). In 1993, eight precipitation events totaling 131 mm produced 37 mm of runoff, of which 12 mm came from a single storm. In contrast, in 1994, three precipitation events totaling only 20 mm resulted in 8 mm of runoff. The largest amount of runoff actually occurred in the fall from a prolonged frontal storm that dropped 65 mm of precipitation in 3 days. For both years, the duration of runoff events varied widely (a few minutes to 6 hours), as did the ratio of runoff to precipitation (8 - 53 %). In general, however, runoff was "flashy" –events were of short duration, and peak flow occurred in minutes after the onset of precipitation.

Scale comparisons were possible the second year, when runoff was measured both from the catchment as a whole and from the four 1-m^2 plots (the plot in an area of high-pumice soil generated very little runoff; runoff from the other three plots was therefore averaged for comparison with runoff from the catchment). For the first two events of the summer, average runoff from the plots was similar to that from the catchment; however, for the third summer event and the fall event, runoff from the plots was considerably smaller than that from the catchment (Table 1). One might expect that runoff from the small plots would be greater than that of the catchment, considering that some 50% of the catchment is tree-covered (and presumably generates little runoff), and perhaps another 20% is characterized by high-pumice soils (which also generate little runoff). We believe that most of the runoff is being generated from areas of the catchment that have little or no cover (bare ground or rock), conditions not represented by our small plots. Clearly, the small-plot network needs to be expanded to include such areas.

Erosion

Adequately estimating erosion rates from a rapidly eroding catchment like Frijolito has been a challenging and enlightening experience, requiring continual modifications in approach. At the outset of the study, we installed 20 small sediment traps (50-cm-long sections of plastic gutter) in various locations as a means of estimating erosion at small scales; these were abandoned because they were constantly overfilled and their contributing areas could not be determined. As an alternative, we installed the 1-m^2 runoff and erosion plots, which have yielded useful data for this purpose. The 0.4-m^3 sediment trap just upstream of the flume has met with mixed success. During the first year, it was filled to capacity by 7 of the 8 runoff events (even 1-mm events were filling the trap). Reasoning that it would be impractical to enlarge this trap sufficiently to catch all the sediment from larger events, we installed four additional sediment traps on tributary channels. With respect to the microtopography measurements, although we were unsure initially whether the resolution would be fine enough for estimates of erosion rates, we have been pleased with the results.

Sediment Yield: Sediment yield is estimated for a number of scales: the catchment, the four tributary channels, and the 1-m^2 plots. Although the capacity of the sediment trap at the flume was inadequate for calculating actual amounts, the data collected can be used to establish limits on sediment yield from the catchment. In 1993, for example, we know that the minimum sediment yield was 4500 kg. An upper limit can be estimated by assuming that sediment yield is proportional to runoff: if, on the basis of the 0.4 m^3 of sediment trapped in the wake of a 0.4-mm runoff event (August 20, 1993 – see Table 1), we conclude that 1 mm of runoff produces 1 m^3 of sediment, then we arrive at a crude estimate of total sediment yield for 1993 of 37 m^3 (55,500 kg).

On the other hand, data collected in 1994 suggest that there may not be a consistent relationship between runoff and sediment yield. The three summer runoff events in 1994 were comparable to several events in 1993, but the quantities of sediment produced were much lower. For example, the 8 mm of summer runoff in 1994 produced only about 0.3 m^3, or 450 kg, well below what would have resulted if each mm of runoff produced 1 m^3 of sediment. The differences in relative sediment yield between the first and second years suggest either that in 1993 there was a large amount of available sediment, which was scoured out by the relatively high runoff amounts, or alternatively, that the several large runoff events in 1993 positioned sediment, perhaps in the channels, such that it could be easily flushed out by the subsequent smaller events. Whatever the cause, the incongruities of these data reflect the complex dynamics of sediment movement from semiarid hillslopes.

For 1994, with the addition of the tributary-channel traps and the small plots, we can make some scale comparisons. Contrary to what we had expected, on a unit-area basis sediment yield seems to be generally higher from the catchment than from either the tributary channels or the small plots. Sediment accumulation in the tributary-channel traps was barely measurable, possibly suggesting that the major sources of sediment are downstream, e.g., in the main channel. The estimated sediment yield (average) from the plots was comparable to or lower than that from the catchment as a whole, which may be linked to the location of the plots, in areas of the catchment that are relatively high in vegetation cover compared with other intercanopy areas of the site.

Microtopography-measurement sites: The microtopographic measurements show that in the summer of 1993, surface elevations changed substantially as a result of erosion and of frost heaving over the winter (Figure 1). Most of the soil erosion (or deposition) occurred in localized zones, which show changes in elevation of up to several centimeters. The average change in elevation at the 20 measurement sites that summer was -3.4 mm. Assuming this rate for the half of the catchment that is intercanopy space, we arrive at an average depth of erosion of 1.7 mm; this translates into 17 m^3 (or 25,500 kg). This is about half the amount estimated as an upper limit for sediment leaving the catchment in 1993. The differences in these estimates imply either that our assumption of a proportional relationship between runoff and sediment transport is not valid or that other sources of sediment, provided by the channels perhaps, exist within the catchment

Microtopography measurements highlight the impact of frost heaving on surface elevation (Figure 1). During the one winter of observation, the surface rose an average of 7.8 mm. Measurements, made between the spring thaw and runoff-producing storms in the summer, indicate that the surface re-compacted about 5 mm as a result of raindrop impact. From the end of June until the beginning of September the surface deflated another 1.4 mm. This leads to the obvious question of how much surface deflation (during the time that runoff occurs) is due to recompaction by raindrops and how much is due to soil erosion. At this point our analyses are not complete enough and perhaps our measurements are not fine enough to answer that question. We cannot rule out the possibility that some of surface deflation measured in 1993 may have resulted from surface compaction by raindrops.

SUMMARY AND CONCLUSIONS

We speculate that the current cycle of erosion was triggered by the 1950s drought, which not only killed all the ponderosa pine on the site but may also have reduced herbaceous cover to some a critical threshold, allowing erosion to be initiated. We estimate that between 25,000 and 50,000 kg of sediment have been removed from the site by erosion between July 1993 and October 1994, most of it during the summer of 1993. These rates are much higher than in more stable pinyon-juniper woodlands (Wilcox 1994). Our results suggest that there may be no consistent relationship between the magnitude of runoff and the degree of erosion (similar types of runoff events resulted in very different erosion rates), and that other factors (perhaps related to geomorphic or climatic processes) may control sediment availability, which affects rates of sediment movement. Comparisons of measurements at different scales indicate that some intercanopy areas of the catchment generate much more runoff and erosion than others. We anticipate that with longer-term and more finely tuned collection of information, we will be able to isolate – and better understand the relative roles of – the factors that control erosion in these rapidly eroding woodlands.

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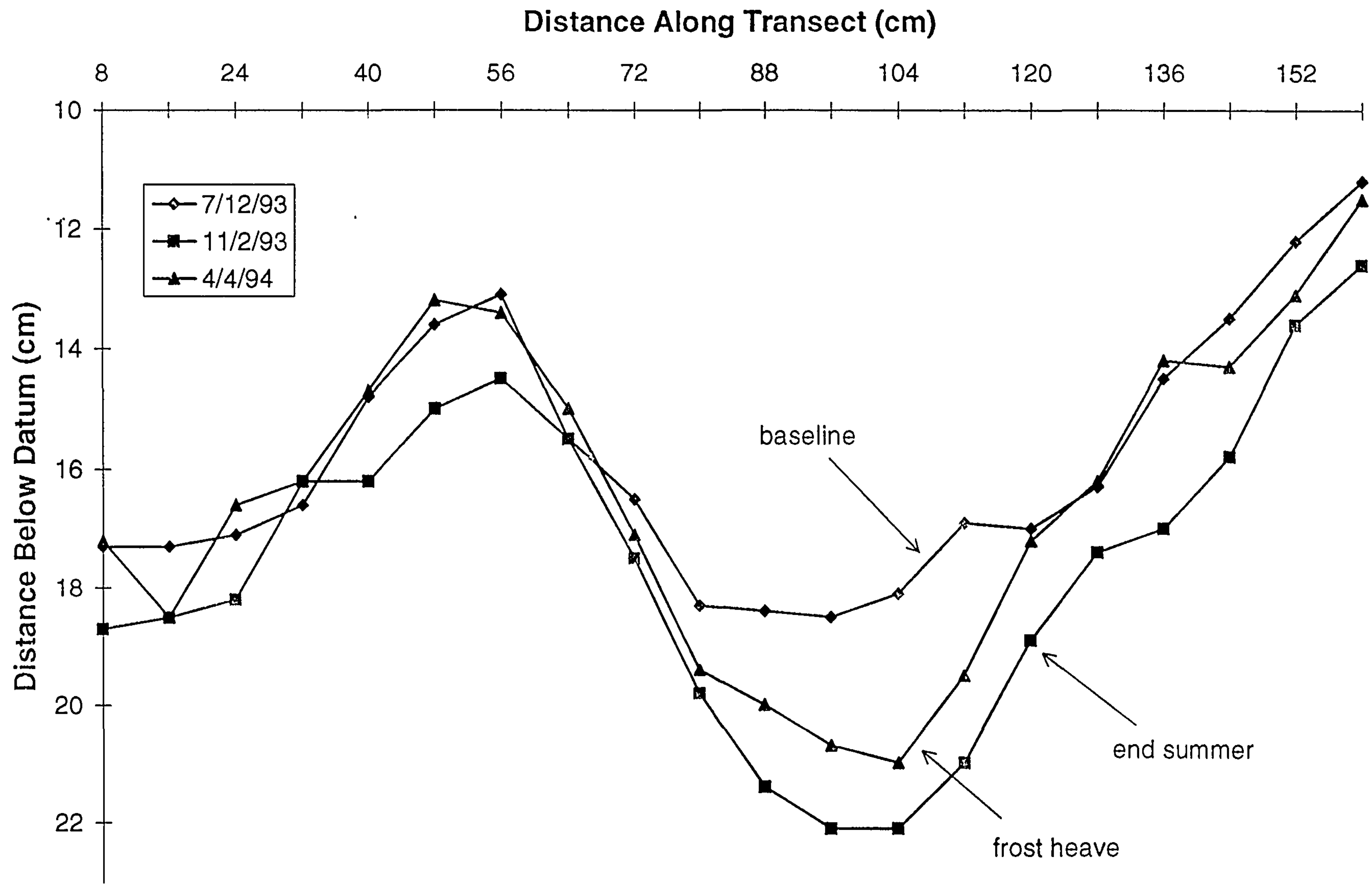
Figure Caption

Figure 1. Microtopography measurements from one location on the catchment.

Table 1. Precipitation, runoff, and erosion information for the Frijolito Watershed (July 1993 - October 1994).

Date	Precipitation			Runoff				Erosion	
	Amount (mm)	Duration (min.)	Peak (mm/min)	Plot (mm)	Catchment (mm)	Duration (min)	Peak Flow (m^3/sec)	Catchment (kg/ha)	Plot (kg/ha)
				1993					
July 28, 1993	36	30+15	1.8		9	33+20	0.061	>600	
Aug 6, 1993	9	15	0.7		1	12	1.016	>600	
Aug 20, 1993	5	14	0.5		<1	8	0.008	600	
Aug 26, 1993	23	120	0.5		4	49+30	0.013	>600	
Aug 27, 1993	24	35	2.0		12	35	0.086	>600	
Aug 28, 1993	11	55+50			3	30+60	0.01	>600	
Sept 6, 1993	19	35	2.0		6	28	0.058	>600	
Sept 13, 1993	4	10	1.0		<1	15	0.0095	264	
				1994					
Aug 2, 1994	6	21	1.0	2	2	20	0.03	36	no sample
Aug 21, 1994	4	6	1.5	2	1	10	0.037	144	164
Sept 5, 1994	10	50	0.7	1	5	34	0.039	216	30
Oct 15, 1994	65	3 days	0.5	11	20	6 hr	0.026	>600	129



Distance Along Transect (cm)
8
24
40
56
72
88
104
120
136
152
10
12
14
16
18
20
22
Distance Below Datum (cm)
7/12/93
11/2/93
4/4/94
baseline
end summer
frost heave