CONF-960984--1

LA-UR- 95-4042

Title: RUNOFF AND EROSION FROM A RAPIDLY ERODING PINYON-JUNIPER HILLSLOPE

Author(s): B. P. Wilcox, EES-15
J. Pitlick, University of Colorado
C. D. Allen, Jemez Mtn. Field Station at Bandelier National Monument
D. W. Davenport, EES-15

Submitted to: British Geomorphological Research Group Symposium
Hillslope Process
September 20-22, 1996
Bristol, England

Los Alamos
NATIONAL LABORATORY

RUNOFF AND EROSION FROM A RAPIDLY ERODING PINYON-JUNIPER HILLSLOPE

By

Bradford P. Wilcox[1], John Pitlick[2], Craig D. Allen[3] and David W. Davenport[4]

Abstract: The dramatic acceleration of erosion associated with the expansion of pinyon-juniper woodlands over the past 100 years has been a widely recognized but poorly understood phenomenon. A more complete understanding will come only through long-term observations of erosion and related factors. To this end, we are conducting a study of a small (1-ha) catchment in a rapidly eroding pinyon-juniper woodland. Since July 1993, we have been collecting data on runoff, erosion, and weather conditions in the catchment, as well as on the topography, soils, and vegetation. Our preliminary results suggest that (1) the catchment is currently in a cycle of accelerated erosion that began concomitant with a shift from ponderosa pine forest to pinyon-juniper woodland that was initiated by a prolonged drought in the 1950s; (2) the intercanopy soils cannot be sustained at the current erosion rates and will be mostly stripped away in about a century; (3) large summer thunderstorms are the most important agents of erosion; (4) erosion increases dramatically (5 - 10 times) as the scale increases from 1 m^2 to 300 m^2; (5) runoff makes up < 10% of the water budget.

---

[1] Hydrologist, Environmental Science Group, MS J495, Los Alamos National Laboratory, Los Alamos, New Mexico 87545.
[2] Assistant Professor of Geomorphology, Dept. of Geography, University of Colorado, Boulder, Colorado 80309
[3] Ecologist, National Biological Survey, Jemez Mountain Field Station at Bandelier National Monument, Los Alamos, New Mexico 87544.
[4] Soil Scientist, Environmental Science Group, MS J495, Los Alamos National Laboratory, Los Alamos, New Mexico 87545.

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, fire control, 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 resulting in 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. 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 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. This site, the subject of this paper, was characterized by low-density ponderosa pine forest (with an understory of pinyon and juniper) until a severe drought in the 1950s, which brought about its conversion to pinyon-juniper woodland (Allen, 1989). Over a 26-month period, we have been gathering data on the hydrology, geomorphology, ecology, and soils of the site. We hypothesize that the accelerated erosion we are observing began with the changeover from ponderosa pine forest and that the soils of the intercanopy areas (areas not covered by tree canopies) are not sustainable under the current rates of erosion.

The long-term objectives of the study are to (1) estimate water and sediment budgets for rapidly eroding semiarid woodlands; (2) determine the effect of the climate-induced 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 semiarid woodlands. Especially in light of 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 3 years into the study, our results to date have already provided support for our hypotheses and added significantly to our knowledge of runoff and erosion dynamics in these important woodlands.

STUDY AREA

The subject catchment is located in northern New Mexico, within the Bandelier National Monument (Figure 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 and volcanic pumice, and the dominant vegetation (until a severe drought in the 1950s) was ponderosa pine mixed with pinyon and juniper. Today, fallen ponderosa pine logs are scattered across the area, but there are no live ponderosa trees. Pinyon and juniper trees, more or less evenly spaced across the site, cover about half the catchment; intercanopy surfaces are mostly bare ground or rock, canopy surfaces mostly litter. In addition to the extensive patches of bare ground and the scant vegetation coverage, evidence of accelerated erosion includes numerous hillslope channels, soil pedestals, and exposed subsoils. Although channeling is extensive, the proximity of bedrock to the soil surface prevents the formation of gullies or deeply incised channels.

METHODS

Characterization of Vegetation and Soils

Vegetation and surface soil conditions were characterized by establishing three transects along the contour and across the width of the catchment, at roughly high-, mid-, and low-elevation positions (Mueller-Dumbois and Ellenberg, 1974). The transects, which measure 50 m, 65 m, and 40 m in length, respectively, are permanently marked by a fiberglass tape stretched along the ground and secured at the endpoints. The nature of the surface cover, including all overstory 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 color, texture, structure (in pits), dry consistence, root density, percent and type of coarse fragments, and boundary characteristics.

Hydrometric and Erosion Measurements

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

Weather 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 ten 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 endpoints 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 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 (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 fall), changes in surface elevations can be mapped.

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 recession limb of the hydrograph 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-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. 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 1). The traps are lined with wood and have a storage capacity of 1 m^3. The four contributing areas (subcatchments) range from 300 to 1100 m^2.

The same year, we established a network of 12 small (1 m^2) 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 liters 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.

RESULTS

Vegetation

Our vegetation characterizations indicate that about 45% of the catchment is canopy (pinyon and juniper). Most of the canopy understory (93%) is litter, whereas most of the intercanopy areas are bare ground (66%) with about 30% litter. The most important herbaceous species is blue grama, which makes up about 1% of basal cover. Cryptogams make up less than 1% of basal cover—another striking piece of evidence of accelerated erosion (in more stable woodlands, cryptogamic cover is found over as much as 50% of the interspaces – Wilcox, 1994).

Soils

Most of the soils in the catchment (which are 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 pumice alluvium, 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 and may have been reworked as alluvium 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 according to 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 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.

Runoff

Catchment scale runoff: A summary of catchment-scale runoff and the precipitation that generated it appears in Table 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 June 29, 1995: 2.7 mm/min. (such intensities are maintained only for very short periods). The debris transported by this event blocked the flume, diverting runoff around it (for this reason, the runoff volume shown in Table 2 for this event was estimated from the small plot data). Runoff at this site is typical of that of many semiarid landscapes, in that it is of short duration and peak flow occurs within minutes of the onset of runoff (Figure 2a).

In terms of volume, the largest runoff event was actually produced by a fall frontal storm, which dropped some 55 mm of precipitation fell in two days. Runoff began after the first 24 hours, during which about 15 mm of rain fell, and continued unabated for a 6-hr period (Figure 2b); another 30 mm of rain fell during that time but with rainfall intensity never exceeding 0.25mm/min. during that time.

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

Water budget calculations are given in Table 2. We have assumed that in semiarid areas such as this one, that groundwater recharge makes up a small 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 year 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 can, however, contribute a much higher percentage of the budget for the monsoon or summer season (Table 2).

Small plot runoff: For the third monsoon season (summer of 1995), we have data from the small plots as well as from the catchments (Table 3). Runoff was recorded for a total of 11 events (those on July 17 and 18 were treated as a single event). Small amounts of runoff were measured in at least some of the plots on 5 occasions when no runoff left the catchment. There was considerable variability from plot to plot, with the intercanopy tuff residua plots producing the most runoff(even within this category, total runoff for the summer ranged from 21 to 50 mm). 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 June 29. One of the tuff residua plots, 94-2, differs from the others in the category in that cryptogamic cover is still partially intact. Runoff from this plot was much lower than from the other tuff residua plots.

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 estimated coverage of each category on the catchment. The canopy plot was weighted 50%, the pumice-soil plot 10%, and the tuff residua plots (average of 10) 40%. The results for each storm were then compared with runoff measured at the flume (Figure 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).

Erosion

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 monsoons, (2) frost heaving in the early spring, and (3) raindrop compaction in the spring and summer. Over a period of 1 year, surface changes due to frost heaving and those due to raindrop compaction cancel each other out. Between July 1993 and September 1995, the average change in elevation at the 20 measurement sites is -6.7 mm, most if not all of which we attribute to soil erosion. Three representative microtopographic profiles are shown in Figure 4: a rapidly eroding section from which as much as 7 cm of soil has been lost in a 26-month period (Figure 4a); a deposition zone in which up to 8 cm of sediment has accumulated, underscoring the dynamic changes occurring on the hillslope (Figure 4b); 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 4c).

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

$$E = (B_d)\,(H)\,(10)$$

where

E = erosion (t/ha)

B_d = soil bulk density (g/cm^3)

H = 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 arrive at an estimate of total erosion from the catchment of about 47 t/ha or 15,600 kg/ha year.

Small Plot Erosion: Erosion data collected from the small plot network in 1995 are shown in Table 4. By far, the bulk of the erosion was produced by the largest storm, that of July 29. 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.

Subcatchment and Catchment Erosion: Estimates of erosion during 1995 for the catchment as a whole and for the four subcatchments are given in Table 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. There was also considerable variability in erosion among the various catchments. Erosion from subcatchment 2 was 4 times greater than that from subcatchment 1. Pumice-soils cover a large portion of subcatchment 1.

As previously noted, because the sediment trap at the catchment outlet was too small for larger amounts of sediment, no estimates are available for the first two events of the year, both of which overtopped the trap. For the three small 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). There are many areas in the catchment hillslopes and channels where sediment are accumulating. We hypothesize, that during larger events these sediment storage sites are evacuated and thus net sediment leaving the catchment is probably in equilibrium with sediments leaving the hillslopes (as represented by the subcatchments).

DISCUSSION AND CONCLUSIONS

The expansion of pinyon-juniper woodlands during the last century is unprecedented and incontrovertible. Although it is widely believed that this expansion has led to increased soil erosion, this belief is based mostly on anecdotal information. 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. 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. 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:

Objective 1: Estimate water and sediment budgets for rapidly eroding semiarid woodlands. In semiarid environments, measurements 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% (perhaps closer to 5%) of the water budget of the catchment, which is consistent with data from other semiarid environments. In the monsoon season, however, runoff makes up perhaps 15 - 20 % of the water budget. For many of the intercanopy areas the runoff percentage during the monsoon may be as high as 40 %.

To estimate erosion from the catchment, we are measuring sediment losses at a number of scales by a variety of different methods: (1) soil morphological changes; (2) microtopography measurements; and (3) measurements of volumes of sediment transported from small (1 m^2) plots, subcatchment (300 -1100 m^2) and the catchment (10,000 m^2). The estimates based on soil morphology are probably the crudest but they are the longest-term estimate and have yielded results remarkably close to those given by the microtopographic measurements: the morphological data indicate an average soil loss in the intercanopy zones of about 4 mm/yr over the last 30 years; microtopographic measurements show a loss of about 2 mm/yr for the past 3 years. Assuming 50 % canopy area, these data suggest an average erosion rate for the catchment of 10,000 - 20,000 kg/ha. In 1995, average erosion from the subcatchments was about 9000 kg/ha. At such rates – 50 - 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 in about a century.

Objective 2: Determine the effect of the climate-induced vegetation change (shift from mixed ponderosa pine to pinyon and juniper) on erosion processes. 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, which not only killed all the ponderosa pine in the area but may also have reduced herbaceous cover to some critical threshold that allowed erosion to increase. We know that the surface was stable at one time because we find moderately well developed argillic horizons, which in semiarid environments require time periods on 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 that are highly eroded.

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 semiarid 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 resulted in comparatively little erosion. We are developing a quantitative data base with which to evaluate runoff/erosion models in semiarid landscapes.

Objective 4: Determine what effect scale has on runoff and erosion in rapidly eroding semiarid 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 a small plot to hillslope (Wilcox, 1994; Wilcox et al., 1995). Most interesting, at this site we found that not only does runoff not diminish with scale (i.e., there is little if any storage of water on the hillslope) but erosion actually increases from the plot to the subcatchment scale. We hypothesize that in rapidly eroding woodlands, the 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 semiarid 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. We believe that this study has already contributed to such an understanding.

REFERENCES CITED

Allen, C. D. (1989). Changes in the landscape of the Jemez Mountains, *N. M.* Ph.D. dissertation, Univ. of California, Berkeley.

Birkeland, P. W. (1984). Soils and Geomorphology. Oxford University Press, New York. 372 p.

Bowen, B. M. (1990). Los Alamos Climatology. *Los Alamos National Laboratory Report LA-11735-MS*, Los Alamos, NM. 254 p.

Longmire, P., S. Reneau, P. Watt, L. McFadden, J. Gardner, C. Duffy, and R. Ryti. (1995). Natural Background Geochemistry, Geomorphology, and Pedogenisis of Selected Soil Profiles and Bandelier Tuff, Los Alamos, New Mexico. *Los Alamos National Laboratory Report LA-12913-MS*, Los Alamos, New Mexico

Miller, R. F. and P. E. Wigland. (1994). Holocene changes in semiarid pinyon-juniper woodlands. BioScience 44(7):465-474.

Mueller-Dombois, D. and H. Ellenberg, (1994). *Aims and Methods of Vegetation Ecology*. John Wiley & Sons, New York, NY. 547 p.

Replogle, J. A., A. J. Clemmens, and M. G. Bos. (1990). Measuring irrigation water. In Hoffman, G. J., T. A. Howell, and K. H. Solomon (eds.) *Management of Farm Irrigation Systems*. ASAE Monograph, American Society of Agricultural Engineers, St. Joseph, MI. p. 345-351.

Schmidt, L. J. (1987). Present and future themes in pinyon-juniper hydrology. Proceedings of the Pinyon-Juniper Conference, USDA-Forest Service, Intermountain Research Station. General Technical Report INT-215.

Shakesby, R. A. (1993). The soil erosion bridge: a device for microprofiling soil surfaces. *Earth Surface Processes and Landforms* 18(9):823-827.

USDA Forest Service. (1995). *Desired Future Conditions for Pinon-Juniper Ecosystems*, USDA-Forest Service, Intermountain Research Station. General Technical Report RM-258.

Wilcox, B. P. (1994). Runoff and erosion in intercanopy zones of pinyon-juniper woodlands. *Journal of Range Management* 47(4):285-295.

Wilcox, B. P. and D. D. Breshears. (1995). Hydrology and ecology of pinyon-juniper woodlands: conceptual framework and field studies. *Desired Future Conditions for Pinon-Juniper Ecosystems*, USDA-Forest Service, Intermountain Research Station. General Technical Report RM-258.

Wilcox, B. P., D. D. Breshears, and K. D. Reid. (1995). Scale-dependent relationships between vegetation patterns and hydrologic behavior in semiarid landscapes. *10th Annual Landscape Ecology Meeting* (abstract).

Figure Captions

Figure 1. Location map and schematic of the study area.
Figure 2. Rainfall and runoff for (a) a summer thunderstorm and (b) a fall frontal storm.
Figure 3. Comparison of runoff calculated from a weighted average of the small plots and that measured at the catchment outlet.
Figure 4. Microtopographic changes at three locations withing the catchment representative of (a) an eroding surface (b) a depositional surface and (c) a relatively stable surface.

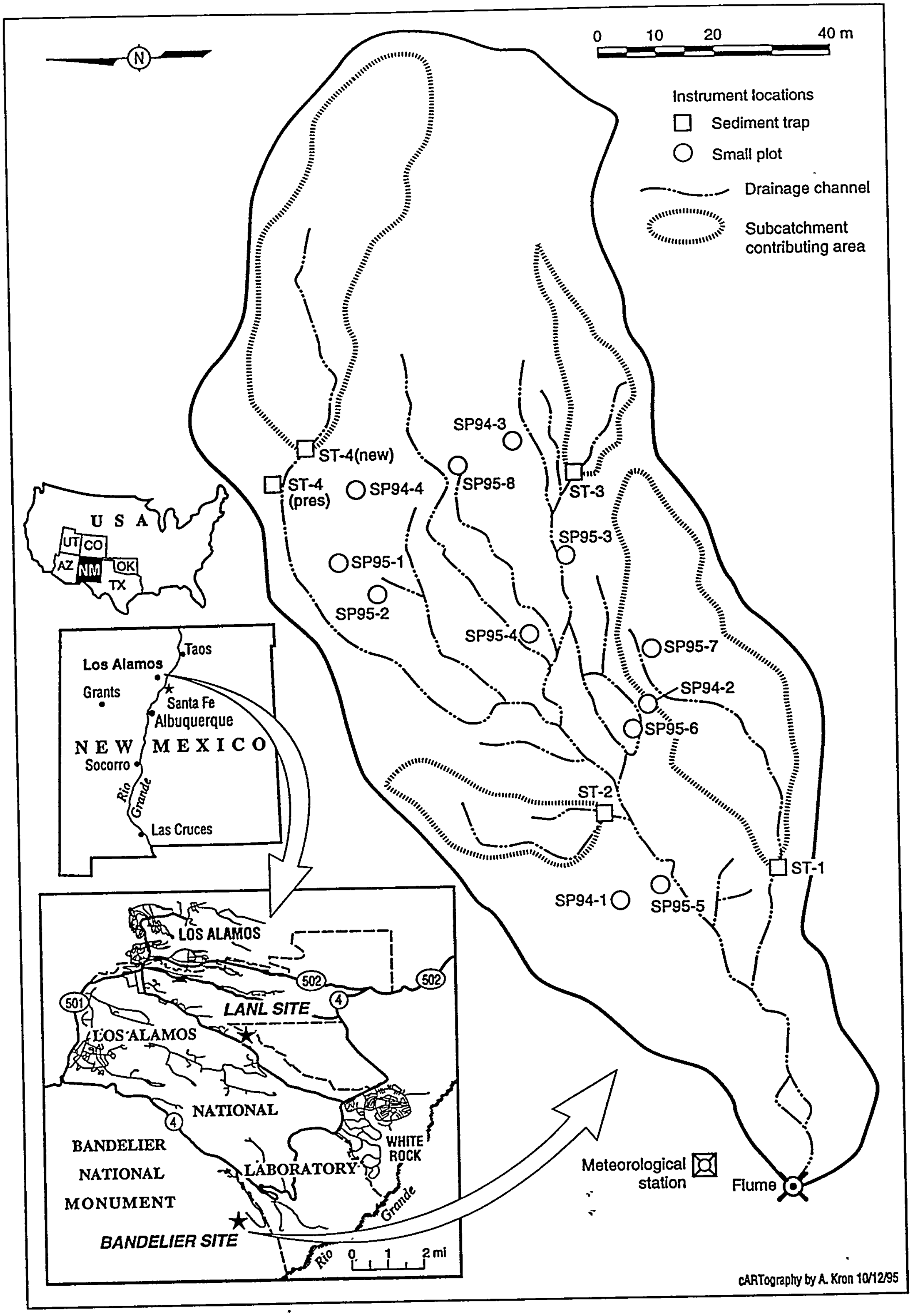

Figure 1. Location of study area including details of Bandelier Site.

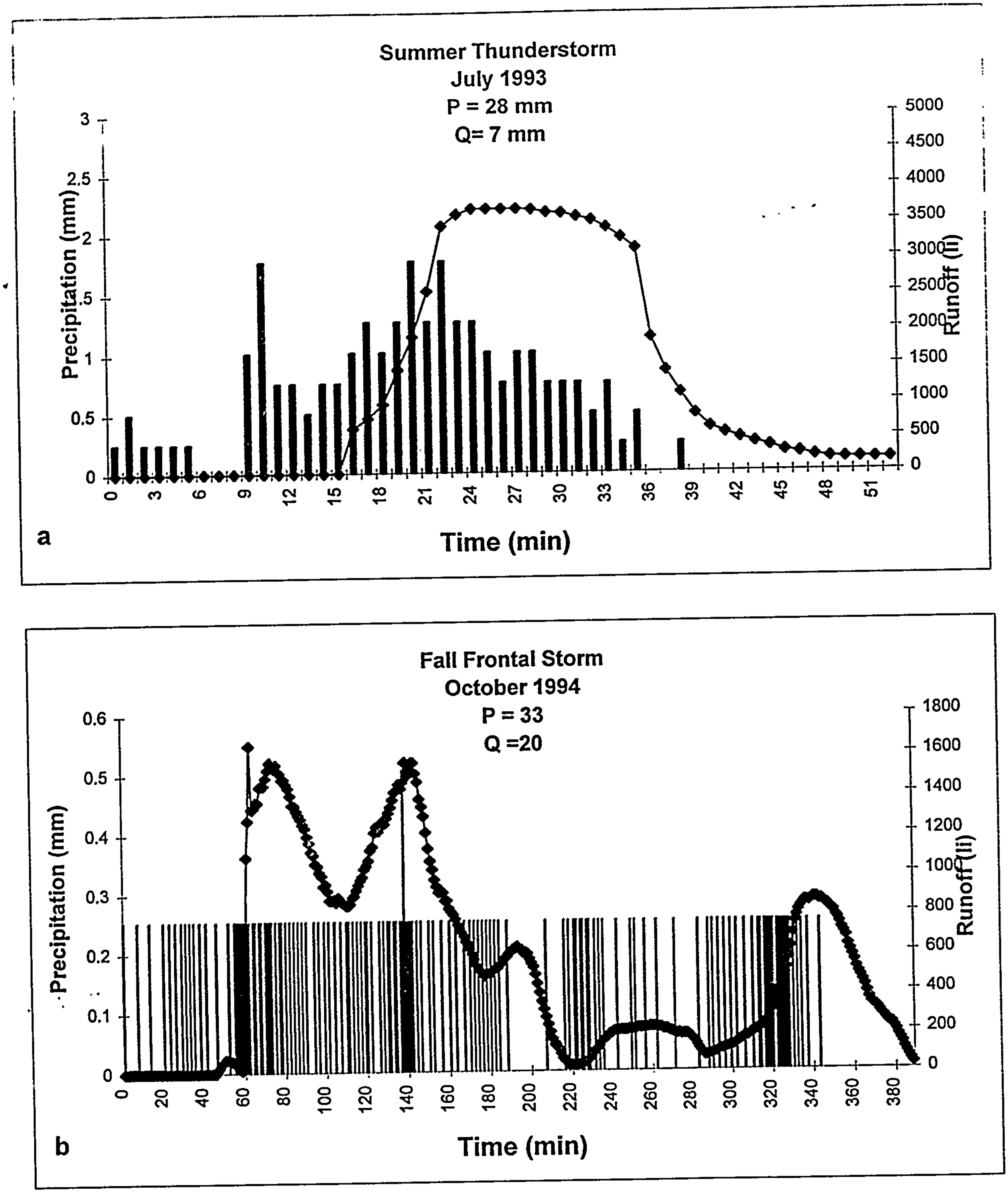

Figure 2. Runoff from a (A) summer thunderstorm and (B) from a fall frontal strom.

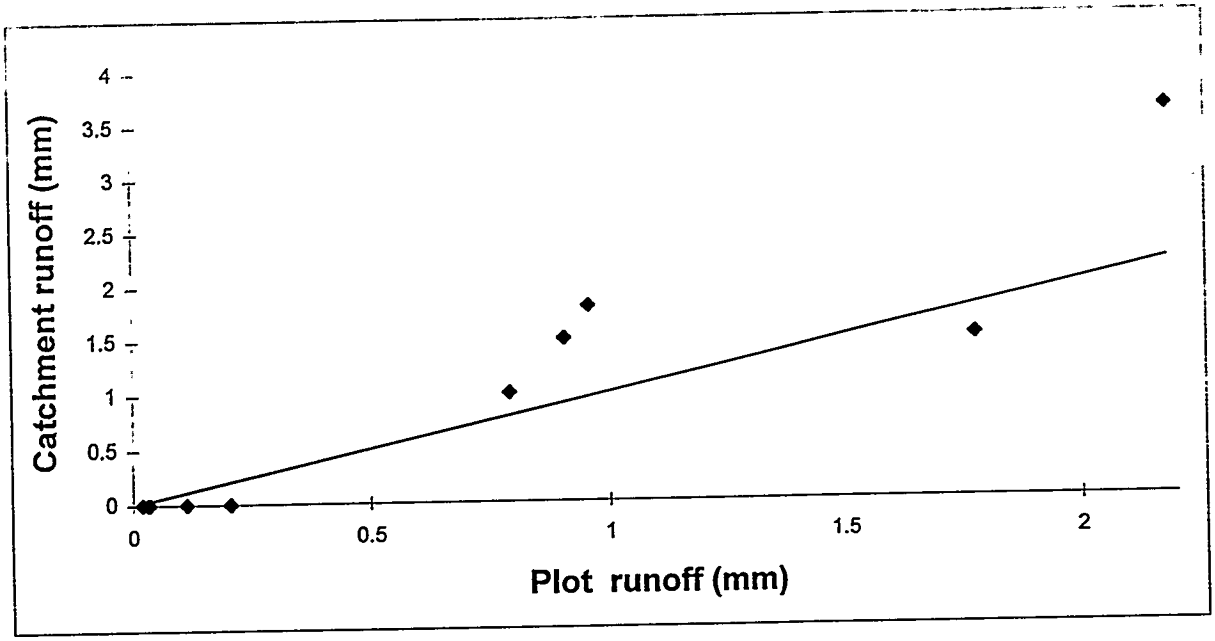

Figure 3. Comparison of runoff calculated from a weighted average of the small plots and that measured at the catchment outlet.

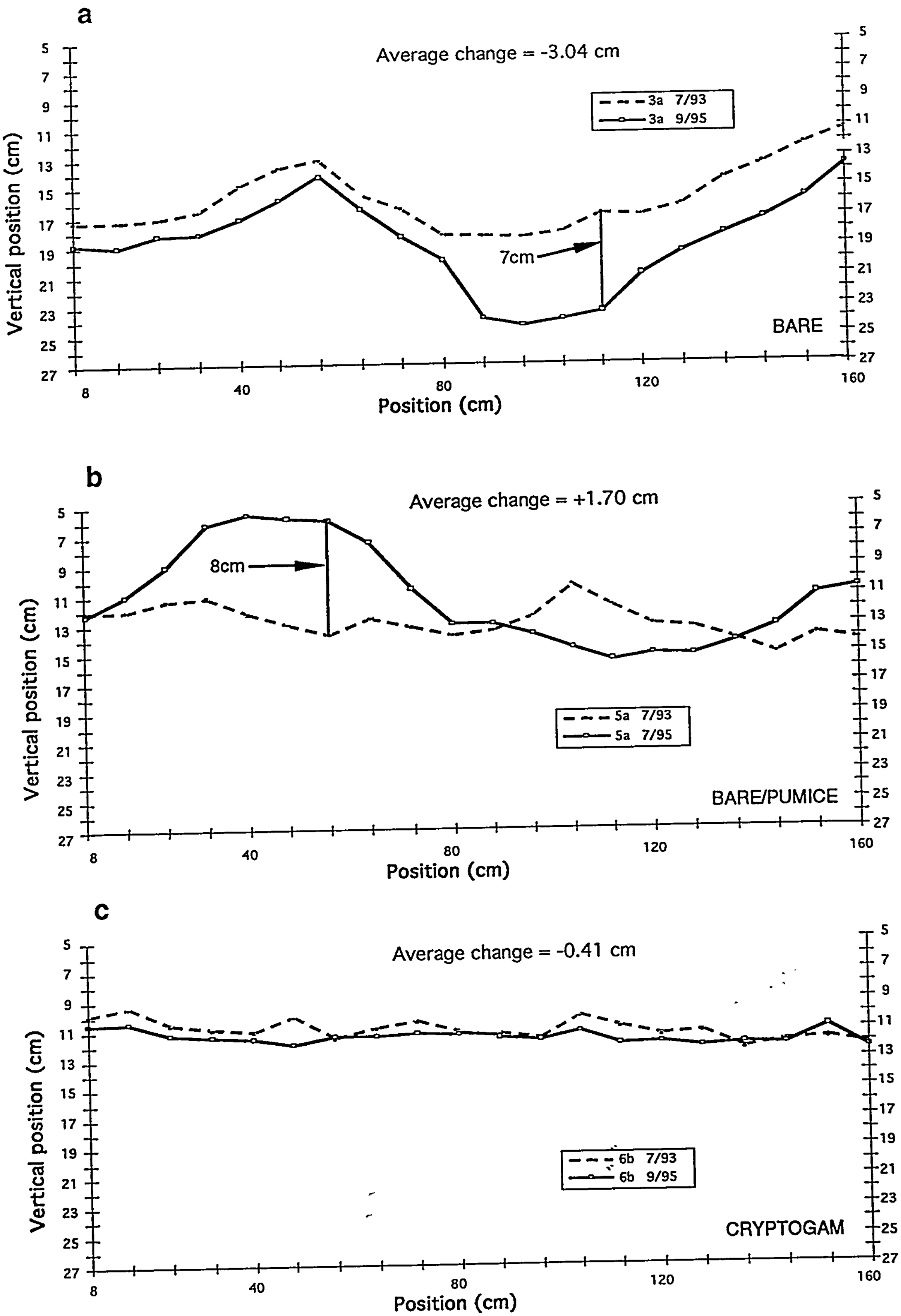
a
Average change = -3.04 cm
3a 7/93
3a 9/95
7cm
BARE
Vertical position (cm)
Position (cm)
b
Average change = +1.70 cm
8cm
5a 7/93
5a 7/95
BARE/PUMICE
Vertical position (cm)
Position (cm)
c
Average change = -0.41 cm
6b 7/93
6b 9/95
CRYPTOGAM
Vertical position (cm)
Position (cm)

Table 1. Catchment-scale runoff (July 1993 - Sept. 1995)

Date	Precipitation (mm)	Peak Precipitation (mm/min)	Catchment runoff (mm)	Peak Flow (li/sec)
		1993		
28 Jul 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 Sep 93	19	2.0	6	3480
13 Sep 93	4	2.0	<1	570
		1994		
2 Aug 94	6	1.0	2	1800
21 Aug 94	4	1.5	1	2220
5 Sep 94	10	0.8	5	2340
15 Oct 94	54	0.5	20	1560
		1995		
29 May 95	14	1.0	4	4070
29 Jun 95	26	2.7	>10*	
17 Jul 95	14	0.5	1	720
18 Jul 95	5	0.2	<1	375
13 Aug 95	10	1.0	2	1540
18 Sep 95	9	1.0	2	1340
29 Sep 95	3	0.8	1	1470

* Flume clogged with debris and runoff volume estimated from the small plot data.

Table 2. Annual and summer (July - Sept.) precipitation and runoff for the period of observation.

Water Year	Total Precipitation (mm)	Summer Precipitation (mm)	Total Runoff (mm)	Summer Runoff (mm)	Total Runoff (%)	Summer Runoff (%)
1993		195 *	35	35		18
1994	384	131	8	8	2	6
1995	549	123	41	21	7	17

*July 26 - Sept 31

Table 3. Summary of small plot runoff in the summer of 1995

Plot #	Plot Description	29-May	26-Jun	29-Jun	30-Jun	16-Jul	17, 18-Ju	5-Aug	13-Aug	10-Sep	17-Sep	29-Sep	Total
		Event Day											
		Total Precipitation (mm)											
		42	6	35	4	10	31	8	14	17.5	8.5	12.5	
		Runoff (mm)											
95-5	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	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	Interspace - tuff soil	*	0.0	19.0	0.0	0.0	0.6	0.0	0.3	0.0	0.5	1.0	21.4
94-2	Interspace - tuff soil	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	17.76

* plot malfunction

Table 4. Summary of small plot erosion, summer 1995

Plot	Description	Event Date											
		29-May	26-Jun	29-Jun	30-Jun	16-Jul	18-Jul	5-Aug	13-Aug	10-Sep	17-Sep	29-Sep	Total
		Erosion (g/m2)											
95-5	Interspace - tuff soil	13	0	179	1	2	8	0	15	3	12	10	244
95-3	Interspace - tuff soil	32	0	393	7	0	17	15	65	2	37	167	736
95-7	Interspace - tuff soil	12	0	224	2	0	3	0	46	3	26	15	330
95-2	Interspace - tuff soil	34	1	167	0	0	2	0	14	0	102	23	344
95-8	Interspace - tuff soil	88	0	250	0	0	3	0	57	0	22	68	488
95-4	Interspace - tuff soil	24	0	93	0	0	2	0	4	0	1	12	136
94-4	Interspace - tuff soil	43	0	257	0	0	2	0	54	0	4	38	398
95-1	Interspace - tuff soil	6	0	84	0	0	0	0	4	0	5	15	114
94-3	Interspace - tuff soil		0	173	0	0	0	0	3	0	1	6	185
94-2	Interspace - tuff soil	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	Interspace - 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

Table 5. Subcatchment and catchment scale sediment yield

		Event Date						
		29-May-95	29-Jun-95	18-Jul-95	13-Aug-95	17-Sep-95	29-Sep-95	Total**
		Catchment Runoff (mm)						
		3.6	>10	1.5	1.5	1.8	1	
	Area (m2)	Erosion (g/m2)						
Subcatchment 1	1046	65	239	10	15	0	14.93	279
Subcatchment 2	308	*	921	15	77	0	101.44	1114
Subcatchment 3	308	294	468	152	25	16.7	25.36	687
Subcatchment 4	1107	*	493	56	28	31.75	14.11	623
Subcatchment Average		180	530	59	36	12	39	855
Catchment	10000	>40	>40	19.5	22.6	17.18	14.06	

* trap not yet installed
** totaled for last three events only