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New Mexico Geological Society Guidebook, 47th Field Conference, Jemez Mountains Region, 1996

RUNOFF AND EROSION ON THE PAJARITO PLATEAU: OBSERVATIONS FROM THE FIELD

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Abstract—Sites within the Pajarito Plateau have widespread, if low levels, of surface contamination. The major mechanism by which contaminants are moved and redistributed is surface runoff and associated soil erosion. To better understand the processes involved, we have been making detailed measurements of water and sediment movement at three sites across the plateau, one located in a ponderosa pine forest, one in a stable pinyon-juniper woodland, and one in a rapidly eroding pinyon-juniper woodland. For the ponderosa pine site, both surface runoff (overland flow) and subsurface runoff (interflow) are important. Overland flow can be generated by intense summer rain storms, more gentle frontal storms, or snowmelt while soils are frozen; interflow, although generated mostly by melting snow, can occur any time of the year. For the pinyon-juniper sites, the most important producer of runoff is summer thunderstorms, but at all scales snowmelt runoff can be important as well. The rapidly eroding pinyon-juniper site produces more runoff than the stable pinyon-juniper site and hundreds of times more erosion than either the stable pinyon-juniper or the ponderosa site. These long-term studies are providing a better conceptual understanding of runoff and erosion on the Pajarito Plateau and other similar semiarid regions and enabling better assessments of the potential for contaminant transport in these systems.

INTRODUCTION

Runoff and erosion processes on the Pajarito Plateau are of particular importance because of the widespread (if low level) surface contamination at some locations on the plateau. The major mechanism by which contaminants are moved and redistributed is surface runoff and associated soil erosion. The latter is also important because many areas, particularly on the eastern and southeastern flank of the plateau, are eroding at rapid rates. At Bandelier National Monument, accelerated erosion is a major natural and cultural resource problem.

Recognizing that our understanding of surface runoff dynamics is limited, we have established a network of hillslope-scale hydrologic studies for long-term monitoring of runoff and erosion; the three sites selected for these studies represent the three major vegetation types on the plateau. These studies are providing data that will significantly improve our conceptual understanding of runoff and erosion processes in semiarid environments. In this paper, we summarize the information collected to date and present the conclusions that we believe can be drawn from these data.

STUDY SITES AND METHODS

Detailed studies of runoff and erosion are under way at three sites on the Pajarito Plateau (Fig. 1); one each in a ponderosa pine forest, a mid-elevation pinyon-juniper woodland, and a lower-elevation pinyon-juniper woodland. The lower-elevation woodland appears to be eroding rapidly, whereas the mid-elevation pinyon-juniper site is quite stable. These sites represent the major vegetation types on the plateau. Ponderosa pine occupies approximately the upper third, and pinyon and juniper the lower two thirds, of the plateau. Interestingly, much of the pinyon-juniper area, especially along the eastern flank of the plateau, is–or in the recent past has been–eroding rapidly, but other portions of this area appear to be very stable.

Ponderosa pine site

This area is an 870-m^2 hillslope (Fig. 1), at an elevation of about 2315 m, in an open ponderosa pine forest with an understory of grasses and forbs. It is part of a gently sloping (average 6%) mesa that drains into a nearby canyon. Average annual precipitation for this site is around 500 mm (Bowen 1990), which represents the lower end of the precipitation spectrum that can support ponderosa pine.

Surface runoff from this hillslope is measured, using separate collection systems, from each of three contributing areas: a 485-m^2 area on the north side of the slope; a 355-m^2 area on the south side; and a 10×3-m plot at the northeast corner. Areas are approximate; although they have been surveyed topographically, boundaries could not be precisely determined because of the complex microtopography.

Interflow is measured by means of a trench, cut perpendicular to the slope of the hill, that intercepts the flow of shallow subsurface runoff. We estimate the contributing area for interflow to be about 700 m^2. The trench is equipped with two 12-m-long collectors: an "upper" collector at 0.2 m from the surface and a "lower" collector at 0.95 m. The upper collector is designed to collect water from the loess-derived A and Bw horizons, which are low in clay content. The lower collector is designed to collect water primarily from the clay-rich Bt horizon. More details of data collection on this site are given by Wilcox et al. (1995).

Some chemical characteristics of interflow were also measured, including stable isotopes by mass spectrometry and chloride by ion chromatography (Newman, 1996). Dissolved organic carbon concentrations were measured using a Dohrmann DC-180 carbon analyzer.

Pinyon-juniper sites

Stable site

This site is located in a pinyon-juniper woodland at an elevation of 2140 m; average annual precipitation is around 380 mm (Bowen, 1990). We are monitoring runoff within this site from six 32.4-m^2 plots and from a hillslope of approximately 2000 m^2 (Fig. 1). We began monitoring runoff and erosion from the six plots in 1991 (Wilcox, 1994). At first, runoff from the plots was routed into steel tanks at the downslope end, and the volumes of runoff and of accumulated sediment were determined for each event. In 1994, small fiberglass flumes were installed on four of the plots, allowing continual measurement of runoff.

Collection of runoff data from the hillslope began in 1994. We estimate the contributing area to be about 2000 m^2, but suspect that the actual area fluctuates-the entire hillslope contributing runoff in very large storms, and much smaller areas contributing runoff in small storms. As at the ponderosa pine site, surface runoff is captured by a 12-m-long gutter placed perpendicular to the hillslope, which routes it through a small flume. Interflow is collected in a trench equipped with collectors at four depths.

Eroding site

This site, which lies within the Bandelier National Monument (Fig. 1), is undergoing rapid erosion. Since 1993 we have been monitoring runoff and erosion from a small (10,000 m^2) catchment and since 1995 from a network of 1 m^2 plots. Because of the high erosion rates, we are putting more effort into quantification of erosion at this site than at the others (see Wilcox et al., 1996, for detailed discussion).

Impressive changes in vegetation have occurred on this site. It was dominated by an open ponderosa pine forest until the late 1800s, when livestock grazing and an associated reduction in fire frequency (from both fire suppression and reduced ground fuel) allowed pinyon and juniper to mark-

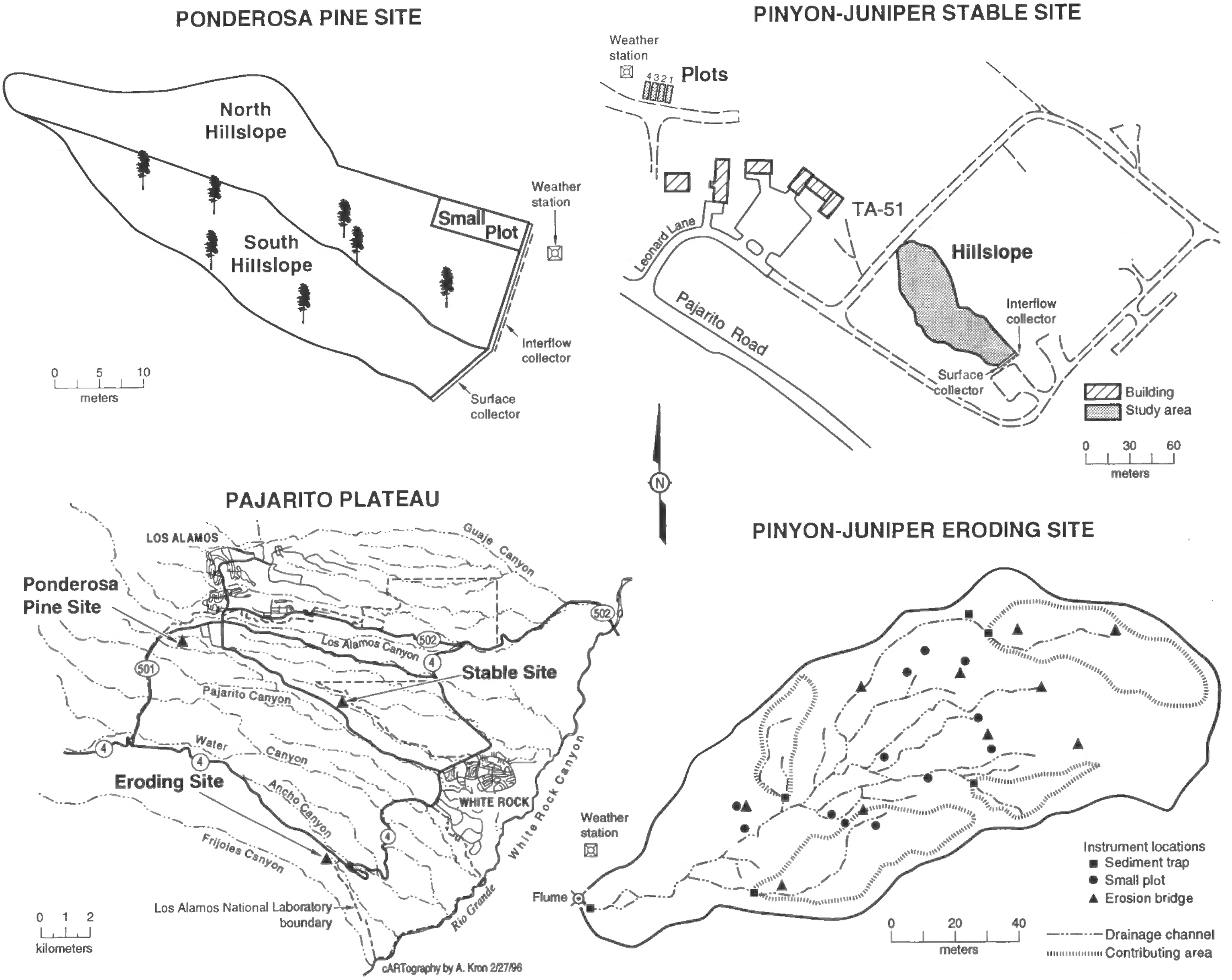

FIGURE 1. Locations and schematic diagrams of the three study sites.

edly increase in density (Allen, 1989). This increase in pinyon and juniper probably caused a further decline in herbaceous cover, added to by the presence of a large feral burro population in the area beginning around 1940. Finally, a severe drought in the 1950s severely reduced herbaceous cover and killed all the ponderosa pine. These events apparently triggered the current episode of accelerated erosion (Gottfried et al., 1995). 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. The slope of the catchment is around 5%. Ground surfaces in intercanopy patches are mostly bare soil or rock, whereas those beneath the canopy are mostly needle litter.

Individual runoff events from the catchment are measured by means of a flume (Replogle et al., 1990) installed in a bedrock-floored segment of the main channel, above the point at which the channel drops into a canyon. 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 (Fig. 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 small plot network, completed in 1995, comprises 12 1 m^2 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.

Changes in microtopography caused by erosion are monitored at 20 permanent sites, located to represent the range of intercanopy cover conditions within the catchment (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.

RESULTS

Ponderosa pine site

Runoff at this site occurs both as interflow and as overland flow, the former being the dominant mechanism in late winter or early spring, when runoff is generated by melting snow or heavy spring rains, and the latter being the dominant mechanism in summer, when runoff is produced mostly by intense thunderstorms (and occasionally by prolonged frontal storms or snow melting over still-frozen soil).

Interflow

Interflow can be a very active mechanism of runoff on this hillslope when the soil becomes saturated, as is common in the late winter or early spring with melting snow, heavy rains, or both. Two of the four winters of our study have seen significant amounts of interflow, the largest during the winter of 1992-1993, when the snowpack was above average.

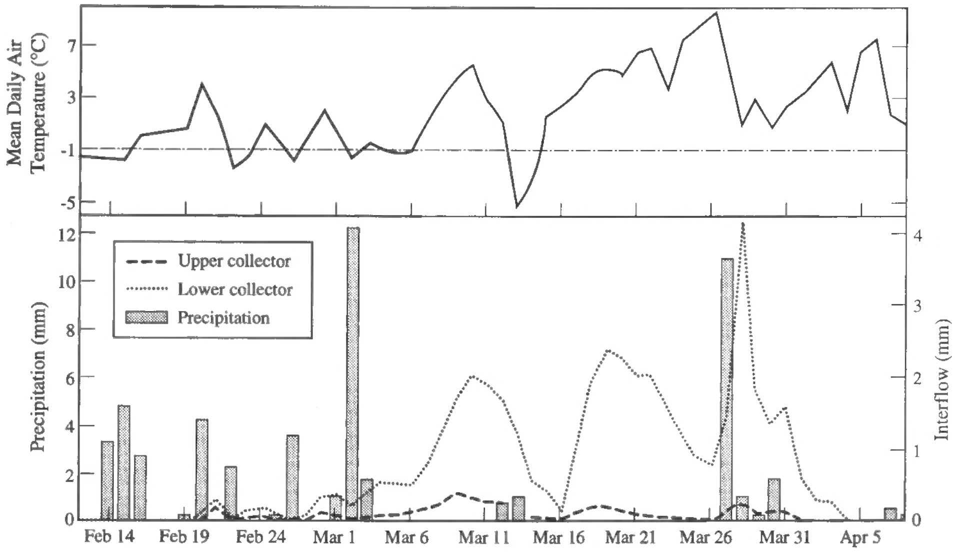

FIGURE 2. Daily interflow vs. temperature and precipitation, February 14 - April 5, 1993.

Nearly 50 mm of interflow was measured, from a contributing area estimated at 700 m^2. Most of it came from the Bt horizon. Soil moisture measurements across the hillslope indicate that a zone of saturation develops at a depth of about 90 cm at the interface between the soil and the underlying tuff bedrock.

Daily interflow measurements for the winter of 1992-93, from both the upper and lower collectors, and their correlation with precipitation and average daily temperature, are shown in Figure 2. We recorded three major interflow phases as the snow pack melted (which began in the latter half of February, when air temperatures began to rise). The first phase, in early March, showed a clear correspondence with rising temperatures; interflow dropped off sharply when a period of below-freezing temperatures ensued in mid-March. The second major phase, which began around March 16, also corresponded with a rise in air temperatures that further reduced the snow pack. The third phase, in late March, resulted from a rain-on-snow event that melted much of the remaining snow pack. In all, interflow amounted to about 45 mm, representing about 20% of the winter snow pack.

Interflow may occur in summer as well, but only in small amounts. On average, interflow has accounted for a small portion of the total water budget for the site. At the same time, our data not only show that interflow can periodically be a very important mechanism of runoff but they reveal its dynamic nature; water can move through these soils at a faster rate than can be explained by the hydraulic properties of the soil matrix. Using stable isotopes and other natural tracers, Newman (1996) demonstrated that water moves preferentially through a macropore network in the soil. The conceptual model developed from these studies explains the preferential flow process and macropore/matrix interactions.

Further, Newman's work showed that the chemistry of interflow can change dramatically. During most of the year, when the soils are unsaturated, little interflow is generated and is chemically dilute. However,during relatively short periods when soils are at or near saturation (such as spring snowmelt), interflow becomes chemically much more concentrated. For example (Fig. 3), concentrations of chloride and dissolved organic carbon increased dramatically between late fall 1994 and spring 1995, a period of very wet overall conditions. Although one might expect that

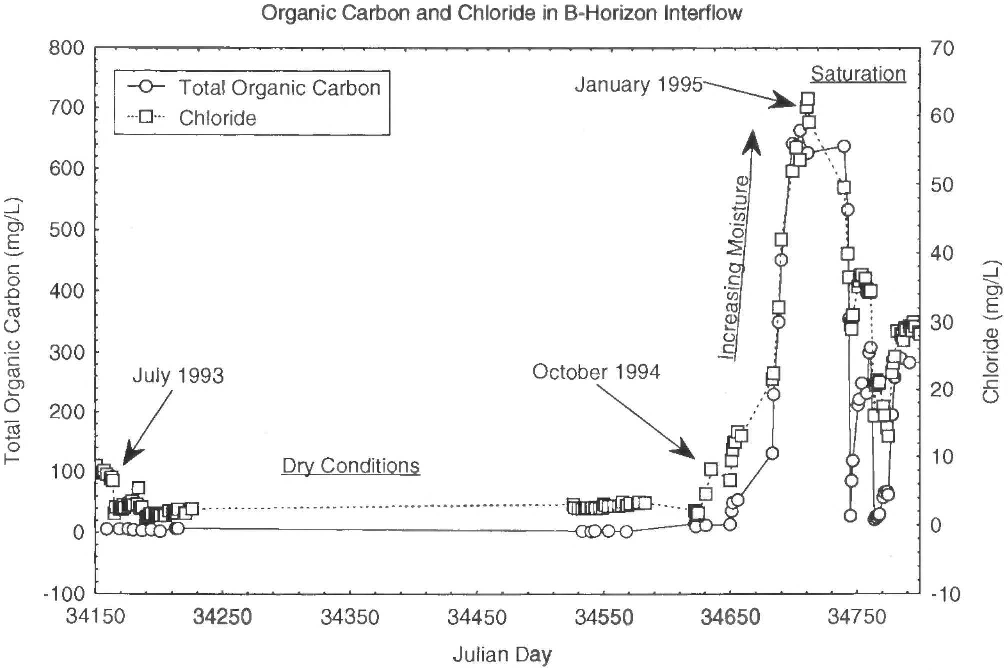

FIGURE 3. Changes in B-horizon total organic carbon and chloride with time. The graph shows dramatic concentration increases as soil moisture content rose to saturation between fall 1994 and spring 1995.

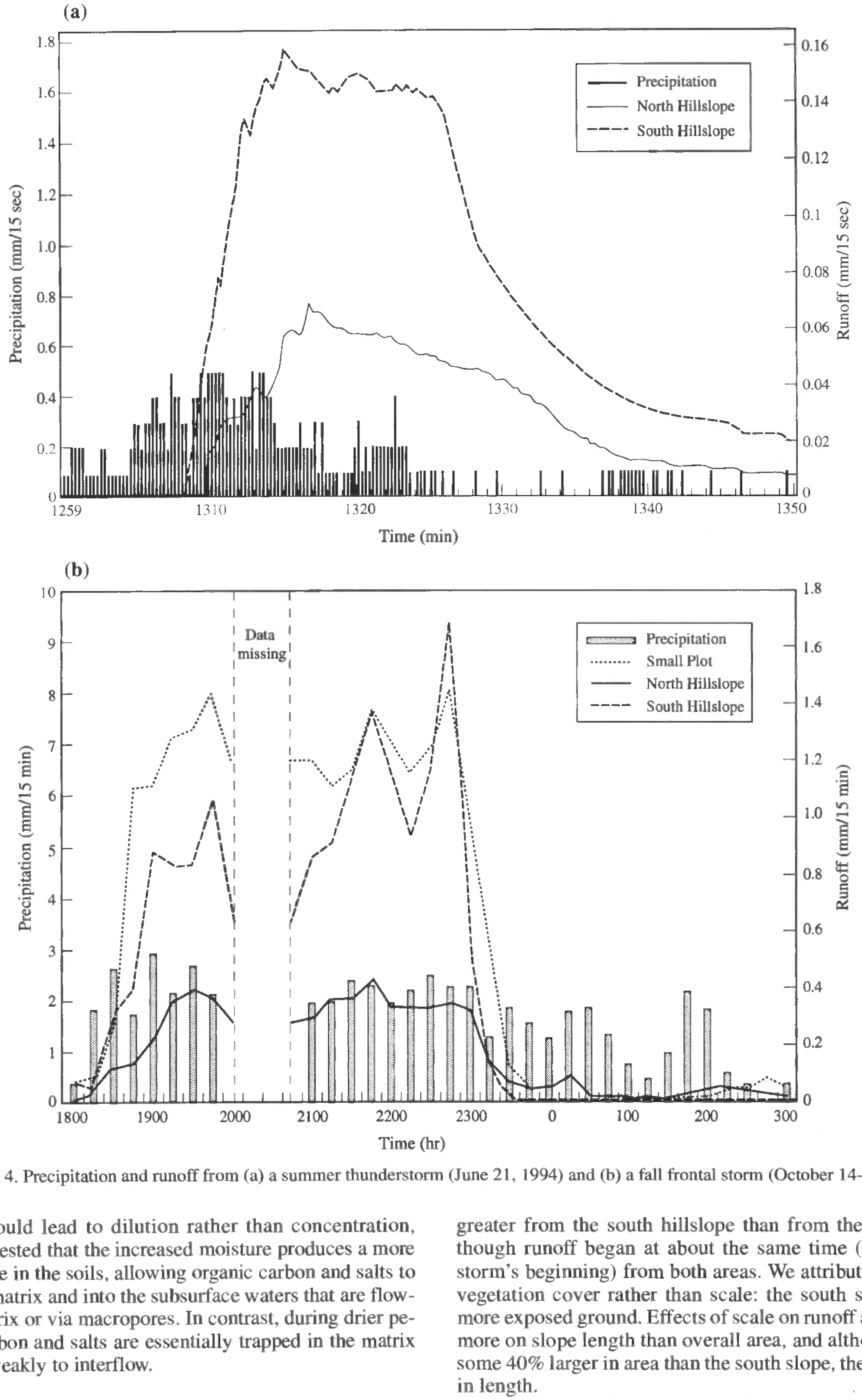

FIGURE 4. Precipitation and runoff from (a) a summer thunderstorm (June 21, 1994) and (b) a fall frontal storm (October 14-15, 1994).

wetter conditions would lead to dilution rather than concentration, Newman (1996) suggested that the increased moisture produces a more continuous fluid phase in the soils, allowing organic carbon and salts to move out of the soil matrix and into the subsurface waters that are flowing either via the matrix or via macropores. In contrast, during drier periods, the organic carbon and salts are essentially trapped in the matrix and contribute only weakly to interflow.

Surface runoff

Surface runoff is generated mainly by intense summer thunderstorms; on occasion, it is produced by more gentle, but more prolonged, frontal storms. Our experimental setup measures surface runoff from three different areas on the hillslope, allowing us to document differences in runoff due to scale of measurement and surface conditions.

On June 21, 1994, an intense summer storm dropped 28 mm of precipitation in about 20 min. Runoff per unit area was almost three times greater from the south hillslope than from the north (Fig. 4a), even though runoff began at about the same time (within minutes of the storm's beginning) from both areas. We attribute this to differences in vegetation cover rather than scale: the south slope has considerably more exposed ground. Effects of scale on runoff appear to depend much more on slope length than overall area, and although the north slope is some 40% larger in area than the south slope, the two are roughly equal in length.

A prolonged fall (October 1994) frontal storm generated the greatest surface runoff. Three distinct phases of precipitation were measured over a 76-hr period. The first phase, during which about 75 mm of precipitation fell in 11 hrs, produced most of the runoff. From all three study areas runoff was continuous for more than 7 hrs (Fig. 4b) and totaled about 21 mm from the small plot, 17 mm from the south hillslope, and 6 mm from the north hillslope. The other two precipitation phases of the storm produced appreciable runoff only from the small plot.

Pinyon-juniper sites

Stable site

At this site, the dominant runoff-generating mechanism is intense summer thunderstorms. We are monitoring surface runoff at both the plot (32.4 m^2) and hillslope (2000 m^2) scales and interflow only at the hillslope scale. Unlike the ponderosa pine site, the pinyon-juniper hillslope rarely yields interflow, and only in trace amounts.

At the plot scale, thunderstorms have generated runoff all four summers of the study. In addition, snowmelt has generated significant runoff; for two of the five winters of observation, runoff from the plots has equalled as much as 40% of the winter snow pack. Total surface runoff from the plots amounts to about 7% of the water budget (see Wilcox, 1994, for a detailed discussion of our results from these plots).

At the hillslope scale, total runoff amounts to less than 1% of the water budget. On a unit-area basis, runoff from the hillslope is much smaller than from the plots. No runoff from snowmelt was measured at the hillslope scale. Apparently water is absorbed en route, into sink or recharge areas such as snow drifts, spaces beneath pinyon-juniper canopies, and alluvial flood plain sediments.

These differences between the hillslope and the plots with respect to the timing and amount of runoff are illustrated in Figure 5. The hydrographs show runoff from the hillslope and from one of the plots, for a storm that occurred on September 8, 1995, and produced 18 mm of rain in about 20 min. Antecedent soil moisture was high as a result of a smaller (11 mm), more gentle rain the previous day, and because of this, runoff efficiency from the plots was quite high (around 11 mm). The hillslope however, produced only about 1 mm of runoff (Fig. 5a)–even though on a volume basis, runoff was about 8 times higher from the hillslope than from the plot (Fig. 5b). These and other similar data are extremely valuable for testing and improving hydrologic models that will be applied to the Pajarito Plateau (Wilcox and Simanton, 1996).

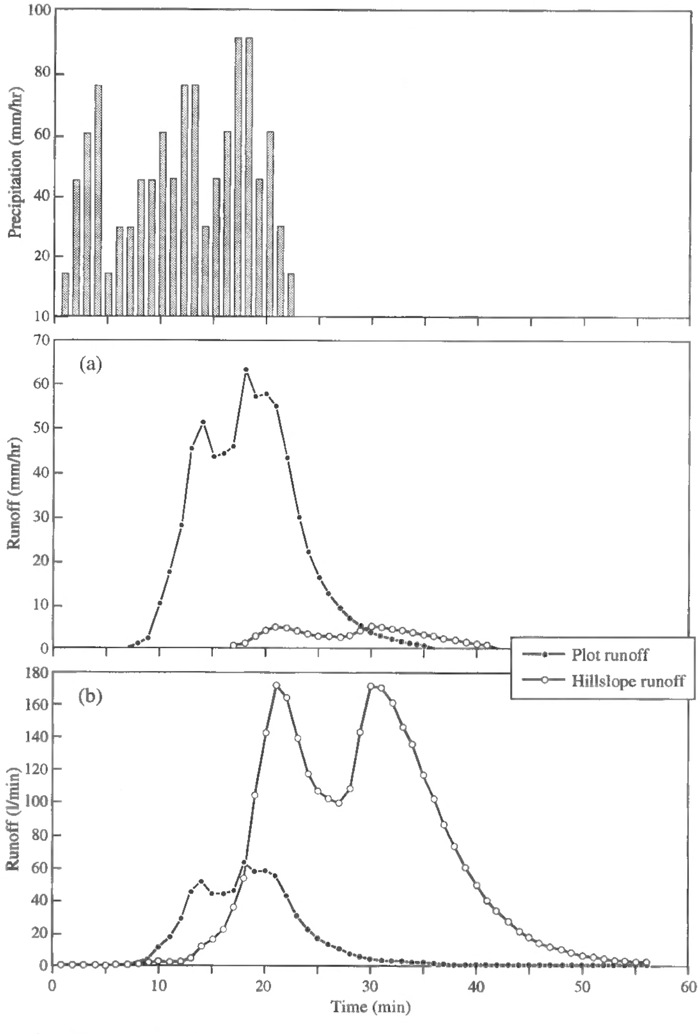

FIGURE 5. Precipitation and runoff at the plot and the hillslope scales at the stable pinyon-juniper site for a storm occurring on September 8, 1995; (a) unit-area runoff and (b) total runoff volume.

We are finding quite low rates of erosion in these stable pinyon-juniper woodlands. At the hillslope scale, erosion is less than 25 kg/ha/yr, considerably lower than from the plots (and corresponding with the lower runoff rates). Erosion from the plots has been less than 100 kg/ha most years,but in the very wet summer of 1991 erosion from plots with good ground cover ranged from about 300 to 3000 kg/ha and was even higher from plots that had been stripped of ground cover.

Eroding site

At this site, surface runoff and erosion are much more active than at the stable pinyon-juniper site, both at the catchment and the plot scale. Since July 1993, when the first runoff measurements were taken, we have recorded 19 runoff events–all but one generated by intense summer thunderstorms. These events are typical of semiarid landscapes in that they are of short duration and peak flow occurs within minutes of the onset of runoff (Fig. 6a). As a fraction of the water budget for the two complete years of observation, the contribution of runoff has been small (2% and 7%).

In terms of volume, the largest runoff event was actually produced by a fall frontal storm that dropped 55 mm of precipitation in two days. Runoff began after the first 24 hrs, during which about 15 mm of rain fell, and continued unabated for a 6-hr period (Figure 6b); 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.

For the third summer rainy season, we have data from the small (1 m^2) plots to compare with those from the catchment. Plot-scale and catchment-sale runoff are about the same, in contrast with our findings for the stable site. We attribute this similarity to the well-developed channel network on the catchment which inhibits storage on the hillslope.

Microtopographic measurements have been taken regularly since July 1993, at 400 points within 20 sites; they show a consistent and predictable pattern of changes in surface elevation in response to soil erosion during the summer rains, frost heaving in the early spring, and raindrop compaction in the spring and summer. Between July 1993 and September 1995, the average change in elevation was -6.7 mm. We attribute most or all of this to soil erosion, having found that over a period of a year, increases in elevation due to frost heaving and decreases due to raindrop compaction more or less cancel out one another.Three representative microtopographic profiles include a rapidly eroding section from which as much as 7 cm of soil has been lost in a 26-month period (Fig. 7a); a deposition zone in which up to 8 cm of sediment has accumulated, underscoring the dynamic changes occurring on the hillslope (Fig. 7b); and a location at which, because of the stabilizing effect of cryptogamic cover, erosion has been comparatively small (Fig. 7c).

Assuming an average loss in surface elevation of 6.7 mm or 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/yr.

We also have direct measurements of erosion for one year. Data from the small plot network and the sediment traps on the subcatchments, gathered in 1995, show that erosion increases dramtically (up to eight times) as the scale of measurement increases from the plot to the subcatchment scale. We estimate that for the latter, erosion was about 9000 kg/ha–several hundred times higher than erosion rates measured at our other sites (see Wilcox et al., 1996).

DISCUSSION AND CONCLUSIONS

Three years of data from our three fully instrumented hillslope hydrology sites are helping us develop a conceptual model of runoff and erosion

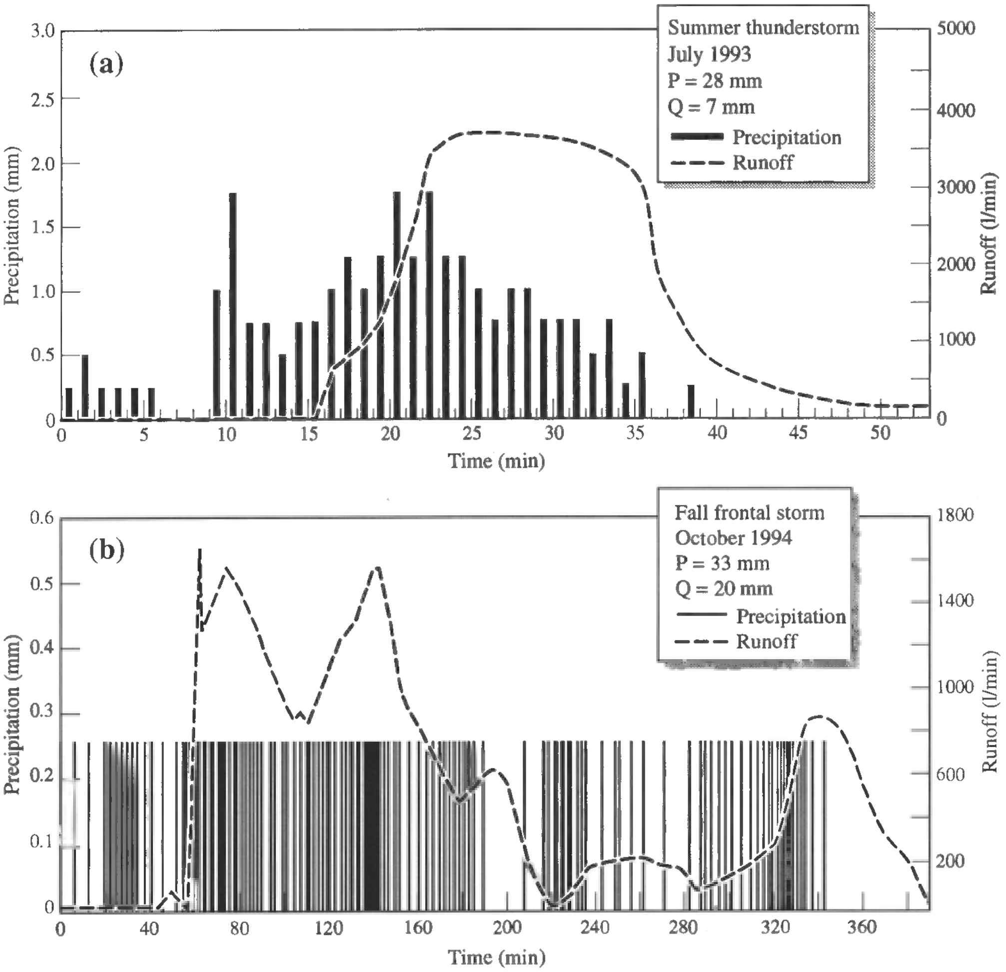

FIGURE 6. Eroding site rainfall (P) and runoff (Q) for (a) a summer thunderstorm and (b) a fall frontal storm.

based on detailed field measurements rather than anecdotal observations. Key components of our conceptual model are discussed below.

Interflow

Interflow is generated from the upper elevations of the Pajarito Plateau (ponderosa pine and higher zones); very little is generated from the lower- elevation pinyon-juniper communities. Interflow occurs primarily when soils are saturated, either by spring snowmelt or by prolonged rainfall. When vertical movement of water through the soil is restricted, as we believe it is by the soil/tuff interface (Wilcox et al., 1995), water is forced to move laterally. We have observed that during periods of active interflow, water may emerge on the surface, coalesce in small channels on the mesa tops, and subsequently drain into the canyons. This process can feed streamflow for several days or even weeks.

Where interflow occurs, it constitutes an additional—and crucial—element in how contaminants are transported, particularly those in colloidal or dissolved form. As discussed earlier, interflow chemistry can change dramatically with changes in soil moisture, and these changes can have a profound effect on contaminant chemistry. For example, the chloride data indicate that both the concentrations of aqueous species and interflow ionic strength changed substantially as the soils became saturated. We must assume that such chemical shifts will affect the sorption, the speciation, and the solubility of metal contaminants that enter the interflow system—all of which will have an effect on the mobility of those contaminants. In addition, dissolved organic matter in the system will affect mobility, through both sorption and complexation. Large peaks observed during the ion chromatography runs for chloride, which do not correspond to the elution times of inorganic anions, probably indicate the existence of negatively charged organic compounds. In other words, some fraction of the organic material is anionic and could act as ligands for the formation of organo-metallic complexes.

Interflow plays a further role in contaminant transport in that it affects the distribution of contaminants between the matrix and macropores. Contaminants that enter the macropore system can move rapidly, while those that enter the matrix will move only very slowly. The process is actually much more complex; throughout most of the year, when soils are dry, the matrix acts as a sink for salts (and presumably contaminants), whereas during wet periods it becomes a source of sequestered salts and contaminants that can be released through diffusion or advection. Under dry soil conditions, then, macropore flow may rapidly flush contaminants out of the system, and interflow will be contaminant-free (or contain only low concentrations) for a time; saturated conditions may later resupply the macropores with contaminants that were stored in the matrix, once again increasing their concentrations in interflow.

Surface runoff

Surface runoff may be generated from the entire plateau, either by summer thunderstorms or, occasionally, by more gentle but more prolonged frontal storms. The summer storms produce the highest peak flows and have the greatest potential for moving sediment (and any contaminants that may be present) to the stream channels, even though these storms generally last only a few hours. Small amounts of surface runoff can also be produced by snow melting over frozen soils.

Erosion

Erosion rates are quite low across the most of the plateau, but a significant area, consisting mostly of lower-elevation pinyon-juniper communities, is eroding at rapid rates. Gottfried et al. (1995) laid out a con-

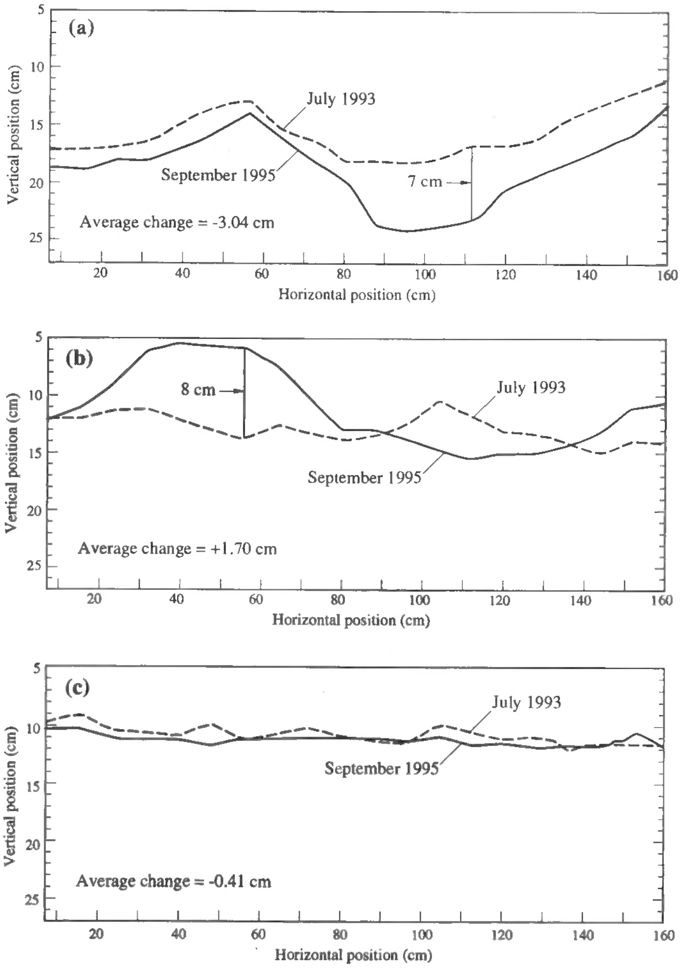

FIGURE 7. Eroding site; microtopographic changes at three locations, representative of (a) an eroding surface; (b) a depositional surface; and (c) a relatively stable surface.

ceptual model of the events that led up to the current cycle of accelerated erosion in this area. This rapidly eroding area, if contaminated at the surface, represents the greatest potential for redistribution of contaminants on the Pajarito Plateau.

Scale effects

Runoff and erosion amounts can vary tremendously with scale of measurement. Understanding these scale relationships is fundamental if we are to successfully model runoff and erosion from the plateau (Wilcox and Breshears, 1995). We are finding that if hillslope channels are not present—in other words, if the site is not undergoing rapid erosion—runoff and erosion will decrease markedly as the scale of measurement increases. The obvious reason is that as slope length increases, so does the opportunity for storage and infiltration. Conversely, data from our eroding site show that under degraded conditions, erosion increases dramatically from the plot to the hillslope scale. Well-developed channel networks can efficiently transport water off the slope, so that runoff amounts decrease little if at all as scale increases from plot to hillslope.

Only through long-term, detailed field observations of runoff and erosion can we develop a solid understanding of these processes on the Pajarito Plateau and other similar semiarid environments. The current studies are beginning to provide the basis for such an understanding, as well as high-quality data for validating and refining the hydrologic models needed to predict the long-term fate of contaminants on the plateau (Wilcox and Simanton, 1996). The ultimate result will be a more solid foundation for risk assessments.

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