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Runoff from a semiarid ponderosa pine hillslope in New Mexico

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Abstract. The mechanisms by which runoff is generated in semiarid forests have been little studied. Over the past 4 years we have been investigating runoff processes in semiarid regions by continuously monitoring runoff, both surface and lateral subsurface, from an 870-m^2 ponderosa pine hillslope in northern New Mexico. We have found that runoff accounts for between 3 and 11% of the annual water budget. We have also found that lateral subsurface flow is a major mechanism of runoff generation, especially following periods of above-average fall and winter precipitation. In one winter, lateral subsurface flow was equivalent to about 20% of the snowpack (about 50 mm). When antecedent soil moisture was high, lateral subsurface flow was extremely responsive to snowmelt and rainfall events and was much more dynamic than would be suggested by the low (laboratory determined) hydraulic conductivity of the soil. The rapidity with which lateral subsurface flow follows these events suggests that macropore flow is occurring. In the case of surface runoff, the major generation mechanisms are intense summer thunderstorms, prolonged frontal storms, and snowmelt over frozen soils. Surface runoff at our site took the form of infiltration-excess overland flow; this type of surface runoff has not been found to dominate at other ponderosa pine sites studied. These detailed and continuous investigations are increasing our understanding of runoff processes in semiarid forests and are thereby laying the groundwork for improved predictions, not only of runoff, but also of the concomitant transport of sediment and contaminants within and from these zones.

1. Introduction

Runoff in semiarid landscapes is an important, yet poorly understood, phenomenon. It is important because it is a major mechanism by which water, sediment, nutrients, and contaminants are moved and redistributed; it is poorly understood because relatively few detailed studies of runoff have been carried out in these regions.

Measuring runoff in semiarid environments presents formidable challenges. Because runoff-producing events are infrequent and of short duration, the time required to adequately characterize runoff is relatively long, and opportunities to correct for equipment failures or a flawed collection strategy may be few and far between. For these reasons, the method of choice for investigating runoff in semiarid landscapes has been rainfall simulation at relatively small scales [*Branson et al.*, 1981]. These studies have unquestionably added to our understanding of semiarid hydrology, for example in the areas of hydraulics of overland flow [*Parsons and Abrahams*, 1992] and relative impacts of various land management practices [*Blackburn et al.*, 1982], but because of their small scale and artificial conditions, they have not led to a deeper understanding of hillslope hydrology per se. Compared with what is known about more humid landscapes, our knowledge of semiarid hillslope hydrology is in its infancy. Basic questions such as how much runoff occurs, at what frequency it occurs, and under what conditions it occurs remain largely unanswered on the hillslope scale [*Thorns*, 1994]. In addition, the scarcity of hillslope-scale studies has increased the need for models capable of simulating runoff processes, but at the same time it is difficult if not impossible to adequately validate such models without long-term, reliable data on runoff processes [*Pilgrim et al.*, 1988].

In most semiarid settings, runoff occurs as rainfall-excess or infiltration-excess overland flow (IEOF), the process whereby the rainfall rate exceeds the infiltration rate of the soil [*Horton*, 1933; *Abrahams et al.*, 1994]. The infiltration rate is controlled by many variables (e.g., vegetation, stone cover, soil characteristics) and is highly spatially variable. Infiltration-excess overland flow, then, may be generated from one area of a hillslope rather than from the entire area, and in many cases the slope length will be great enough that much of the runoff will infiltrate before reaching a stream channel. These dynamics explain why, on a unit-area basis, runoff in semiarid landscapes is often observed to decrease as the scale of measurement increases [*Yair and Lavee*, 1985].

Saturation-excess overland flow (SEOF) is relatively uncommon in semiarid settings [*Graf*, 1988]. Notable exceptions are the pinyon-juniper and ponderosa pine woodlands of Arizona, where prolonged frontal rainfall or snowmelt can saturate the shallow, low-permeability soils, causing overland runoff to be generated [*Lopes and Ffolliot*, 1993].

Finally, lateral subsurface flow is not commonly considered an important agent of runoff generation in semiarid environments, although some previous researchers have found pedogenic evidence that it does occur [*Thorns*, 1994].

Semiarid woodlands and forests have probably been even less investigated than other areas within the semiarid zone. In

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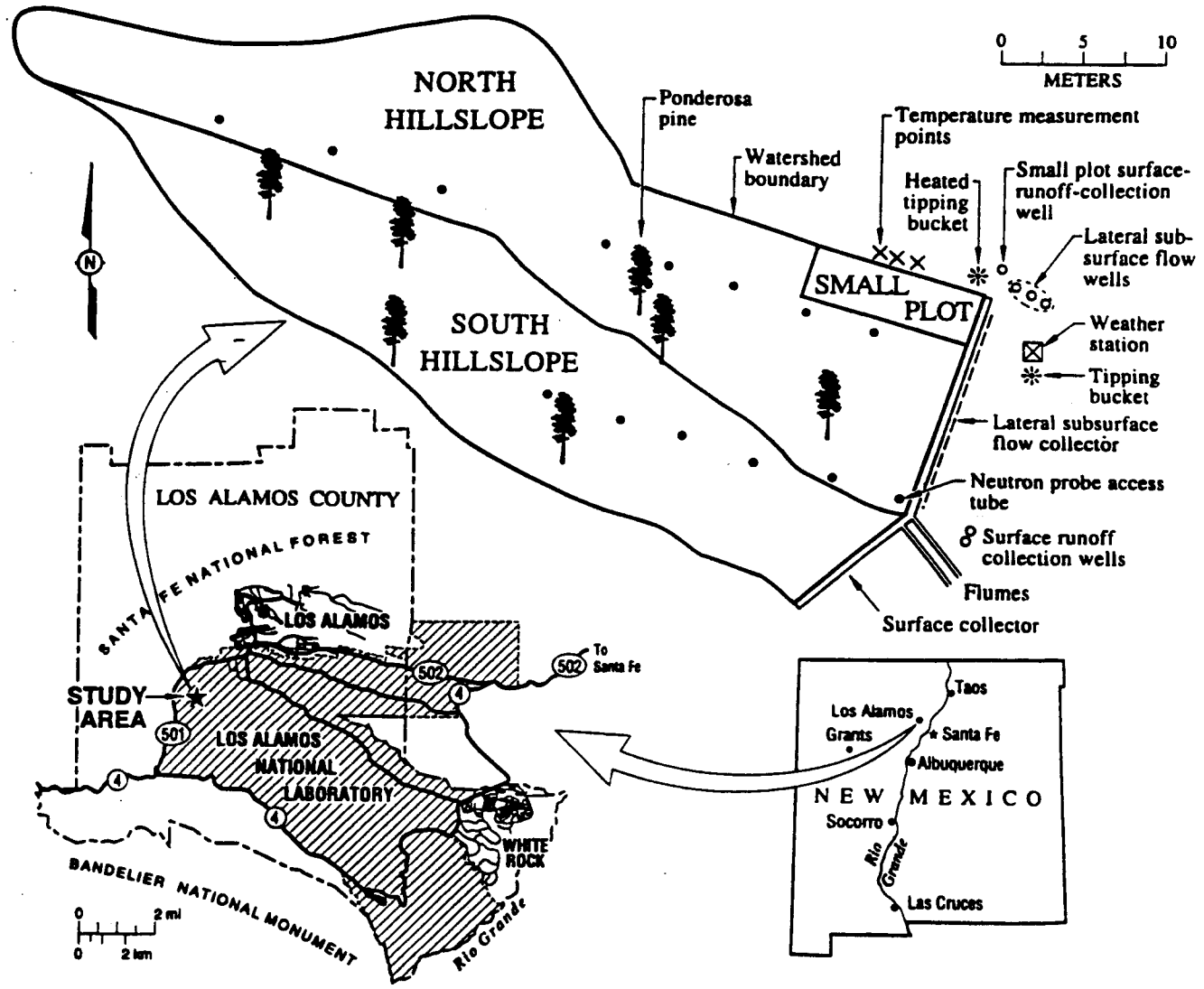

Figure 1. Location map and schematic of study area.

3.4. Lateral Subsurface Flow

Lateral subsurface flow was measured from the north hillslope and the small plot. A trench, cut perpendicular to the slope of the hill, intercepts the flow of shallow subsurface runoff from these two areas (Figures 1 and 2). The trench is equipped with two 12-m-long collectors: an "upper" collector at 20 cm from the surface and a "lower" collector at 95 cm. The upper collector is designed to collect water from the loess-derived A and Bw horizons. The lower collector is designed to collect water primarily from the Bt horizons. Each collector routes the water to a well that is equipped with a pressure transducer and a flow meter for monitoring the volume of flow.

For the purposes of our analysis, we have estimated the contributing area for lateral subsurface flow to be about 700 m^2. This estimate (which assumes contributing area boundaries that are exactly perpendicular to the trench for the length of the hillslope) is probably high; if subsurface flow lines follow those of surface flow, then the area may be closer to 500 m^2. We have chosen the higher, and thus more conservative, value so as not to overestimate the importance of lateral subsurface flow.

3.5. Weather

We installed a weather station on site to monitor precipitation, wind speed and direction, ambient temperature, relative humidity, and solar radiation. Rainfall is measured by means of a tipping-bucket rain gauge. Precipitation from snowfall was not measured on the site itself until October of 1993, when a heated tipping-bucket gauge was installed; but we did obtain data on winter precipitation for the period from November 1992 to February 1993 from an area of similar elevation nearby (about 2 km south of the site) that was equipped with such a gauge.

3.6. Soil Moisture and Temperature

Soil moisture is generally measured weekly, by neutron thermalization [*Gardner*, 1986]. Measurements were taken at 11 locations initially and have been taken at 14 locations since December 1993. At each location, measurements are taken every 15 cm to a depth of 150 cm and thereafter every 30 cm to a depth of 300 cm. Soil temperature is monitored every 2 hours by temperature probe to a depth of about 100 cm, on the north border of the hillslope.

Table 3. Final Infiltration Rates, as Measured by Ponded Infiltrometer

Location	Surface Description	Cover, %	Hillslope Location	Antecedent Moisture, %	Final Infiltration Rate, mm/h
1	bare ground	0	south	27	6
2	bare ground	0	south	26	90
3	bare ground	0	south	31	6
4	grass, bare ground	60	south	28	51
5	cryptogam, bare ground, soil cracks	20	north	22	156
6	cryptogam, bare ground	20	north	26	27
7	bare ground	0	north/south boundary	26	7
8	grass, bare ground, cryptogam	40	north	26	24
9	grass, bare ground	75	south	26	3
10	pine needles	100	north	20	36
11	grass, pine needles	100	north	26	39

example, surface runoff was significantly different in both amount and timing, owing to the differences in degree of cover, extent of frozen soil, depth of snowpack, and scale of the three areas (Figure 3). Surface runoff occurred mainly during two periods of the year: late winter (in response to melting snow) and late summer (as a result of intense summer thunderstorms).

4.1. Fall and Winter Runoff

The major factors affecting the type and amounts of fall and winter runoff are the amount and type of precipitation, patterns of snow accumulation, and patterns of soil freezing. The first two factors affect runoff generation not only directly, but also indirectly (by influencing soil moisture levels).

Winter moisture conditions are largely a function of precipitation from October through March. We will consider winter precipitation to be the total amount of precipitation received during these months. In the 4 years of observation, there have been two wet winters (water years 1993 (WY93) and 1995 (WY95)), one average winter (WY94), and one very dry winter (WY96). The precipitation characteristics of the two wet-winter years were quite different: in the winter of WY93, most of the precipitation fell as snow, which produced a large snowpack; in contrast, during the fall and winter of WY95, the bulk of the precipitation was rainfall, most of which occurred in the fall. These differences in type of precipitation account for the differences between the 2 years in both the nature and amounts of runoff (Table 4).

Snow cover on the hillslope is generally continuous throughout the winter. The locations where snowdrifts developed were consistent from year to year, the two primary areas being (1) the lower south hillslope and (2) near the top of the hill, on both the north and south sides. The relatively larger drifts on the south hillslope were a major contributor to the generally larger amounts of surface runoff generated from this area.

The patterns and timing of soil freezing can profoundly affect runoff. If snow begins to accumulate before temperatures drop below freezing for prolonged periods, the ground may remain unfrozen owing to the insulation of the snow cover. If, however, prolonged periods of freezing commence before there is snow cover, the ground will remain frozen all winter. The degree of shading also plays a role in patterns of soil freezing: the south side of the hillslope stays frozen longer as a result of the shade provided by the trees along the south border.

4.1.1. WY93: Wet winter, large snowpack. By far the most winter runoff was produced in the winter of WY93, when the snowpack was unusually large. Winter precipitation, which fell mostly as snow, was almost double the average amount. When the snow melted, large quantities of runoff were generated,

Table 4. Monthly Summary of Precipitation and Runoff

	Water Year 1993			Water Year 1994			Water Year 1995			Water Year 1996		
Month	Precipitation	Total Subsurface Runoff	Total Surface Runoff	Precipitation	Total Subsurface Runoff	Total Surface Runoff	Precipitation	Total Subsurface Runoff	Total Surface Runoff	Precipitation	Total Subsurface Runoff	Total Surface Runoff
Oct.	21	0	0	16	0	0	126	*t*	15	0	0	0
Nov.	34	0	0	45	0	0	58	*t*	5	11	0	0
Dec.	44	0	0	7	0	0	21	*t*	1	21	0	0
Jan.	89	0	0	8	0	0	64	*t*	0	33	0	0
Feb.	67	2	0	15	0	1	32	*t*	10	19	0	0
March	33	45	2	58	0	4	40	6	3	15	0	0
April	2	1	0	48	0	0	31	1	0	5	0	0
May	35	0	0	77	0	5	59	*t*	0	0	0	0
June	20	*t*	0	46	*t*	9	65	*t*	0	108	0	7
July	57	2	2	102	*t*	8	34	*t*	0	102	0	2
Aug.	127	*t*	3	73	*t*	6	106	*t*	2	79	0	1
Sept.	34	*t*	1	27	*t*	0	57	*t*	0	68	*t*	2
Total	563	50	8	522	*t*	33	693	8	36	461	*t*	12

All values are in millimeters; *t* indicates trace amounts.

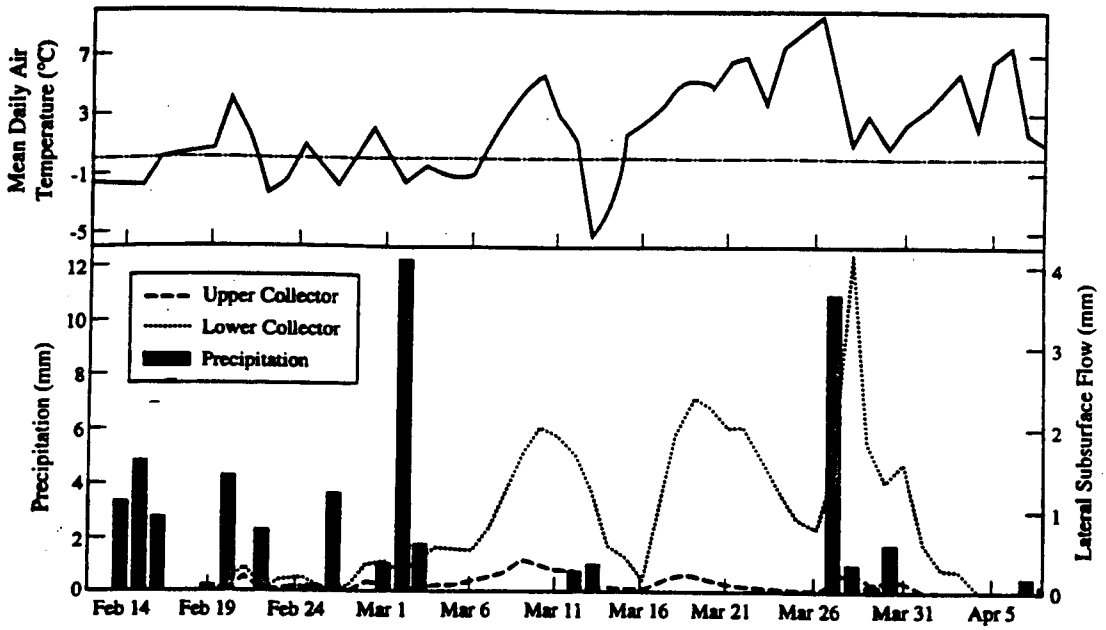

Figure 4. Daily lateral subsurface flow versus temperature and precipitation, February 14 to April 5, 1993.

of precipitation, rain or rain mixed with snow, fell in October and November. Freezing temperatures then set in before any permanent snow cover developed, and the soils froze. Precipitation for the remainder of the winter was close to "normal."

The frontal storm that occurred in October was exceptional for this region. About 125 mm of precipitation (a mixture of rain and snow) fell over a 76-hour period, producing 15 mm of runoff from the hillslope, the largest single surface runoff event in the 4 years of observation (Table 4). In November a similar low-intensity frontal storm also generated surface runoff.

Surface runoff for the remainder of the winter of WY95 was high compared with the levels observed during the winter of WY93 (Table 4, Figures 3a and 3c). A concrete-like soil frost developed with the onset of sustained freezing temperatures in December, when the soils were wet but not covered by snow. The snowpack that accumulated later began to melt in February, when significant portions of the surface of the hillslope were still frozen. The north hillslope and the small plot produced about the same amount of runoff per unit area, although runoff began sooner from the small plot. The largest amount of surface runoff was produced from the drift on the south hillslope, where soils remained frozen longer because they were shaded by the trees along the south border.

Lateral subsurface flow occurred in the winter of WY95 but not to the extent that it did in WY93, even though there was more total winter precipitation in WY95. The two frontal storms in October and November generated trace amounts, but most of the lateral subsurface flow was measured over a 3-day period in March (Figure 6). The conditions that led to this late winter event included (1) near-saturated soils due to high precipitation in the fall, added to by the melting of the snowpack, and (2) a week of precipitation (26 mm of snow and 13 mm of rain). On the north hillslope, where soils had thawed by the time of this rain-on-snow event, lateral subsurface flow began with the onset of rainfall and continued for over a month, although most of it was measured in the first 3 days. Peak hourly flow was an order of magnitude higher than the highest recorded during the winter of WY93. At the same time, surface runoff was being generated from the south hillslope, where soils remained frozen because of shading; this runoff was highly diurnal in nature (Figure 6).

4.1.3. WY94: Normal precipitation. Winter precipitation in WY94 was very close to normal (Table 4). The snowpack that developed was small and generated only surface runoff when it melted; no lateral subsurface flow was measured. Most of the runoff was generated from the drift on the south hillslope (Figure 3b). As in the winter of 1995, while this drift was melting, the downslope soils remained frozen. Surface runoff followed a diurnal pattern similar to but smaller than that observed in WY95, shown in Figure 6.

4.1.4. WY96: Dry winter. In the winter of WY96, precipitation was only about 65% of normal, and no runoff was observed.

4.2. Summer Runoff

Summer runoff at our site is generated primarily by thunderstorms that form over the adjacent Jemez Mountains in the afternoon and evening and drift down the plateau. These storms are typically brief but very intense, producing short bursts of rain as high as 2 mm/min.

A summary of summer runoff amounts for the 4 years of observation is given in Table 5. At the hillslope scale we measured 29 surface runoff events, but most of these were quite small; only six produced more than 1 mm of runoff. Neutron probe data indicated that rainfall was never sufficient to saturate the soils.

The quantities of lateral subsurface flow observed in the summer have been very small. Only two rainfall events, both of them the first summer, yielded measurable amounts (Table 5). The lateral subsurface flow generated by these events began just 40–80 min following rainfall and was measurable for periods of 60–210 min.

5. Discussion

In this semiarid forest, we found that although runoff accounts for a relatively small portion of the annual water budget

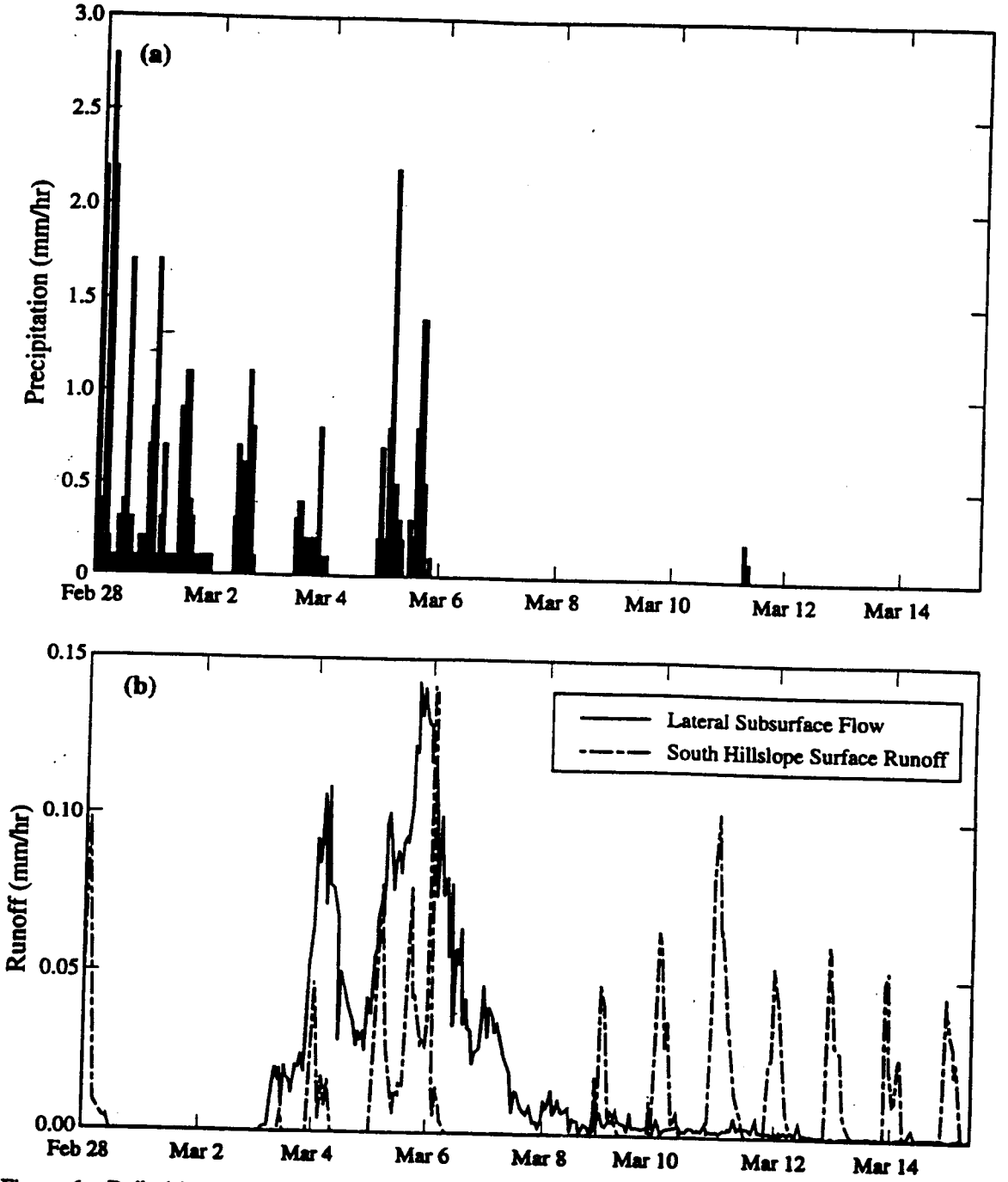

Figure 6. Daily (a) precipitation and (b) total lateral subsurface flow (from north hillslope and small plot) and surface runoff (from south hillslope), March 1995.

lateral subsurface flow suggests that the water is moving through the subsurface via a network of macropores.

Generally, for substantial volumes of lateral subsurface flow to occur, there must be present (1) an impermeable, or nearly impermeable, soil or subsoil horizon that restricts the vertical movement of water and (2) enough water to saturate the soil above this horizon [*Whipkey*, 1965; *Freeze*, 1972; *Mosley*, 1979]. At our site, evidence for the first condition comes from soil moisture data (Figure 5), which indicate that a barrier or impediment to water movement exists at or near the interface between the soil and the unweathered tuff.

We had expected, initially, that if a restrictive horizon was present, it would be the upper portion of the Bt horizon, which is very high in clay content and low in (laboratory determined) hydraulic conductivity. For this reason, it was somewhat surprising to discover that lateral subsurface flow was in fact taking place in this horizon. The logical explanation, of course, is the presence of macropores in the Bt horizon. We have observed macropore flow, via root channels, in this horizon in other areas (nearby road cuts and exposed pits) following snowmelt and rain showers. Concurrent work with natural tracers also suggests the presence of a macropore network [*Newman*, 1996].

Most soils contain macropores, but they seem to be best

5.2. Surface Runoff

5.2.1. Frozen soil runoff. In the winter, most surface runoff occurs as frozen soil runoff. Frozen soil runoff has been reported in regions as widely separated as Vermont [*Dunne and Black*, 1971] and the sagebrush rangelands of the northwest [*Seyfried and Wilcox*, 1995]. We believe that the major factors affecting the presence and spatial distribution of this type of runoff at our site are (1) timing of freezing temperatures in relation to development of the winter snowpack, (2) soil moisture levels at the time of freezing, (3) spatial distribution of snow drifts, and (4) distribution of shade. When prolonged periods of freezing commence before there is snow cover, the ground will remain frozen all winter, setting up the conditions for frozen soil runoff. Areas that receive more shade will stay frozen longer. (If, on the other hand, snow cover develops before the onset of freezing temperatures, the ground may remain unfrozen all winter, and surface runoff will be minimal.) If soils are wet when they freeze (concrete soil frost), the infiltrability of the soil becomes zero or very close to zero, greatly facilitating runoff. Finally, if a snowdrift develops upslope from an area of frozen soil, runoff will be greater.

We found that the south slope produced the most frozen soil runoff. The dense stand of trees bordering this area contributed to the development of a snowdrift but also provided shading, with the result that downslope soils remained frozen during melting of a large portion of the drift. During frozen soil runoff the upper few centimeters of the soil were thawed and completely saturated. In addition, we found that frozen soil runoff was highly diurnal in nature (Figure 6).

5.2.2. Infiltration-excess overland flow. Surface runoff that is generated by rainfall (both thunderstorms and frontal storms) occurs as IEOF. The most frequent agent of this type of runoff at our site, and the one that produced the highest peak flows, was short, intense summer thunderstorms. A second agent was frontal storms lasting several days; these produce more sustained runoff and larger total volumes. In both cases, surface runoff occurred as IEOF. Our observations of IEOF in a ponderosa pine forest contrast with those of other investigators, who concluded that IEOF rarely occurs in ponderosa pine forests [*Dunford*, 1954; *Heede*, 1984; *Williams and Buckhouse*, 1993]. Surface runoff was important in the Beaver Creek watershed but took the form of SEOF. At that site, widespread saturated conditions were created by the low permeability of the soils (conditions similar to those seen in tropical rain forests of Australia [*Bonell and Gilmour*, 1978] and Amazonia [*Elsenbeer and Cassel*, 1991]).

We see no evidence for SEOF at our site. In the case of runoff resulting from the brief, intense thunderstorms of summer, the IEOF mechanism is clear. Data from two storms (Figure 7) are typical: within minutes of the onset of rainfall, the infiltration rate of the soil seems to be exceeded, and runoff begins; it generally lasts less than 20 min. Following the methodology of *Williams and Bonell* [1988], we calculated cumulative infiltration (rainfall minus runoff) from the small plot for these two storms. The cumulative curves are shown in Figure 7. Note that in both cases, the infiltration rate (indicated by the slope of the line) falls off rapidly within a few minutes after runoff begins. From these curves we estimate that the final infiltration rate was ~5 mm/h for the first storm (August 29, 1995) and ~7 mm/h for the second storm (June 26, 1996). These rates are well below the precipitation rates, which indicates IEOF. In addition, these rates, determined under rainfall conditions, are also lower than the infiltration rates measured by ponded infiltrometer (Table 3). This difference is consistent with results from rangeland studies, which also show that infiltration rates under rainfall conditions are typically much lower than ponded infiltration rates [*Scoging and Thornes*, 1979; *Gifford et al.*, 1986].

In the case of runoff produced by low-intensity frontal storms, we again see no evidence of SEOF. The largest event of this kind, in terms of volume (75 mm), occurred in October 1994. The data (Figure 8) show that although rainfall intensities were quite low, rainfall was unusually prolonged. Most of the runoff occurred during the first 5 hours of the storm; runoff then continued at a much lower rate for an additional 4 hours, stopping with the onset of snow. The infiltration rate for this event on the small plot, calculated using the cumulative infiltration method described above, was around 4 mm/h, which was about half the average precipitation rate.

Even under the wettest of conditions, SEOF is unlikely at our site because (1) there is considerable storage capacity above the restrictive layer and (2) once a saturated zone does develop in the B horizon, water is quickly routed off the hillslope through the mechanism of lateral subsurface flow.

5.2.3. Surface cover. Differences in runoff between the north and south hillslopes are due largely to differences in surface cover. The south hillslope contributes by far the bulk of the total runoff coming from the hillslope (Table 4). As was mentioned earlier, the north and south hillslopes are similar in length but differ with respect to vegetation cover; specifically, there is more bare ground on the south side. These differences in vegetation cover affect not only soil infiltration rates (Table 3) but also storage capacity and ability to transport water. For the most part, the patches of bare ground on the south side form a continuum, making them an effective conduit for transporting water off the slope.

5.2.4. Scale. The influence of scale was not great. It was most pronounced for the small, high-intensity events and for the low-intensity frontal events.

In evaluating the effect of scale, we compared runoff from the north hillslope with that from the small plot, because the surface cover characteristics of the two are roughly comparable. We found that runoff per unit area was usually greater from the small plot than from the north hillslope, but overall, the differences were quite small. Differences were greatest for the very small high-intensity events, as illustrated in Figure 7a, and for the low-intensity frontal storms (Figure 8). In those cases, the differences in runoff appear to be attributable to increased opportunity for infiltration with increasing slope length. Interestingly, for the larger summer storms, scale seemed to make little difference (Figure 7b). For these larger storms the storage capacity of the hillslope surface may be quickly overwhelmed, and runoff pathways can then be connected over the entire hillslope. Further data will be required to verify this explanation.

6. Conclusions

This study was designed to answer some basic questions about runoff generation from semiarid ponderosa pine forests, such as how much runoff occurs, at what frequency it occurs, and under what conditions it occurs. Because of the infrequent nature of runoff in semiarid landscapes, observations need to be long-term and detailed if such questions are to be adequately answered. Unfortunately, because of the paucity of

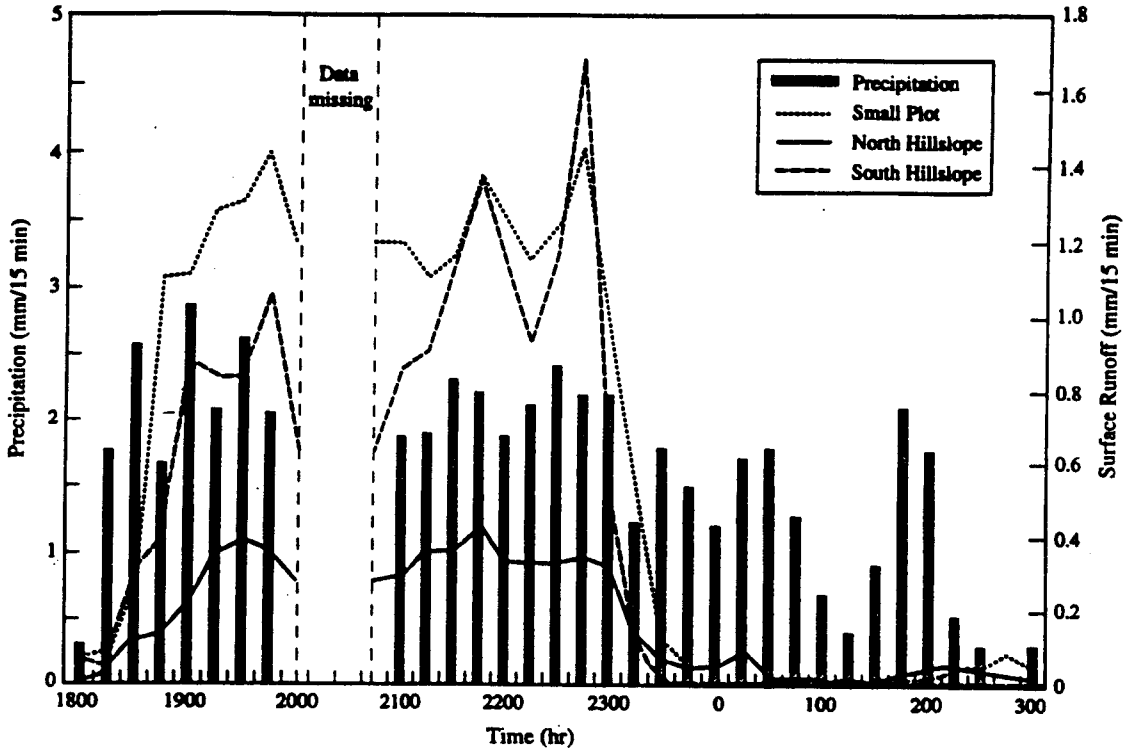

Figure 8. Precipitation and surface runoff for the storm of October 14–15, 1994. Precipitation is depicted only for the period of runoff.

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