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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 [*Thoms*, 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 Ffolliott*, 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 [*Thoms*, 1994].

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

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the United States, some work has been done in pinyon-juniper [*Baker*, 1982; *Wilcox*, 1994; *Wilcox et al.*, 1996] and chaparral [*Hibbert et al.*, 1982] ecosystems, and in the last decade the Australians have actively investigated hillslope runoff processes in semiarid tropical woodlands [*Bonell and Williams*, 1986; *Williams and Bonell*, 1988; *Burch et al.*, 1989].

Most of the hydrologic studies of ponderosa pine forests have been carried out within the subhumid and humid zones, although these forests span precipitation regimes from as low as 500 mm/yr to as high as 1000 mm/yr [*Baker*, 1986]. In the higher-precipitation zones, ponderosa forests may even generate perennial flow [*Dortignac*, 1956; *Lopes and Ffolliott*, 1993]. The best known and most extensive catchment-scale hydrologic studies in ponderosa pine forests were conducted at the Beaver Creek Experimental Watershed in Arizona [*Brown et al.*, 1974; *Baker*, 1982, 1986]. Runoff from ponderosa pine stands has also been monitored at Workman Creek in Arizona [*Rich and Gottfried*, 1976]; on the Coconino Plateau in Arizona [*Heede*, 1984]; in eastern Oregon [*Williams and Buckhouse*, 1993]; in the Manitou Experimental Forest in Colorado [*Dunford*, 1954]; and in northern New Mexico [*Gosz*, 1975].

Our study differs from previous investigations in that it focuses on runoff generation from a ponderosa pine hillslope within the semiarid zone (at the lower end of the precipitation spectrum that will support ponderosa). The primary objectives of the study were to determine the quantitative importance of runoff and to identify the mechanisms by which runoff is generated in this zone. The study is part of a broader effort to develop a high-quality, long-term database of runoff and related parameters that can be used to calibrate and/or evaluate the models needed for predicting the fate and transport of contaminants on the Los Alamos National Laboratory (LANL) site. Our methodology consists of detailed measurement of surface and subsurface flow, weather parameters, soil temperature, soil moisture, and snow accumulation on the hillslope over a multiyear period.

We are particularly interested in the little-studied phenomenon of lateral subsurface flow in semiarid landscapes. We have found, after 4 years of detailed observation, that lateral subsurface flow can be an important component of runoff in semiarid ponderosa pine forests, especially during periods of above-average snowfall. In addition, we have found that at our site, unlike other ponderosa pine forests studied, IEOF is also an important mechanism of runoff generation.

## 2. Description of the Study Site

Our study site lies within the Los Alamos National Laboratory's Environmental Research Park on the Pajarito Plateau of north central New Mexico (Figure 1). It consists of an 870-m$^2$ hillslope at an elevation of about 2315 m, in an open ponderosa pine forest with an understory of grasses and forbs. The hillslope, part of a gently sloping (average 6%) mesa that drains into a nearby canyon, is divided into three experimental areas: (1) a 485-m$^2$ area on the north side of the hillslope; (2) a 355-m$^2$ area on the south side; and (3) a 10- × 3-m plot at the northeast corner. These three areas, hereinafter referred to as the "north hillslope," the "south hillslope," and the "small plot," are outlined in Figure 1.

The precipitation regime is semiarid in that the average annual precipitation of about 500 mm is well below potential evapotranspiration, which is around 1700 mm/yr [*Bowen*, 1990]. This regime represents the lower end of the precipitation spectrum that can support ponderosa pine. About 45% of the annual precipitation occurs in July, August, and September. The depth to groundwater is more than 250 m [*Purtymun*, 1984].

Soils at the site were described during excavation of the subsurface flow trench at the bottom of the hillslope [*Watt and McFadden*, 1993] and by soil coring at 19 locations on the hillslope (D. W. Davenport, LANL, unpublished report, 1996). The general soil profile is shown schematically in Figure 2. The B horizon soils developed primarily from alluvium overlying Bandelier Tuff. This horizon is composed of a clay-rich Bt horizon, containing root channels and void spaces between peds, and a CB horizon that is lower in clay content and forms a transition zone between the soil and the Bandelier Tuff. The B horizon is capped by about 0.2 m of loess in which A and Bw horizons have developed. Hydraulic properties of the soil were determined for the four main horizons at one location on the hillslope (Table 1).

## 3. Methods

### 3.1. Surface Cover

The character of understory vegetation cover was determined through line-intercept transects established by stretching a fiberglass tape along the ground between permanently marked endpoints. Data were recorded at 1-cm intervals along one edge of the tape [*Mueller-Dombois and Ellenberg*, 1974]. One transect was established on the small plot, two on the north hillslope, and two on the south hillslope.

### 3.2. Soil Infiltrability

A 0.5-m ring infiltrometer [*Bouwer*, 1986] was used to measure soil infiltrability in situ at 11 locations across the hillslope. The ring was large enough for integration of small-scale surface variability while minimizing the significance of capillary suction effects at its edge. Infiltration tests were conducted for a variety of surface cover conditions, defined according to the dominant plant type (grass, litter, bare soil, cryptogams); these were done in summer 1996, when antecedent soil moisture was between 20 and 30% of saturation by volume. The tests were continued until infiltration rates became relatively constant.

### 3.3. Surface Runoff

Surface runoff from the 870-m$^2$ hillslope is measured, using separate collection systems, from each of the three experimental areas. In this way, we can document differences in runoff associated with differences in vegetation cover and with differences in scale.

A collector constructed from 15-inch polyvinyl chloride (PVC) pipe was installed at the downslope end of each of the three areas for capturing and routing runoff (Figures 1 and 2). In the summer, runoff from the north and south hillslopes is routed through 15-cm-diameter circular flumes equipped with collection wells and pressure transducers [after *Replogle et al.*, 1990]. In the winter, because flow rates are much lower, runoff from each of the hillslope areas is routed into a separate collection well that is instrumented with a pressure transducer for determining water levels. Water is removed when a specified depth is reached. As a backup, the volume of water pumped from the wells is also monitored, by means of a flow meter. For the small plot, only a collection well is used to monitor both summer and winter surface runoff.

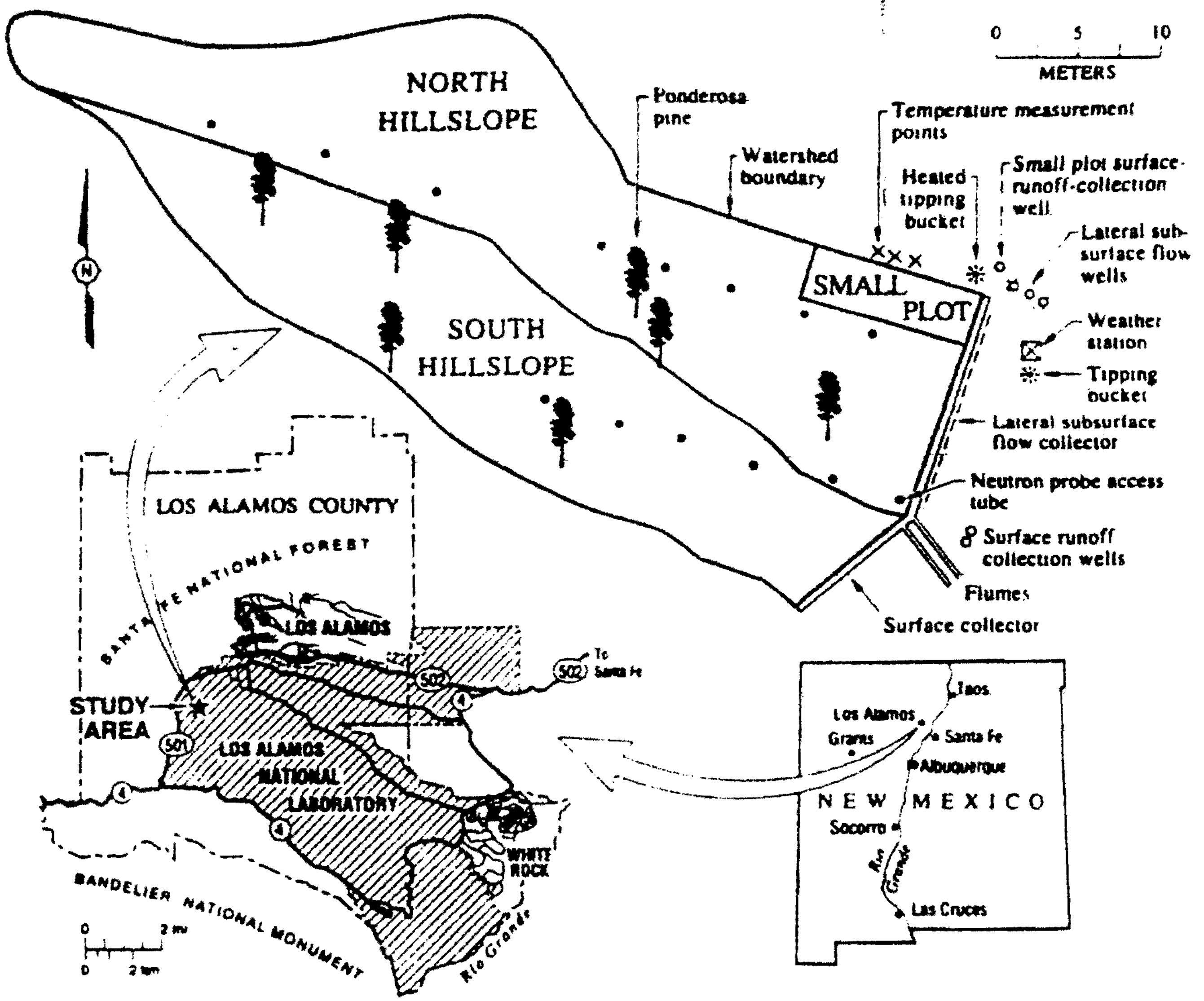


**Figure 1.** Location map and schematic of study area

### 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.

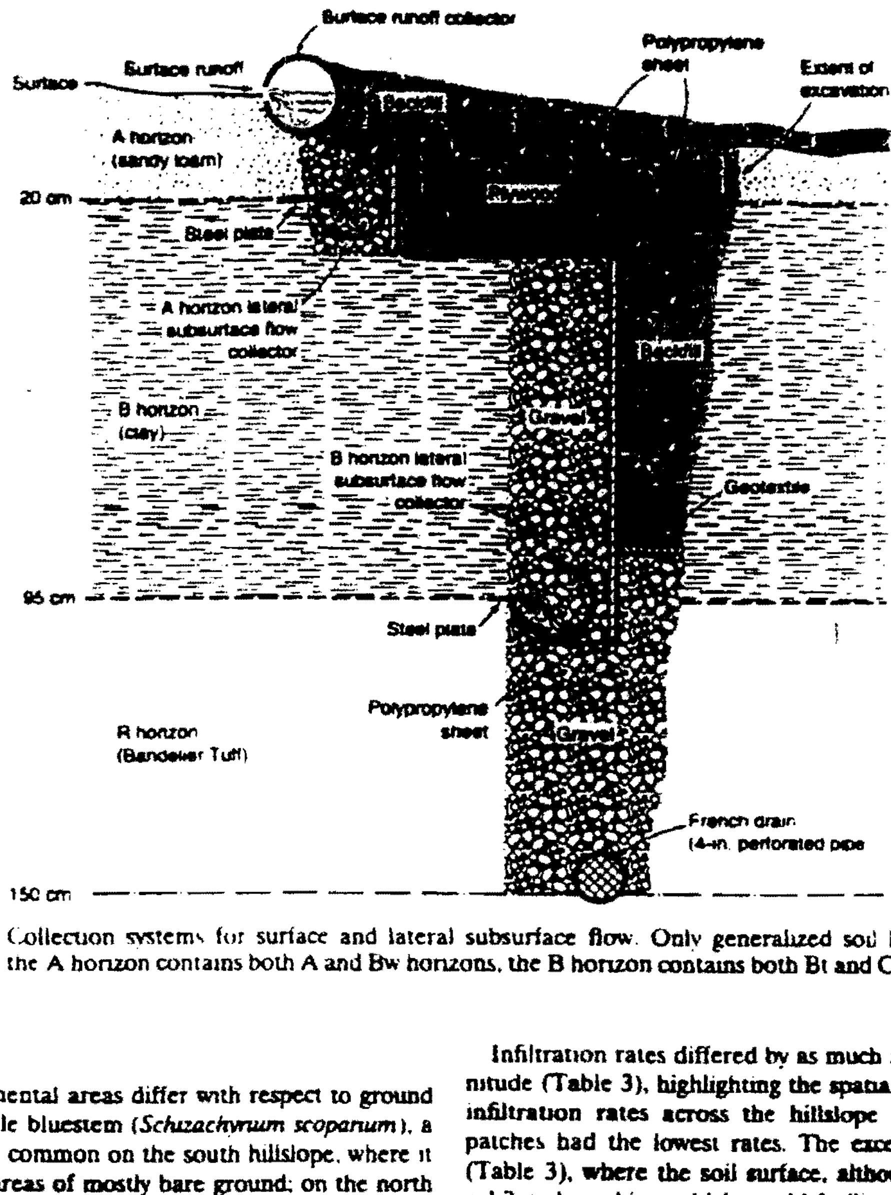


Figure 2. Collection systems for surface and lateral subsurface flow. Only generalized soil horizons are shown (i.e., the A horizon contains both A and Bw horizons, the B horizon contains both Bt and CB horizons).

## 4. Results

The three experimental areas differ with respect to ground cover (Table 2). Little bluestem (*Schizachyrium scoparium*), a bunch grass, is more common on the south hillslope, where it is interspaced with areas of mostly bare ground; on the north hillslope, which has less bare ground, sod grasses (*Koleria cristata*, *Bouteloua gracilis*) and pine needles provide most of the cover. The small plot has the highest percentage of ground cover.

**Table 1.** Laboratory Analysis of Hydraulic Properties at One Location on the Hillslope

| Horizon | Depth, cm | Parent Material | Porosity, % | $K_s$,* mm/h |
|---|---|---|---|---|
| A | 6 | loess | 46 | 2.7 |
| Bw | 18 | loess | 41 | $2.1 \times 10^{-2}$ |
| Bt | 43 | alluvium | 40 | $9 \times 10^{-4}$ |
| CB | 84 | alluvium | 48 | $4.7 \times 10^{-3}$ |
| R | NA | NA | NA | 360–3600 |

Source. *Abeele et al.* [1981], *Stephens* [1993], and P. M. Watt and L. D. McFadden, LANL (unpublished report, 1993). NA, not applicable.

*Values of saturated hydraulic conductivity $K_s$ for the A–CB horizons were measured using 10- × 30-cm-diameter core samples from the hillslope. $K_s$ values for the R horizon (tuff) are based on a range of samples collected at different locations on the Pajarito Plateau by *Abeele et al.* [1981].

Infiltration rates differed by as much as two orders of magnitude (Table 3), highlighting the spatial variability of surface infiltration rates across the hillslope. Generally, the bare patches had the lowest rates. The exception was location 5 (Table 3), where the soil surface, although mostly bare, also exhibited cracking, which would facilitate infiltration. Soil excavations in selected locations indicated that infiltration of water was essentially vertical.

A monthly summary of precipitation and runoff for the 4-year study period is given in Table 4. The data are presented according to water year (October–September). Precipitation ranged from less than 500 mm to almost 700 mm, and runoff accounted for between 3 and 11% of the annual water budget. Runoff took the forms of both lateral subsurface flow and surface runoff; in the case of the latter, the volumes measured varied among the three areas of the hillslope. In winter, for

**Table 2.** Estimated Surface Cover for the Three Areas of the Hillslope

| | Small Plot | North Hillslope | South Hillslope |
|---|---|---|---|
| Number of data points | 92 | 818 | 590 |
| Grass, % | 9 | 9 | 10 |
| Cryptogam, % | 3 | 2 | 7 |
| Litter, % | 88 | 79 | 65 |
| Bare ground, % | 0 | 10 | 18 |

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.

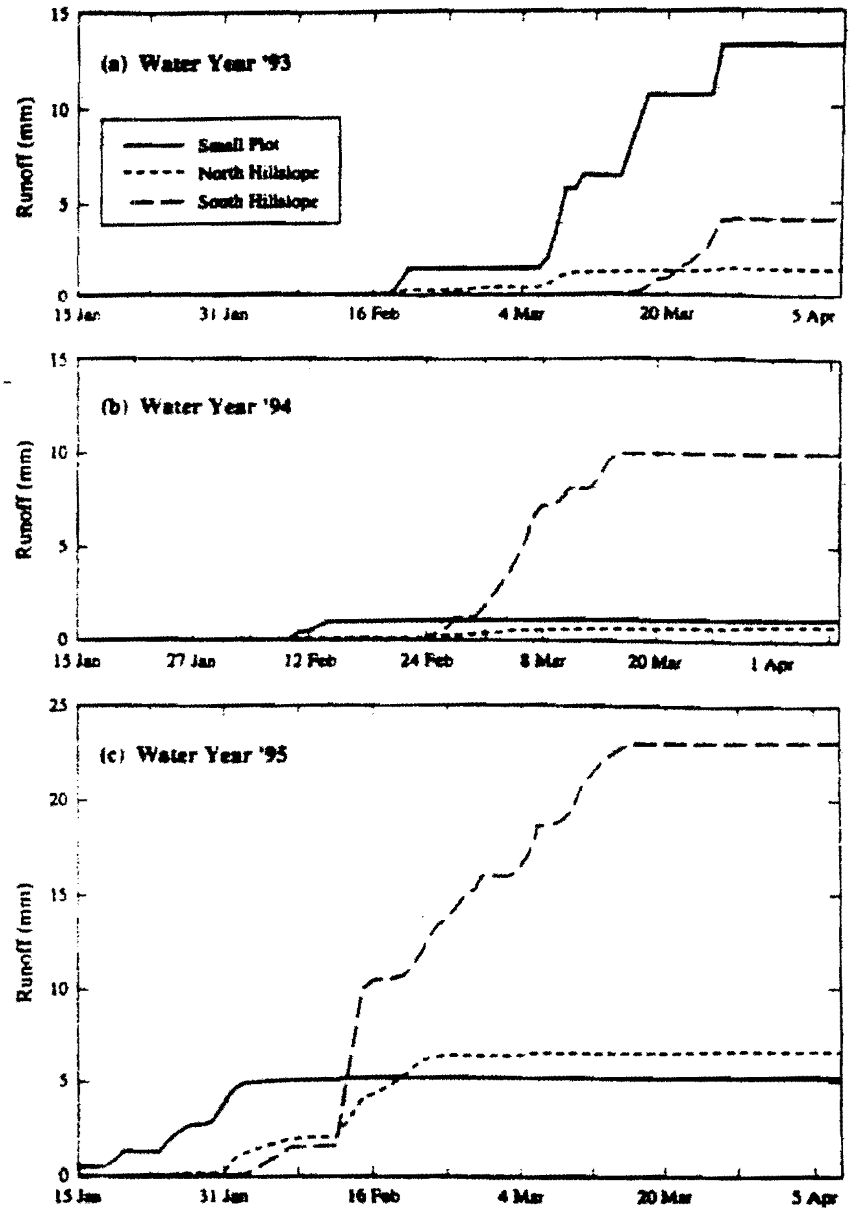


**Figure 3.** Cumulative surface runoff during the winters of water years (a) 1993, (b) 1994, and (c) 1995.

mainly as lateral subsurface flow. Surface runoff was quite low (Table 4).

A summary of daily lateral subsurface flow, for both the upper (A and Bw horizons) and the lower (Bt horizons) collectors, is shown in Figure 4, along with precipitation and temperature data. Melting of the snowpack began in the latter half of February, when air temperatures began to rise. We recorded three major lateral subsurface flow events in March, the first two of which clearly correlated with air temperatures. The third resulted from a rain-on-snow event late in the month that melted much of the remaining snowpack. An examination of hourly lateral subsurface flow data showed that in general, peak flow lagged peak daily temperature by about 3 hours.

Soil moisture data collected during WY93 (Figure 5) indicate that the tuff underlying the soils on the hillslope remains consistently dry and that the lateral subsurface flow observed in March was produced by the development of a zone of saturation within the overlying soils. On the south side of the hillslope, two soil moisture peaks were recorded, one at a depth of 0.4–0.5 m and one at 0.6–1.0 m. The first corresponds to the middle-to-lower portion of the clay-rich Bt horizon, and the second corresponds to the CB horizon immediately above the unweathered tuff (Table 1). On the north hillslope, where the CB horizon is absent or very thin, a single moisture peak was recorded that corresponds to the Bt horizon just above the soil-tuff interface.

In spite of the heavy snowfall in WY93, very little surface runoff was measured from the north and south hillslopes during snowmelt (Table 4; Figure 3a). Because soils remained unfrozen, soil infiltrability was high enough to absorb the runoff. In contrast, a relatively large amount of surface runoff was recorded from the small plot, largely because the collector was close to a melting snowdrift.

4.1.2. **WY95: Wet fall, normal snowpack.** The winter of WY95 was a wet one as well, but both the timing and amount of precipitation differed from those of WY93. Almost 200 mm

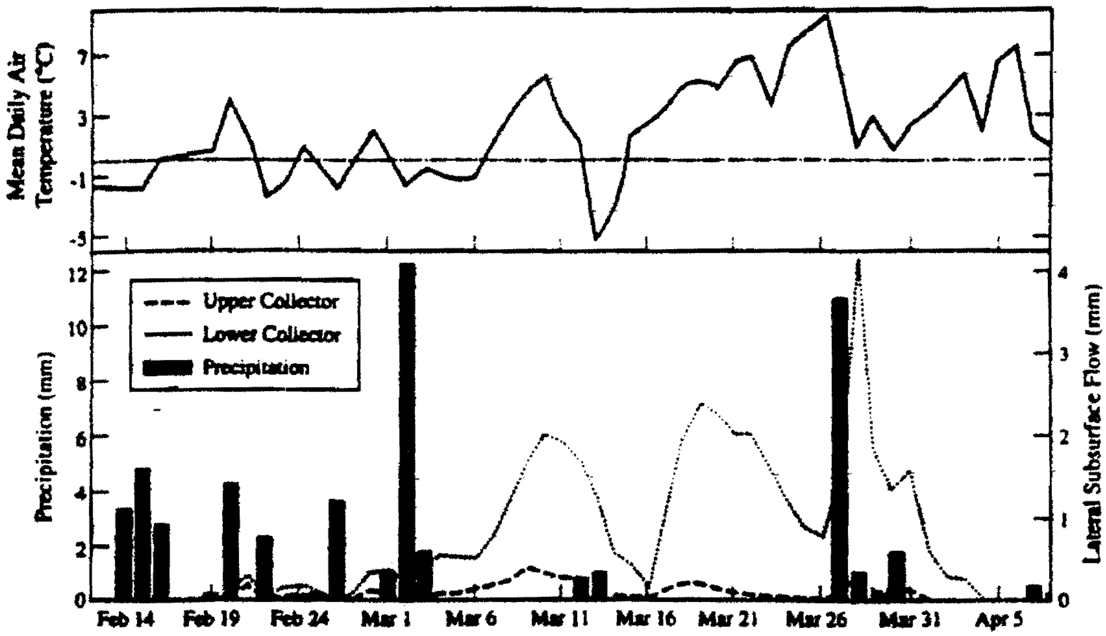


**Figure 4.** Daily lateral subsurface flow versus temperature and precipitation, February 14 to April 5, 1993.

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

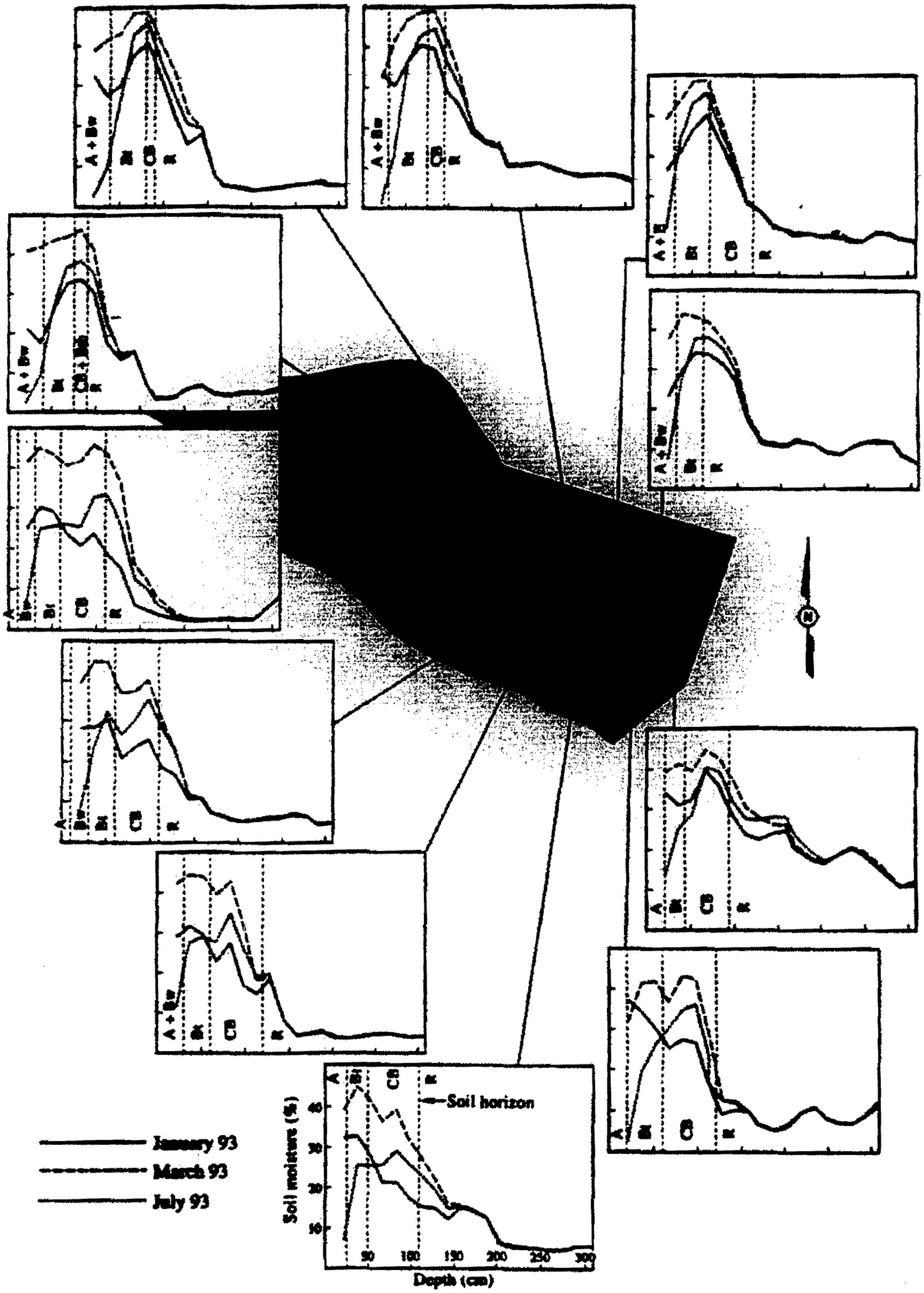


Figure 5. Soil moisture measurements from 11 neutron probe locations for January, March, and July 1993 (shown with soil horizons superimposed).

(between 3 and 11%), it can be important under specific conditions, such as melting of an unusually heavy snowpack, intense summer thunderstorms, and prolonged frontal storms in spring or fall. Runoff is generated both as lateral subsurface flow and as surface runoff.

### 5.1. Lateral Subsurface Flow

During periods of above-average moisture, a perched saturated zone develops within about 1 m of the soil surface, forcing lateral flow. The dynamic and responsive nature of

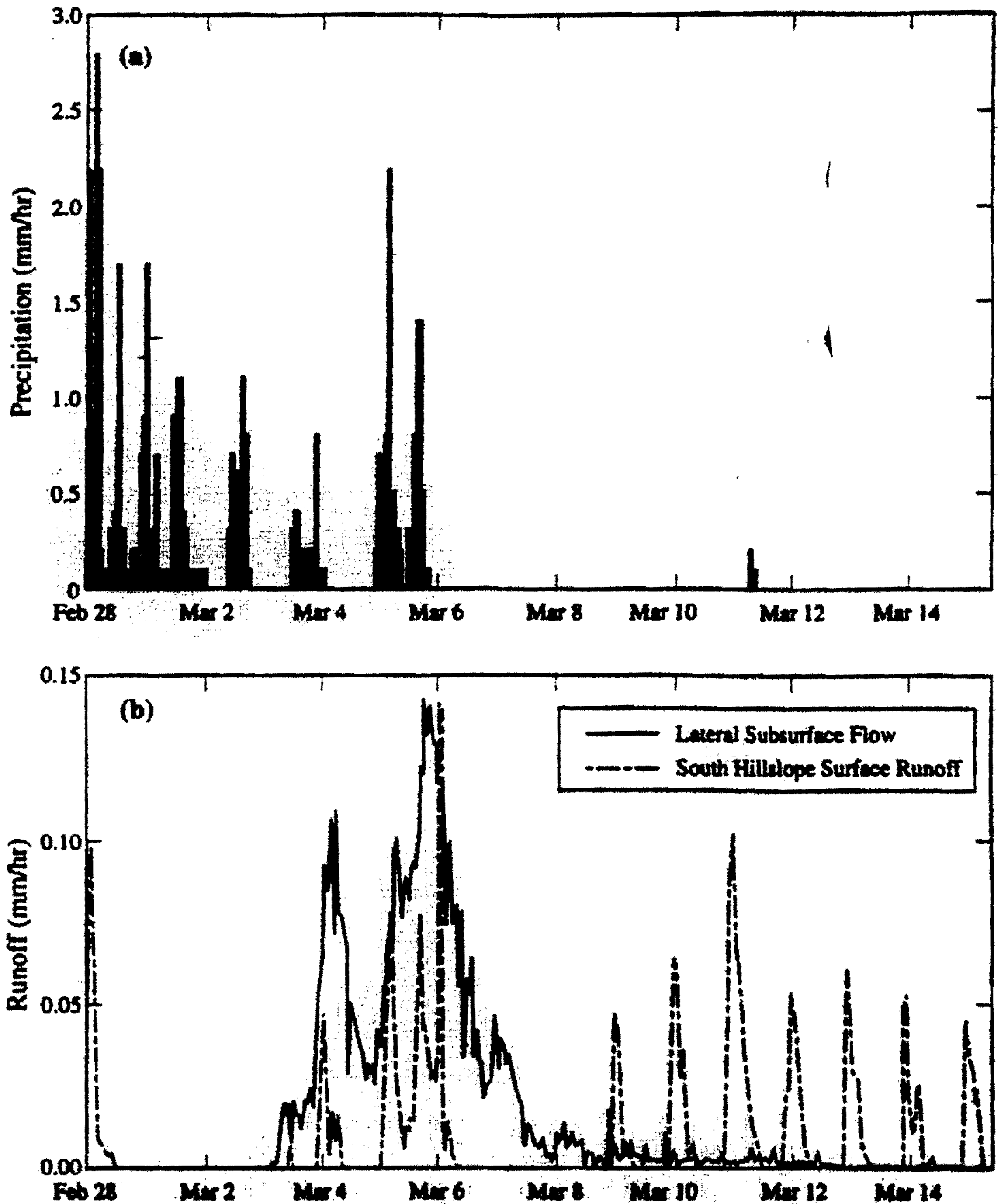


Figure 6. Daily (a) precipitation and (b) total lateral subsurface flow (from north hillslope and small plot) and surface runoff (from south hillslope), March 1995.

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

**Table 5.** Characteristics of Summer Runoff

| Date | Precipitation, mm | Maximum Precipitation Intensity, mm/min | Surface Runoff, mm | | | | Lateral Subsurface Flow, mm |
|---|---|---|---|---|---|---|---|
| | | | 870-m² Hillslope | 30-m² Small Plot | 485-m² North Hillslope | 355-m² South Hillslope | |
| *1993** | | | | | | | |
| June 15 | 20.3 | ...† | 0.2 | 1.6 | ND | ND | 0.0 |
| July 14 | 30.7 | ... | 2.0 | 6.5 | ND | ND | 0.1 |
| July 19 | 9.9 | ... | 0.1 | 0.6 | ND | ND | 0.0 |
| July 20 | 12.0 | ... | 0.3 | 1.1 | ND | ND | 0.0 |
| Aug. 3 | 8.6 | 1.0 | 0.2 | 0.5 | ND | ND | 0.0 |
| Aug. 6 | 10.4 | 2.0 | 0.4 | 1.3 | ND | ND | 0.0 |
| Aug. 7 | 13.7 | 1.0 | 1.0 | ...‡ | ND | ND | 0.1 |
| Aug. 13 | 11.1 | 0.5 | 0.2 | ...‡ | ND | ND | 0.0 |
| Aug. 26 | 7.4 | 1.0 | 0.2 | 0.7 | ND | ND | 0.0 |
| Aug. 26 | 12.7 | 0.3 | 0.3 | 2.6 | ND | ND | 0.0 |
| Aug. 27 | 8.4 | 0.8 | 0.6 | 2.1 | ND | ND | 0.0 |
| Sept. 6 | 11.4 | 0.8 | ...‡ | 2.4 | ND | ND | 0.0 |
| Sept. 6 | 7.6 | 1.0 | ...‡ | 2.6 | ND | ND | 0.0 |
| Sept. 12 | 8.6 | 0.3 | 0.1 | 0.4 | ND | ND | 0.0 |
| *1994* | | | | | | | |
| June 21 | 28.2 | 2.0 | 8.8 | ... | 5.3 | 13.6 | 0.0 |
| July 19 | 13.6 | 1.5 | 0.6 | 1.4 | 0.2 | 1.2 | 0.0 |
| July 24 | 43.0 | 2.1 | 7.7 | ... | 5.6 | 10.5 | 0.0 |
| July 28 | 12.2 | 0.3 | 0.1 | 0.2 | 0.0 | 0.1 | 0.0 |
| Aug. 1 | 11.7 | 0.8 | 0.3 | 0.3 | 0.1 | 0.6 | 0.0 |
| Aug. 24 | 17.0 | 0.3 | 3.0 | 1.7 | 1.6 | 4.9 | 0.0 |
| *1995* | | | | | | | |
| May 29 | 26.0 | 0.6 | 0.1 | 0.4 | 0.2 | t | 0.0 |
| June 17 | 36.9 | 0.7 | 0.3 | 0.5 | 0.5 | 0.1 | 0.0 |
| Aug. 11 | 15.9 | 0.6 | 0.1 | 0.5 | 0.1 | 0.0 | 0.0 |
| Aug. 13 | 17.6 | 0.9 | t | 0.4 | 0.0 | t | 0.0 |
| Aug. 29 | 16.8 | 1.8 | 1.4 | 2.0 | 0.4 | 2.7 | 0.0 |
| Sept. 7 | 13.2 | 0.8 | 0.2 | 0.8 | 0.0 | 0.2 | 0.0 |
| *1996* | | | | | | | |
| June 26 | 26.9 | 2 | 7.0 | 4.5 | 3.6 | 11.7 | 0.0 |
| July 17 | 22.9 | 0.9 | 1.5 | 1.9 | 0.7 | 2.6 | 0.0 |
| Aug. 22 | 27.9 | 1 | 0.8 | 1.7 | 0.2 | 1.9 | 0.0 |

ND indicates no data collected.
*In 1993, summer runoff from the north and south hillslopes was routed to a single collector.
†Precipitation data recorded at 15-minute intervals only.
‡Equipment malfunction.

developed in undisturbed forests [*Beven and Germann*, 1982]. Indeed, a growing body of evidence suggests that delivery of lateral subsurface flow is greatly accelerated by macropores, especially on forested hillslopes [*Beasley*, 1976; *Pilgrim et al.*, 1978; *Wilson et al.*, 1990]. Water movement via interpedal macropore networks in high-clay soils is well documented: not only vertical movement [*Bouma*, 1981], but also lateral movement, in both forested soils [*Mosley*, 1979] and agricultural soils [*Parlange et al.*, 1989; *Inoue*, 1993].

It is difficult to pinpoint either the nature or the exact location of the barrier to vertical water movement on our hillslope. The R horizon (unweathered Bandelier Tuff) is an unlikely candidate, given its high hydraulic conductivity: reported measurements are in the range 360–3600 mm/h [*Abeele et al.*, 1981], which is 3–4 orders of magnitude higher than those of the overlying soils. A more likely candidate is the zone of weathered tuff (CB horizon) found between the Bt and R horizons, which is prominent on the south hillslope (and may be present, as a much thinner layer, on the north side as well). Our measurements of hydraulic conductivity for this layer are very low (Table 1), and the weathered tuff is probably devoid of macropores. A second possibility is suggested by a feature we have noted consistently at the soil-tuff interface: a thin "smear" of translocated clay that may be plugging pores on the tuff surface, limiting entry of water into the tuff. A third possibility is that flow could be restricted at the base of the Bt horizon, as is suggested by soil moisture data from some locations on the hillslope (Figure 5).

We also observed small volumes of lateral subsurface flow under unsaturated conditions: many of the events that yielded trace amounts, shown in Table 5, occurred under such conditions. These events occurred in response to either individual rainstorms or continuous drainage following winter snowmelt (Table 4). Lateral macropore flow can occur under unsaturated conditions when the flux of water (precipitation or snowmelt) is greater than the hydraulic conductivity of the matrix [*McDonnell*, 1991], and a comparison of infiltration and precipitation rates at our site (described below) is consistent with this process. *Wilson et al.* [1990] also noted lateral subsurface flow in dry soils and suggested that the water might be traveling via macropores, either because mineral coatings on ped faces made the macropore walls hydrophobic or because the high-clay soils at their site were resistant to wetting. Similar factors could be facilitating lateral subsurface flow at our site during periods when the soils are unsaturated.

### 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

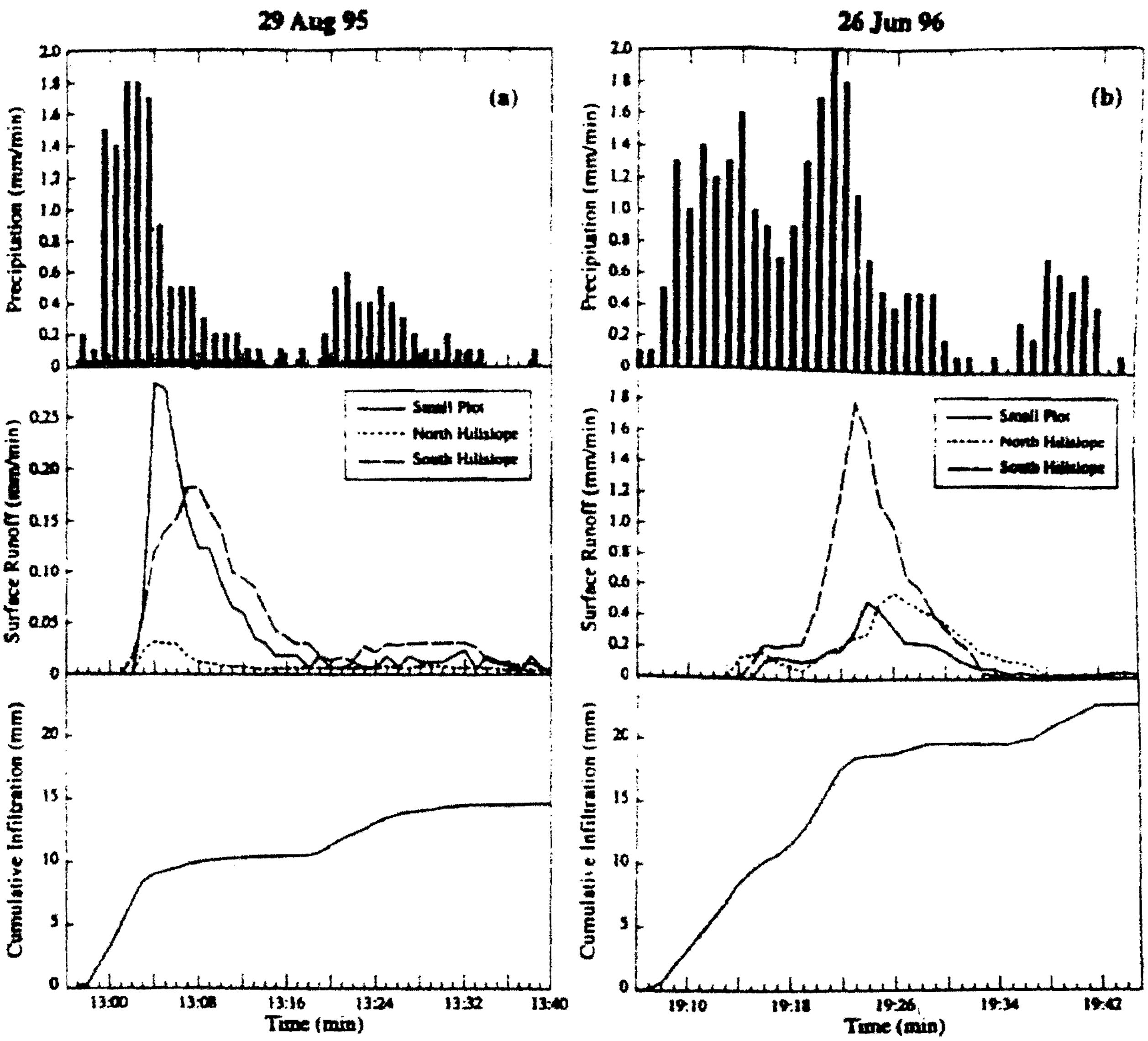


Figure 7. Precipitation, surface runoff, and cumulative infiltration for the storms of (a) August 29, 1995, and (b) June 26, 1996.

long-term, detailed data, conclusions are often drawn on the basis of anecdotal information or unvalidated hydrologic models.

We have found, after 4 years of observation and monitoring, that runoff in the semiarid forest we are studying is remarkably variable, being influenced by a number of agents. As is typical of semiarid environments, runoff at our site was ephemeral and occurred only as a result of "extreme" precipitation events (such as greater-than-average snowfall, very intense rainfall, or unusually prolonged frontal storms). The nature of these events, along with the physical properties of the soil, determined what form the runoff took. For example, lateral subsurface flow was important at our site because the combination of occasional very wet conditions and the presence of a shallow restrictive horizon allowed a shallow zone of saturation to develop, while a network of macropores facilitated this type of flow. Macropores also facilitated small amounts of flow when the soils were unsaturated.

Surface runoff was also important and occurred in the form of IEOF. During the winter, this type of runoff was facilitated by frozen soils. During other periods, it was generated by intense thunderstorms or prolonged frontal storms. At the hillslope scale, frozen soil runoff was strongly affected by degree of shading and location of snowdrifts, whereas rainfall-generated runoff was affected more by extent of vegetation cover (considerably more surface runoff of this type was generated from the south hillslope, which had more exposed bare ground, than from the north hillslope).

Our results highlight the pitfalls of relying on climate-based predictions of runoff behavior. Previously, lateral subsurface flow was not recognized as a runoff pathway on the Pajarito Plateau because of the semiarid climate. It is now clear that runoff processes need to be studied on the basis of a thorough understanding of the timing, intensity, and volume of precipitation and snowmelt events and of the morphology and hydrologic properties of the soil and bedrock. Such an understanding can be gained only through detailed field work over extended periods, particularly in dry environments where episodic events dominate the generation of runoff. In addition, the data gathered through such field work are necessary for the development and testing of runoff models.

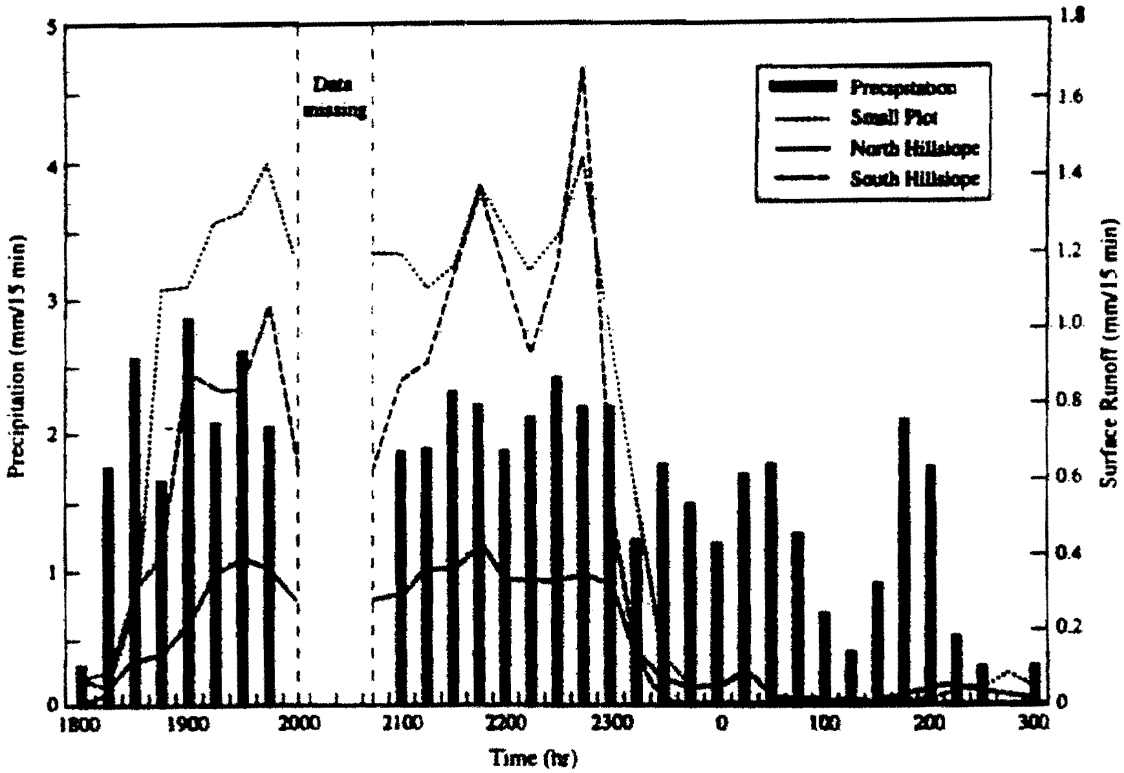


Figure 8. Precipitation and surface runoff for the storm of October 14–15, 1994. Precipitation is depicted only for the period of runoff.

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