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Lateral subsurface flow pathways in a semiarid ponderosa pine hillslope

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Abstract. The mechanisms controlling lateral subsurface flow in semiarid environments have received relatively little attention despite the fact that lateral subsurface flow can be an important runoff process in these environments. The objective of the current study is to better understand lateral subsurface flow process in semiarid environments. Natural chloride, dissolved organic carbon, and stable isotope (δD and δ^{18}O) tracers were used to investigate the lateral subsurface flow process and the chemical changes that occur as a result of lateral subsurface flow. Observed differences in chemistry between soil matrix water and lateral subsurface flow were large (for example, chloride concentrations in matrix soil water samples were >200 mg/L, compared with only 2 mg/L in lateral subsurface flow samples obtained at the same time). This difference in chemistry is indicative of a two-domain flow system in which macropores conduct lateral subsurface flow that is not in chemical or hydrological equilibrium with the soil matrix. The size of precipitation events appeared to have a strong influence on the variations in old/new water percentages, and examples of both old and new water dominated events were observed. There were also large variations in the chemistry of lateral subsurface flow with time. For example, chloride and dissolved organic carbon concentrations were 10 and 70 times greater, respectively, under saturated conditions than under unsaturated conditions.

1. Introduction

Lateral subsurface flow or subsurface stormflow is the lateral movement of water through near-surface soils, regolith, and bedrock [*Anderson and Burt*, 1990; *Satterlund and Adams*, 1992]. Most of our knowledge about lateral subsurface flow processes comes from studies conducted at humid sites. In contrast, lateral subsurface flow in semiarid regions of the United States has been little studied, probably because it was not considered an important hydrologic process: These regions have few perennial streams, receive relatively small amounts of precipitation, and have low soil-moisture contents throughout much of the year. Humid systems receive much larger amounts of water and are characterized by less variable moisture conditions.

Lateral subsurface flow can be generated via matrix or macropore pathways. Many researchers have stressed the importance of macropores in the generation of vertical and lateral flow in soils, even under unsaturated conditions [e.g., *Germann*, 1990; *McDonnell*, 1990, 1991; *Smettem et al*., 1991; *Wilson et al*., 1991; *Leaney et al*., 1993]. Macropores can conduct lateral subsurface flow directly or can feed shallow, perched saturated zones overlying low permeability bedrock, indirectly producing flow [*Whipkey*, 1965; *McDonnell*, 1991; *Peters et al*., 1995; *Turton et al*., 1995]. Macropore flow under unsaturated conditions occurs when the flux of water (precipitation or snowmelt) is greater than the hydraulic conductivity of the matrix [*Germann*, 1990; *Sklash*, 1990; *McDonnell*, 1990, 1991]. This process will be enhanced in areas that are characterized by large or intense rains or snowmelt events and/or where the soils have low matrix conductivities.

Stable isotope tracers have been used to ascertain how much lateral subsurface flow or streamflow in humid environments is "old" water and how much is "new" water. Old, or preevent, water has been in storage and is forced out of the soil by a current storm or snowmelt event. New, or event, water comes directly from the current event. Many of the stable isotope studies have shown that most of the hydrograph rise in streams is caused by old water [e.g., *Bottomley et al*., 1984; *Pearce et al*., 1986; *McDonnell*, 1990, 1991; *Anderson et al*., 1994; *DeWalle and Pionke*, 1994]. To explain this dominance of old water, *Sklash and Farvolden* [1979] proposed the groundwater ridging concept, in which water in the tension saturated zone near the stream channel is quickly converted to a phreatic state by a relatively small additional input of water, causing a fast release of old water to the channel. *McDonnell* [1990] proposed an alternative model whereby crack-pipe macropore flow can

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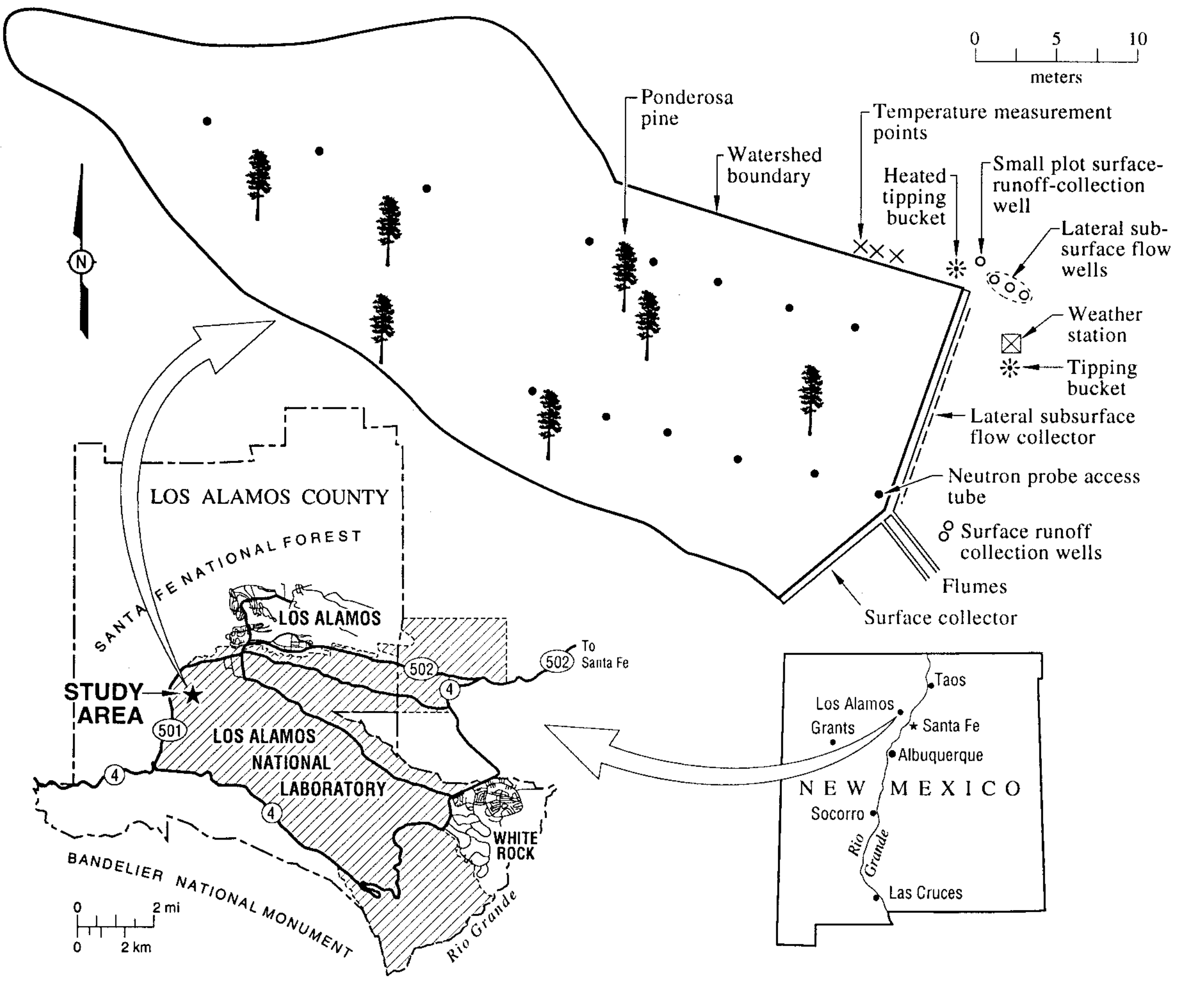


Figure 1. Location map and schematic of the ponderosa pine hillslope.

dominantly contribute old water to a stream because of disequilibrium in potential during wetting. In other words, inhomogeneities or macropores in the soil create disequilibrium during wetting which allows the release of water much earlier than would be predicted by measured potential/moisture content [$\psi(\theta)$] relations. However, it does appear that new water can be an important contributor to streamflow in some areas [*Elsenbeer et al.*, 1995] and in upslope areas away from stream channels [*Wilson et al.*, 1991; *Turton et al.*, 1995]. Another important factor in controlling new water contributions to streamflow and lateral subsurface flow is the type of storm event. Both *Elsenbeer et al.* [1995] and *Turton et al.* [1995] noted that new water was an important component of lateral subsurface flow during high intensity storms, while old water dominated during small storms.

The need for an improved understanding of how rain and snowmelt move through the soil as lateral subsurface flow and the importance of hillslope hydrology tracer studies to gain that understanding was pointed out by *Sklash* [1990]. Such an understanding is vital because the processes that control the movement of water through soils affect the mobility of contaminants, the distribution of nutrients, and the acid-base chemistry of surface waters [*Mulholland et al.*, 1990]. As outlined above, great strides have been made in understanding the process of lateral subsurface flow generation in humid environments. This study contributes to the development of a comparable understanding for semiarid systems which, with the exception of one site in Australia [*Smettem et al.*, 1991; *Chittleborough et al.*, 1992; *Leaney et al.*, 1993], have seen only limited investigation.

The current study uses natural chloride, dissolved organic carbon, and stable isotope tracers ($\delta^{18}O$ and δD) to investigate the processes that control lateral subsurface flow in a semiarid hillslope. Conducted at a ponderosa pine hillslope site at Los Alamos, New Mexico (Figure 1), this study extends the work of *Wilcox et al.* [1997]. Overland (surface) flow had been considered to be the major mechanism of runoff generation in these environments, but *Wilcox et al.* [1997] found that lateral subsurface flow can be the major runoff mechanism under particular circumstances. They found that lateral subsurface flow was most active during spring snowmelt and, surprisingly, was moving mostly through a dense, clay Bt soil horizon having a low-saturated hydraulic conductivity (2.5×10^{-10} m/s). The observation of the dynamic nature of lateral subsurface flow led *Wilcox et al.* [1997] to hypothesize that lateral subsurface flow was moving, at least in part, through macropores. The hydrometric measurements used in their study suggested that lateral subsurface flow rates were rapid enough to require such an explanation, but these measurements alone were not sufficient for a detailed model of lateral subsurface flow generation. Other methods are needed to determine the pathway of lateral subsurface flow (macropores versus soil matrix), the

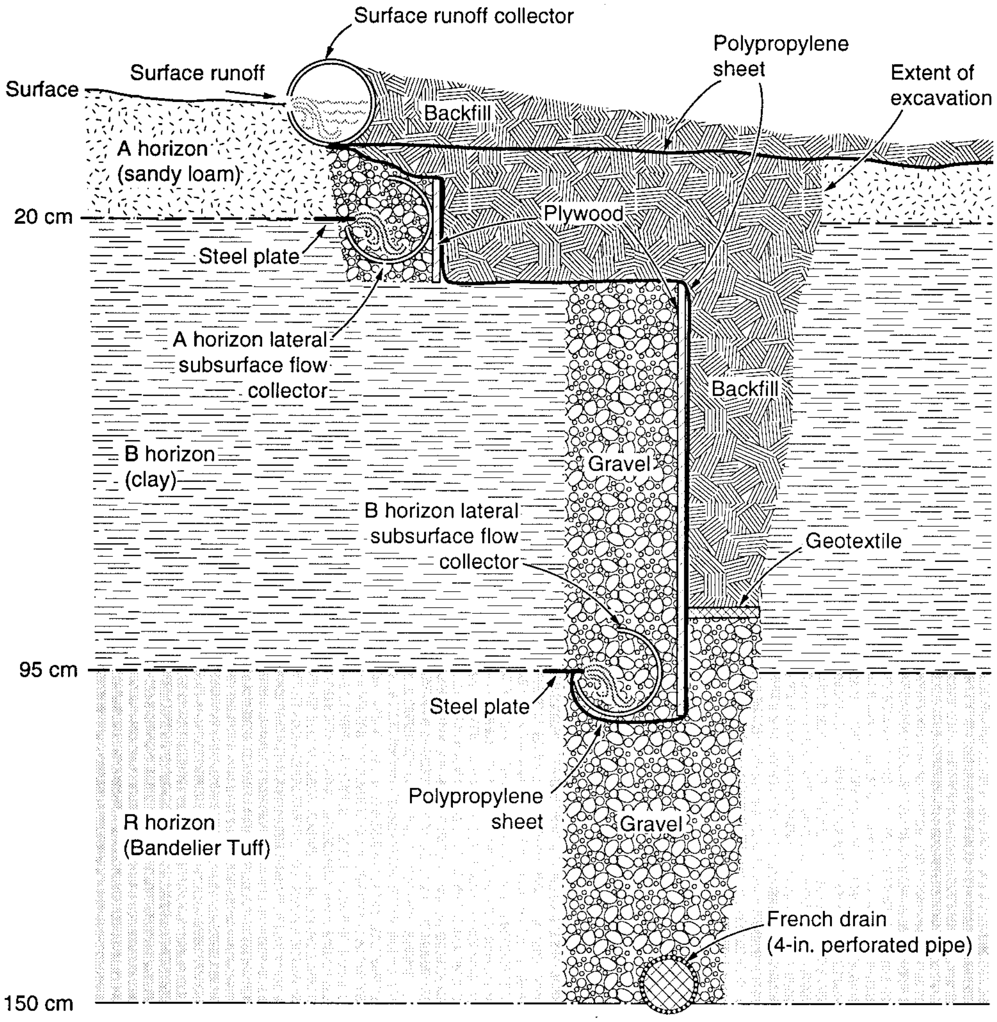


Figure 2. Diagram of the lateral subsurface flow collection trench showing soil stratigraphy and location of the lateral subsurface flow collectors.

rate of water movement, and the effects of lateral subsurface flow on soil water chemistry. Therefore in our study, a multiple-tracer approach was used to develop a conceptual model for semiarid lateral subsurface flow processes. In addition, this approach enables the processes controlling lateral subsurface flow in semiarid regions to be compared with those in humid regions, thereby increasing our understanding of lateral subsurface flow generation across a wider range of environmental conditions.

2. Methods and Materials

2.1. Site Description

The 870-m^2 ponderosa pine hillslope study area is covered by ponderosa pine forest and lies within the Los Alamos National Laboratory's Environmental Research Park on the Pajarito Plateau of north central New Mexico; it is described in detail by *Wilcox et al.* [1997] (Figure 1). The site slopes gently (average 6%) and drains into a nearby canyon. The elevation is 2315 m and the average annual precipitation is 510 mm [*Bowen*, 1990]. The depth to groundwater is ~250 m.

A detailed description of the site stratigraphy are given by *Newman et al.* [1997] and a brief overview is provided here. The Bandelier tuff (R horizon) lies at the base of the soils and is overlain by CB horizons that are transitional soils having characteristics of the tuff below and the dense, smectite clay Bt horizons that lie above the CB horizons. The Bt horizons show well-developed soil structure and contain root channels, cracks, and voids between ped faces. The top of the profile is made up of sandy loam (A and Bw) horizons. Measured saturated hydraulic conductivities are 5.7×10^{-9} to 7.5×10^{-7} m/sec for the A and Bw horizons, 2.5×10^{-10} m/sec for the Bt horizon, and 1.3×10^{-9} to 7.1×10^{-9} m/sec for the CB horizon [*Stephens*, 1993]. The hydraulic conductivity of unweathered Bandelier tuff ranges from 2×10^{-7} to 2.35×10^{-6} m/sec [*Abeele et al.*, 1981].

A trench, 16 × 2 × 1.5 m deep, was dug across the bottom of the hillslope, perpendicular to the slope of the hill (Figure 1). It is equipped with two collectors so that water can be collected separately from the upper sandy loam and the lower clay-rich horizons (Figure 2). For the purposes of this paper, we refer to the sandy loam layer as the A horizon and the lower clay-rich layer as the B horizon. The reason for combining the A and Bw and Bt and CB soil horizons is that irregular and transitional contacts made them difficult to isolate. One goal of the study was to evaluate the differences between the sandy loam and clay-rich layers, and the collection system was designed accordingly. We do not mean to imply that the soil horizons can be combined in a soil taxonomic sense, but rather use the designation of "A and B horizons" in the text for convenience and consistency with *Wilcox et al*. [1997]. A French drain at the bottom of the trench was installed to collect water from the upper part of the tuff. However, no flow was ever observed from this collector. The A- and B-horizon collectors drain into separate stilling wells, in which pressure transducers electronically measure the lateral subsurface flow produced at least every 15 min. A meteorological station at the site continuously records temperature, humidity, wind speed and direction, and precipitation. Soil moisture is monitored on a weekly basis, by neutron thermalization, at 10 locations on the hillslope. Additional information on the hydrometric data collection system is given by *Wilcox et al*. [1997].

2.2. Sampling and Analytical Methods

Collection of hydrometric data from the hillslope has been ongoing since November 1992. Stable isotope and chloride tracer sampling began in June 1993 and included samples of lateral subsurface flow, overland flow, precipitation, and the bulk soils.

2.2.1. Lateral subsurface flow and precipitation samples. To obtain lateral subsurface flow samples, small-volume (~50 mL) PVC collectors were inserted into the pipes that feed the stilling wells; the collectors were designed to minimize evaporation, which would adversely affect the stable isotope results. Precipitation samples were collected with a large, polyethylene funnel that drained into a 1/4-inch-diameter tube which had an elbow bend. Water drained from the tube into a 1-L polyethylene bottle having an overflow spout which was also bent and held a plug of water once the bottle overflowed. Snow samples were collected by hand as soon as possible after the event. Snowmelt samples were collected from the surface runoff collection wells (Figure 1).

The samples were usually collected daily, and two duplicate samples were taken whenever possible; one was analyzed for stable isotopes; the other was analyzed for chloride. Samples were stored in 10- or 20-mL glass vials with polyseal caps (vials were rinsed with a small amount of sample before being filled). Samples were then stored in a refrigerator, at 4°C, pending analysis.

Stable isotope analyses were conducted at the New Mexico Tech and Southern Methodist University stable isotope laboratories. The hydrogen and oxygen isotopes are reported in delta (δ) notation, as per mil (‰) differences relative to the Vienna-Standard Mean Ocean Water (V-SMOW) international standard:

$$\delta D \text{ or } \delta^{18}\mathrm{O} = \left[\frac{R_{\text{sample}} - R_{\text{V-SMOW}}}{R_{\text{V-SMOW}}}\right] \times 1000 \tag{1}$$

where R is the D/H or $^{18}\mathrm{O}/^{16}\mathrm{O}$ ratio. The $\delta^{18}\mathrm{O}$ analyses were based on the $\mathrm{CO_2}$ equilibration method [*Socki et al*., 1992]. The δD analyses were based on the uranium method [*Bigeleisen et al*., 1952]. Sample splits were analyzed at both laboratories to ensure consistency of the data. Variation in $\delta^{18}\mathrm{O}$ of sample splits analyzed at both laboratories was <0.2‰. All of the δD analyses were performed at the Southern Methodist laboratory, so no interlaboratory comparison of δD analyses was done. Analytical precision was better than 0.2‰ and 2‰ for the $\delta^{18}\mathrm{O}$ and δD analyses, respectively.

Chloride concentrations were determined using a Dionex ion chromatograph. A 1.08-mM $\mathrm{Na_2CO_3}$/1.02 mM $\mathrm{NaHCO_3}$ eluant was used with a Dionex AS4A column and self-regenerating suppressor. Calibration curves were established on the basis of five standards prepared by serial dilution from an National Institute of Standards and Technology (NIST) standard chloride solution. After every five analyses, one standard and deionized water (DI) blank were run, and, after every ten samples, duplicate sample analyses were run to ensure that adequate accuracy and precision were maintained. Accuracy was 10% or better based on the periodic analyses of standards, and precision was better than 2%.

2.2.2. Dissolved organic carbon. Total dissolved organic carbon concentrations were determined for 0.45 μm-filtered lateral subsurface flow samples using a Dohrmann DC-180 carbon analyzer. Organic carbon was calculated from the difference between analyses of total carbon and inorganic carbon. Total carbon was determined using an ultraviolet promoted persulfate oxidation method, and inorganic carbon was determined using phosphoric acid digestion. The $\mathrm{CO_2}$ produced by these processes was measured using a nondispersive infrared detector. Peak integrations were performed using Dohrmann software. Calibration was performed using carbon standards prepared with either potassium hydrogen phthalate or sodium carbonate. Precision was typically 5% or better for both total carbon and inorganic carbon analyses.

2.2.3. Soil cores. Soil water chloride concentrations were determined from cores taken through the entire soil profile in July 1993, August 1994, and June 1995. For each core, soil stratigraphy was described; the core was then split into 10-cm lengths and stored in clean mason jars or zip-lock bags. Latex gloves were worn at all times to prevent contamination of the samples. At the Los Alamos Environmental Science Group Laboratory, the core samples were first air-dried for 48 hours, and then 100-g splits were mixed with 100 mL of 17-mΩ DI water. The solutions were stirred with a glass stirring rod and allowed to equilibrate for 48 hours. A control, consisting of a beaker filled with 100 mL of the DI water, was prepared for every six soil samples. After equilibration, the solutions (leachates) were decanted, centrifuged, and filtered using disposable 0.2-μm Gelman ion chromatography filters. Leachates were analyzed for chloride using the same ion chromatography procedure described earlier for the lateral subsurface flow and precipitation samples. Soil moisture contents were determined gravimetrically or by neutron probe. The soil bulk density values that are needed to calculate the soil water chloride concentrations from the leachate concentrations were measured previously and are given by *Stephens* [1993].

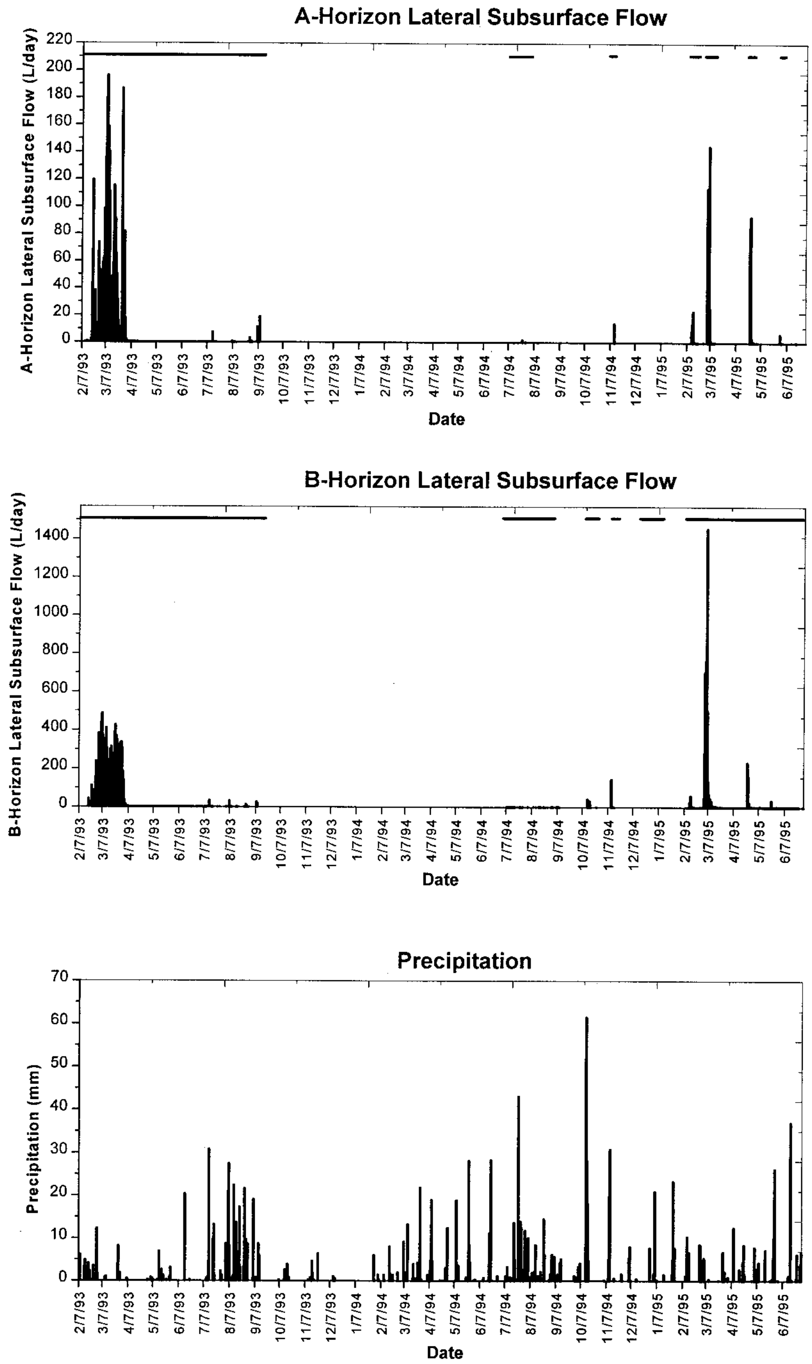
2.3.4. Mixing models. The two-component equation of *Pinder and Jones* [1969] was used to estimate old and new water percentages using the stable isotope data:

$$Q_o = \left[\frac{C_l - C_n}{C_o - C_n}\right] Q_l \tag{2}$$

and

$$Q_n = Q_l - Q_o \tag{3}$$

where Q is discharge, C is tracer concentration, and the subscripts l, n, and o correspond to lateral subsurface flow, new water, and old water, respectively. C_n was obtained from the precipitation sample. For most of the calculations, C_o was obtained from the lateral subsurface flow sample collected 24 hours before the date of interest. In these cases, subsurface flow was continuous from a few days to weeks prior to the date



A-Horizon Lateral Subsurface Flow

B-Horizon Lateral Subsurface Flow

Precipitation

Figure 3. Graphs of A- and B-horizon lateral subsurface flow volume and precipitation. Note that the y axes have different scales. Solid bars at the top of the lateral subsurface flow graphs indicate periods of continuous lateral subsurface flow generation.

of interest, so the isotopic composition of the old water can be adequately constrained. In one case (October 15, 1994), there was no flow for ~1 month prior to the event. For this case, the old water composition was bounded by the isotopic value of the last lateral subsurface flow sample from September 1994 and the isotopic composition of precipitation that fell between the time that lateral subsurface flow stopped and October 1994 flow began. In other words, two calculations were performed: one for the isotopically heaviest possible old water condition (based on precipitation analyses) and the other for the isotopically lightest condition (final September 1994 lateral flow value).

3. Results

3.1. Hydrometric

The hydrometric results for the hillslope are discussed in detail by *Wilcox et al.* [1997], so only a brief overview is given here. Lateral subsurface flow from the hillslope is episodic; the largest events generally occur in the spring as a result of saturated conditions from melting snow and spring rainfall. Most of this water (~80%) flows through the B horizon, with the balance flowing through the A horizon. Lateral subsurface flow volumes from the A and B horizons and precipitation for the

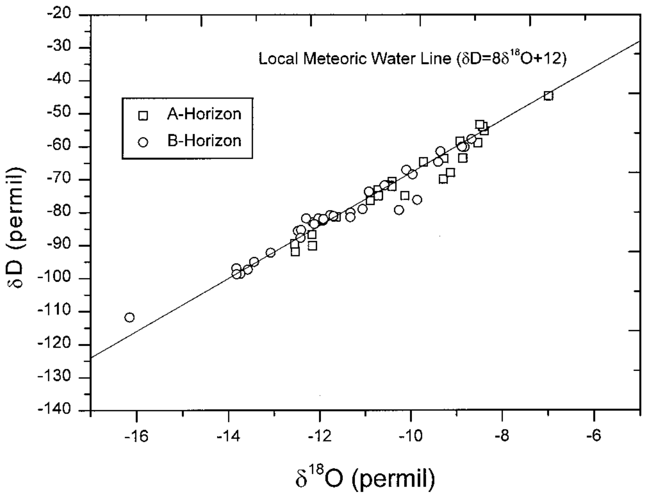


Figure 4. The δ^{18}O versus δD for A- and B-horizon lateral subsurface flow plotted against the Los Alamos local meteoric water line (solid line) of *Vuataz and Goff* [1986].

period February 1993 through June 1995 are shown in Figure 3. The horizontal bars at the top of the lateral subsurface flow graphs in Figure 3 give an indication of the frequency and duration of A-horizon and B-horizon flow. Other than in the spring and summer of 1993, which followed an exceptionally wet winter, periods of continuous A-horizon lateral subsurface flow generation were shorter than that of the B-horizon (Figure 3). In the 3 years of observation, there were three periods during which combined A- and B-horizon lateral subsurface flow rates exceeded 200 L/d: spring 1993, fall 1994, and spring 1995 (Figure 3). Small quantities of lateral subsurface flow were measured at other times, generated by individual storms or fronts. Although it makes up only a small portion of the annual water budget (~2%), lateral subsurface flow can be important for shorter periods; for example, in the 1993 water year (October 1992 through September 1993], lateral subsurface flow accounted for 19% of the winter-spring water budget.

3.2. Stable Isotopes

A δ^{18}O-δD plot (Figure 4) comparing A- and B-horizon lateral subsurface flow to the Los Alamos local meteoric waterline (LMWL) of *Vuataz and Goff* [1986] shows that very little evaporation of the lateral subsurface flow waters occurred because all of the data fall on or near the LMWL. In addition, the close agreement between lateral subsurface flow water and the LMWL shows that sample integrity was preserved during the sampling process and that the analyses are of good quality.

For the A horizon, the δ^{18}O of lateral subsurface flow and of precipitation from June 1993 to April 1995 are shown in Figure 5. The variability of A-horizon lateral subsurface flow δ^{18}O values is much less than that of precipitation. Percentages of old and new water from selected events (as calculated from (2) and (3)), are shown in Table 1a. The small volume lateral subsurface flow events (<0.5 L/d) were dominated by old water and occurred during unsaturated conditions (where average volumetric moisture contents were less than ~33%). Contributions from new water were large only on July 14, 1993, and February 15, 1995, during large rain or snowmelt events. Old/new water percentages could not be determined for the large lateral subsurface flow event of March 1995 that accounted for the majority of A-horizon lateral subsurface flow generated during the sampling period. This event was initiated by a thaw, and not enough snowmelt was generated to produce sufficient surface runoff for sampling. Old/new water percentages could not be calculated for subsequent events either because the isotopic compositions of the mixing model components were too similar. *Leaney et al.* [1993] noted the same problem, which is a substantial limitation of the mixing model approach.

As in the A horizon, B-horizon δ^{18}O values do not show as large a seasonal variation as precipitation (Figure 5). Some isotopically distinct precipitation events produced large changes in the δ^{18}O values of B-horizon lateral subsurface flow, (e.g., the October 15, 1994, period (Figure 5)), while other isotopically distinct events produced little change at all (e.g., events between November 12, 1994, and March 6, 1995). This difference in the effect of various storms on lateral subsurface flow isotopic composition is related to the volume of precipitation and antecedent moisture conditions. For example, when a large storm occurs during low antecedent moisture conditions, subsurface isotope compositions may be affected more than when a small storm occurs during high antecedent moisture conditions. As in the A horizon, old water dominates in small volume events (Table 1b). New water contributions were large only on days with low antecedent soil moisture and prolonged rain events or when the soil was near saturation. For the large March 1995 event and subsequent events, old/new water percentages could not be determined because of the same problems mentioned above for the A horizon.

Finally, a comparison of old water percentages for five dates on which both A- and B-horizon lateral subsurface flow were measured is shown in Table 1c. For a given date, the percentages are similar for both horizons, though A-horizon lateral subsurface flow tended to have a higher proportion of new water than did B-horizon lateral subsurface flow (however, this difference may not be significant).

3.3. Chloride

Prior to the unusually wet fall 1994 to spring 1995 period, chloride concentrations in A-horizon lateral subsurface flow rose with increases in moisture content (e.g., Figure 6 (July–August 1993 peak)) and then declined as moisture content decreased. The maximum chloride concentration was measured in March 1995, when the A horizon became saturated.

Between June 1993 and mid-October 1994 the B horizon was relatively dry having an average moisture content below ~33%; during this period, chloride concentrations in B-horizon lateral subsurface flow were <10 mg/L (Figure 6). Starting in mid-October 1994, the soils began to approach saturation; chloride concentrations increased dramatically, reaching peak levels about 6 weeks before the soils became completely saturated in March 1995. Chloride concentrations then dropped throughout the spring of 1995. The decline in chloride concentrations was marked by sharp dips. These dips correspond to large-volume, lateral subsurface flow periods during which chloride was diluted by new precipitation or snowmelt waters. The declines may also reflect increases in the rate of preferential flow that would reduce the time available for diffusion of chloride from the soil matrix into the macropores. Nevertheless, in terms of total mass, more chloride was removed during the March and February events than during the rest of the June 1993 to April 1995 period because these discharges were so large.

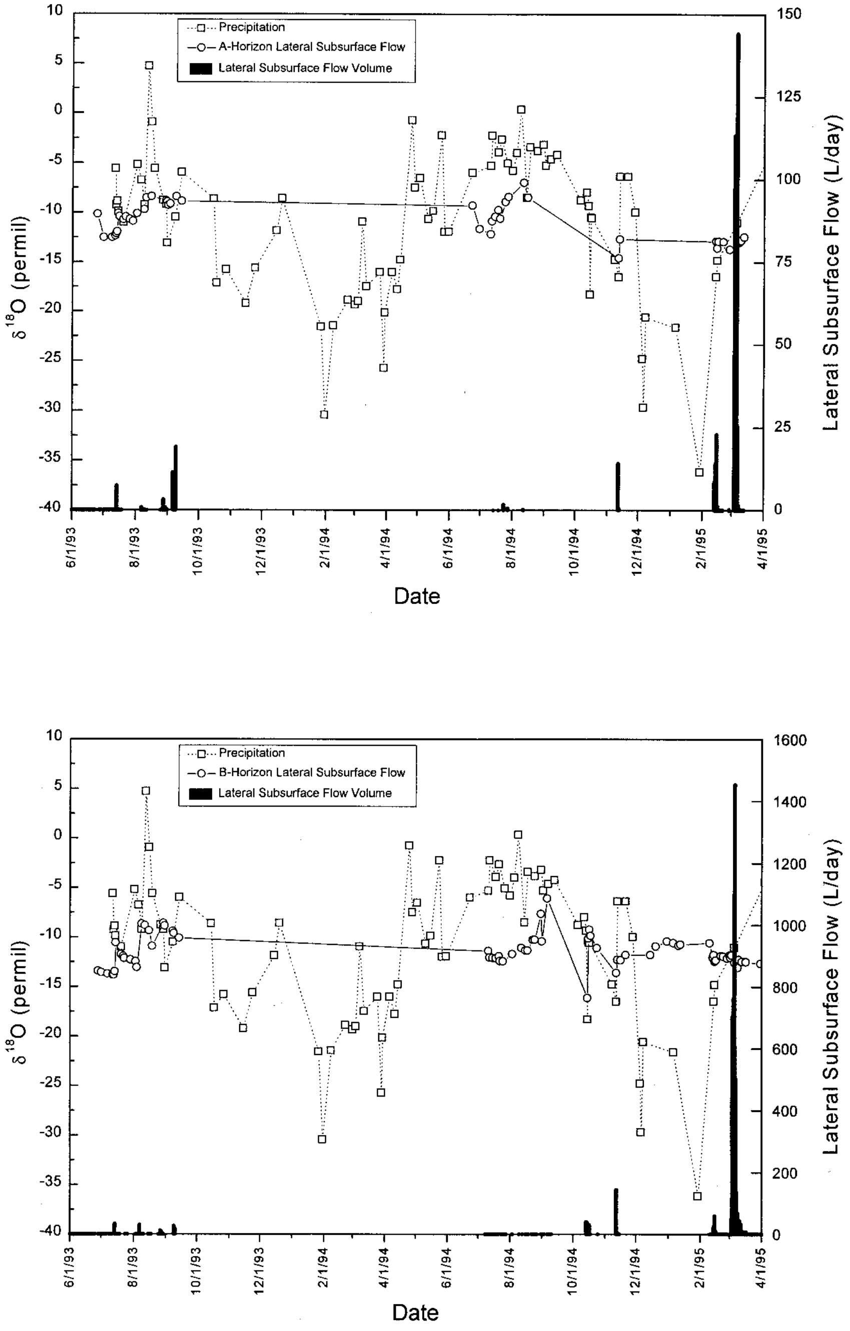


Figure 5. Comparison of the $\delta^{18}O$ of precipitation and (top) A- and (bottom) B-horizon lateral subsurface flow with time. Daily lateral subsurface flow volumes are also shown.

Table 1a. Old and New Water Percentages for Lateral Subsurface Flow: A Horizon $\delta^{18}O$

Date	Q_l, L/day	Precip., mm	Moisture, %	C_l, ‰	C_n, ‰	C_o, ‰	% Old
July 12, 1993	0.06	1.0	5	−12.4	−5.6	−12.6	97.6
July 14, 1993	7.4	31.0	5	−10.1	−9.9	−12	10
Aug. 31, 1993	0.22	4.3	26	−8.9	−13.1	−8.8	97.3
July 12, 1994	0.02	2.5	12	−10.9	−2.2	−12.2	87.0
Feb. 15, 1995	22.9	6.6	33	−13.6	−14.8	−12.9	63

Q_l is the cumulative daily volume, moisture is the average antecedent volumetric moisture for the horizon, C_l is the lateral subsurface flow isotopic composition, C_n is the new water isotopic composition, and C_o is the old water isotopic composition. Precip., precipitation.

Table 1b. Old and New Water Percentages for Lateral Subsurface Flow: B Horizon δ^{18}O

Date	Q_l, L/day	Precip., mm	Moisture, %	C_l, ‰	C_n, ‰	C_o, ‰	% Old
July 12, 1993	0.02	0.5	28	−13.8	−5.6	−13.7	102
July 14, 1993	33	31.0	28	−10.6	−9.9	−13.5	19
Aug. 31, 1993	0.02	4.3	28	−8.9	−13.1	−8.6	93
July 12, 1994	0.05	2.5	33	−12.0	−2.2	−11.4	107
Oct. 15, 1994*	61	60.9	30	−15.5	−18.3	−4	20
Oct. 15, 1994*	61	60.9	30	−15.5	−18.3	−9.3	31
Feb. 15, 1995	26	6.6	42	−12.5	−14.8	−11.8	77

Q_l is the cumulative daily volume, moisture is the average antecedent volumetric moisture for the horizon, C_l is the lateral subsurface flow isotopic composition, C_n is the new water isotopic composition, and C_o is the old water isotopic composition. Precip., precipitation.

*The old water value is bounded by the δ^{18}O values of the previous lateral subsurface flow sample and all precipitation that occured between the previous and October 15, 1994, sample. The two calculations represent the lightest and heaviest possible old water values.

3.4. Soil Cores

Soil cores were taken in the summers of 1993, 1994, and 1995 for soil water chloride determination. Chloride concentrations increased nonlinearly with depth, and increases were especially large in the B horizon (Figure 7). The core analyses reflect the chloride concentrations in the soil matrix pore waters and are more concentrated than the lateral subsurface flow waters for the three comparison dates (Table 2), indicating that some of the flow bypasses the chloride-rich, B-horizon soil matrix. Additional details of the soil-core chloride results are given by *Newman et al*. [1997].

3.5. Organic Carbon

Total dissolved organic carbon concentrations in B-horizon lateral subsurface flow ranged from 1.8–663 mg/L (Figure 8). The concentration changes closely followed those of chloride, with low concentrations during unsaturated or dry conditions (from June 1993 through mid-October 1994) and high concentrations close to and during saturation (mid-October 1994 through June 1995).

4. Discussion

Before a description of the conceptual model of lateral subsurface flow at the hillslope can be made, some discussion of how macropore flow might occur under unsaturated conditions is in order. According to *McDonnell* [1990, 1991], the minimal requirement for water flow via macropores is a flux density of rain that is greater than the hydraulic conductivity of the matrix. In other words, the rate of input of water exceeds that of infiltration into the matrix, causing the excess water to flow into macropores. Such a mechanism could explain the generation of both A- and B-horizon lateral subsurface flow under unsaturated conditions. However, in the case of the ponderosa pine hillslope, the excess water may be accumulating at the A/B interface as well as on the soil surface. The measured saturated hydraulic conductivity of the B-horizon clays is low (2.5×10^{-10} m/sec) and could readily be exceeded by the flux of water through the A horizon. The excess water could then flow into B-horizon macropores generating lateral subsurface flow; or, if the excess water does not encounter any macropores, it could pond on top of the B horizon, generating lateral subsurface flow in a portion of the A-horizon matrix.

The ponding hypothesis is supported by small hydraulic conductivity of the B-horizon matrix and because some matrix flow apparently occurs in the A horizon. Matrix flow is suggested by the varying chloride concentrations shown by the multiple peaks in Figure 6, which are apparently caused by chloride accumulation during periods of no flow and flushing when flow begins. If macropores were the dominant pathway, then a less marked flushing effect would be expected. The infrequency and small volumes of A-horizon lateral subsurface flow during unsaturated periods suggest that ponding may be a small-scale or localized occurrence.

In contrast to the A horizon, preferential flow, probably via macropores, is dominant in the B horizon. This conclusion is supported by two of this study's findings. First, comparison of the δ^{18}O of precipitation with that of B-horizon lateral subsurface flow shows that new water can move through the system within 24 hours (see the October 15 case in Table 1 and Figure 5); such movement would not be consistent with matrix flow, given the small bulk hydraulic conductivities of the soils. Second, comparison of chloride concentrations in matrix soil water with those in lateral subsurface flow (Table 2) shows that the two are not equilibrated, indicating that lateral subsurface flow is bypassing the salt-rich matrix and moving through macropores. This is consistent with the suggestion of *Thomas and Phillips* [1979] and *Luxmore et al*. [1990] that macropores serve mainly as physical conduits and have only minor effects on aqueous chemistry. Other evidence that macropore flow can occur in the B horizon at this site is the presence of shrinkage cracks, root channels, voids between soil peds, and mineral accumulation on the walls of some macropores.

Note that lateral subsurface flow generation under unsaturated conditions (less than ~33% average volumetric moisture) represents only a small fraction of the total lateral subsurface flow for the sampling period. Over 90% of the total lateral subsurface flow generated occurred during snowmelt and

Table 1c. Comparison of A- and B-horizon percent old water estimated from δ^{18}O

Date	A percent Old	B percent Old
July 12, 1993	98	102
July 15, 1993	10	19
Aug. 31, 1993	97	93
July 12, 1994	87	107
Feb. 15, 1995	63	77

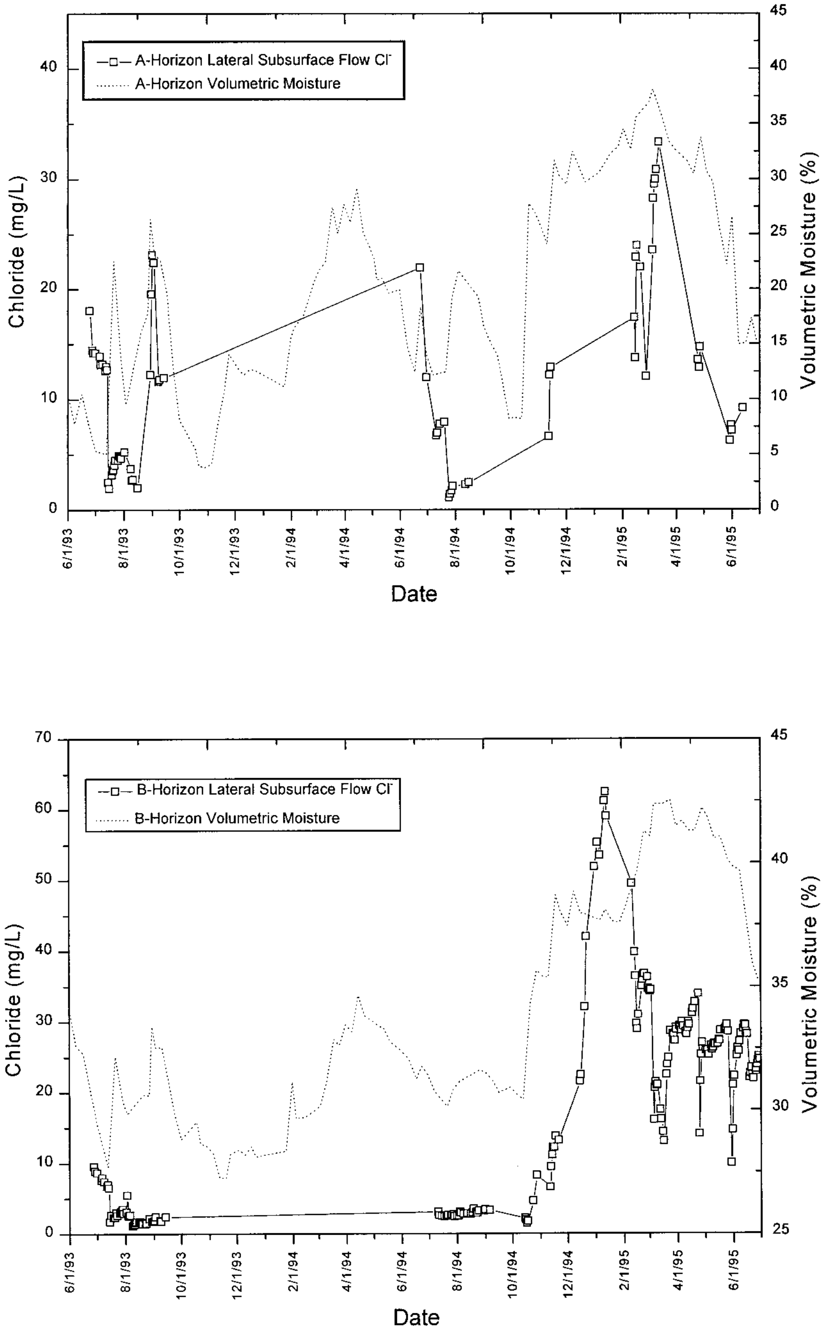


Figure 6. Changes in (top) A- and (bottom) B-horizon lateral subsurface flow chloride concentrations and volumetric moisture contents with time. Volumetric moisture is the average for all neutron access tubes on the hillslope for the horizon.

spring rain events when the soils were at or near saturation. This period was also when most of the chloride and organic carbon was mobilized.

4.1. Conceptual Model of Lateral Subsurface Flow

The conceptual model describes lateral subsurface flow generation under two volumetric soil moisture regimes: (1) moisture content below ~33% and (2) moisture content above ~33% (Figure 9). The ~33% moisture content appears to be a threshold above which major changes occur in lateral subsurface flow volumes as well as chloride and organic carbon concentrations (Figure 6). Moisture contents less than ~33% represent lateral subsurface flow processes under unsaturated conditions, whereas moisture contents greater than ~33% represent soil moisture conditions that are at or near saturation. The 33% threshold probably only applies to the local area or sites with similar soils and may not apply to other systems.

When volumetric moisture content is less than ~33%, infiltrating water is either absorbed by the A-horizon matrix or bypasses the matrix and enters the macropore system in the B horizon, where it then moves laterally. Bypassing of the A-horizon matrix is suggested because lateral subsurface flow wa-

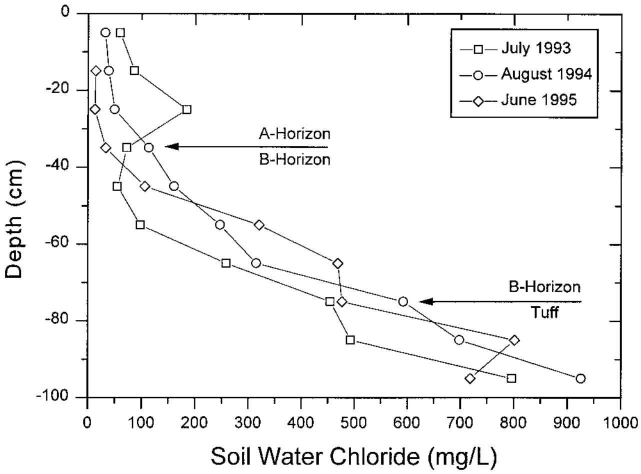


Figure 7. Chloride soil-water concentration profiles with depth from soil cores taken in July 1993, August 1994, and June 1995. Indicated depths of the soil horizon interfaces are approximate because of small differences in interface depths between the three cores. Data from these analyses were used to establish the matrix chloride concentrations in Table 2.

ters are not subject to much evaporation (Figure 4), which indicates that they move relatively quickly through the shallow evaporative zone in the soil. Matrix bypassing is also suggested by the low chloride concentrations of B-horizon lateral subsurface flow (see June 1993 to October 1994 period in Figure 6). When B-horizon lateral subsurface flow is generated under unsaturated conditions, small amounts (<0.5 L/day) of dominantly old water flow result. The small volumes of dominantly old water with low chloride concentrations suggest that the water is stored within the macropore domain. Under this moisture regime, the B horizon acts as a two-domain system: The macropore domain generates lateral subsurface flow, while in the matrix domain, water that manages to infiltrate moves very slowly and is subject to transpiration, which causes the chloride concentration to increase. Any A-horizon lateral subsurface flow that occurs is very small in volume and may come from localized ponding on top of the B horizon. If large-volume rains occur under this soil moisture regime, moderate volumes of B-horizon lateral subsurface flow can be generated (of the order of 30 L/d) that will be dominated by new water, as was observed in July 1993 and October 1994 (Table 1).

Table 2. Comparison of Chloride Concentrations in Lateral Subsurface Flow and Soil Matrix Water

Date	Lateral Subsurface Flow Cl$^-$, mg/L	Matrix Cl$^-$, mg/L*
	A Horizon	
July 19, 1993	3.2	101 (59–184)
Aug. 16, 1994	2.5	58 (32–113)
June 12, 1995	9.2	20 (14–33)
	B Horizon	
July 19, 1993	2.3	216 (55–455)
Aug. 16, 1994	2.8	329 (161–593)
June 12, 1995	29	298 (106–477)

All cores were taken in the same part of the hillslope.

*Average and range, in parentheses, of concentrations of the A and B horizon in the core.

When the high moisture-content regime (>33% volumetric moisture) is in effect (and maintained longer than a week or so), the apparent independence of the macropore- and matrix-flow domains disappears. Solute flushing and diffusion of chloride and dissolved organic carbon from the matrix increase, causing concentrations in lateral subsurface flow to rise substantially (Figure 8). The fact that both chloride and organic carbon concentrations vary together is a strong indication that a major change in lateral subsurface flow chemistry occurs under the high moisture-content regime. It seems counterintuitive that chloride and organic carbon concentrations would rise, rather than decline because of dilution, as the soils become wetter; however, in this region, the two-domain flow regime is in effect for most of the year, causing the soil matrix to act as a solute sink. Only when the soils are at or near saturation is there a continuous fluid phase that allows solutes to be transported out of the soil matrix. Both *Jardine et al.* [1990] and *Chittleborough et al.* [1992] noted that organic carbon concentrations vary with time. *Jardine et al.* [1990] found that at the Walker Branch watershed in Tennessee, organic carbon concentrations were highest during peak flow. They pointed out that small pores tend to have large stores of organic carbon, and, during the wettest conditions, these pores contribute organic carbon to lateral subsurface flow causing concentrations to rise. During the high moisture-content regime at the ponderosa pine site, lateral subsurface flow volumes also increase dramatically and can constitute >90% of the annual lateral subsurface flow volume (Figure 3).

4.2. Semiarid- versus Humid-Region Lateral Subsurface Flow

When the results from this study are compared with those from humid regions, more similarities than differences are found. Macropore flow generation by the excess water mechanism appears to be important in both environments, effecting rapid movement of water through the soil. The importance of macropore flow is also consistent with the semiarid Onkaparinga study [*Smettem et al.*, 1991].

Before comparing old/new water ratios between semiarid and humid sites, the observation of old water dominance observed in many of the humid-zone studies needs to be clarified. An important point is that not all humid sites show an old water dominance [e.g., *Elsenbeer et al.*, 1995]. In addition, the

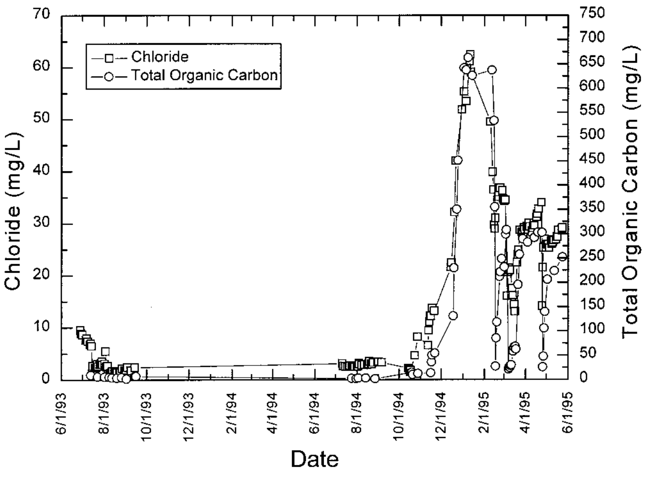
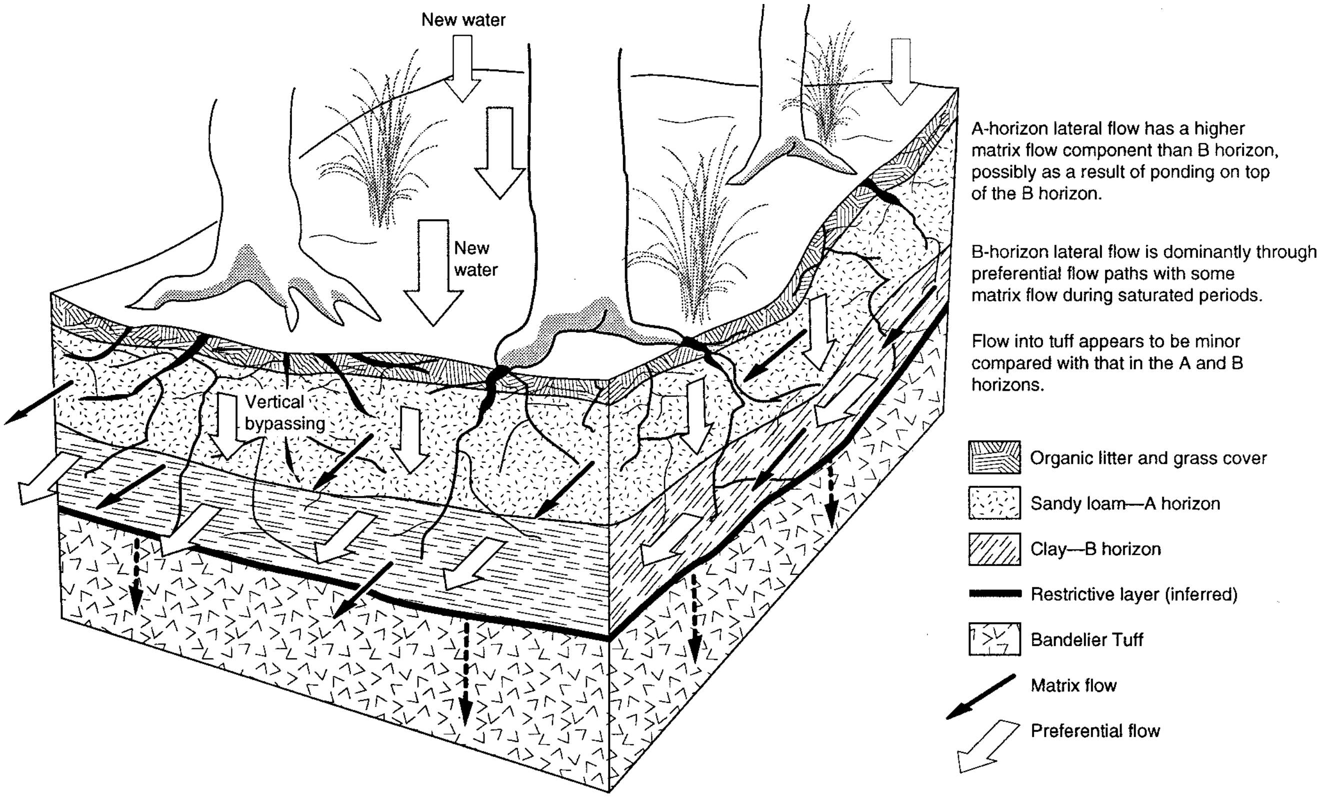


Figure 8. Changes in B-horizon lateral subsurface flow chloride and dissolved organic carbon concentrations through time.



A-horizon lateral flow has a higher matrix flow component than B horizon, possibly as a result of ponding on top of the B horizon.

B-horizon lateral flow is dominantly through preferential flow paths with some matrix flow during saturated periods.

Flow into tuff appears to be minor compared with that in the A and B horizons.

Figure 9. Illustration of the conceptual flow model for the hillslope.

studies that have shown an old water dominance have focused mainly on the hydrograph rise in streams. However, the results from humid-zone studies that have considered flow in upslope areas (which this site represents) suggest an increased importance of new water and more variable old/new water ratios between events [*McDonnell et al.*, 1990; *Turton et al.*, 1995]. For example, *Turton et al.* [1995] found that at the Alum Creek site in Arkansas, new water becomes important during infrequent large storms, while old water is dominant during the frequent small storms. During unsaturated periods at the ponderosa pine site, large storms produce substantial percentages of new water (e.g., the mid-October 1994 storm produced over 80 mm of rain and 69–80% new water in B-horizon flow), while during the majority of the year, most of the lateral subsurface flow is old water. The differences between upslope and near-stream areas arise in part because there tends to be a larger store of old water in the near-stream zone, thus the new water signal can become diluted. *Wilson et al.* [1991] found that new water was less important in the lower part of the Walker Branch site and suggested this was because of a larger reservoir of old water than was present upslope. Thus, in upslope areas, *Sklash and Farvolden*'s [1979] groundwater ridging mechanism and *McDonnell*'s [1990] crack-pipe model for old water dominance do not appear to apply.

One major difference between semiarid and humid lateral subsurface flow involves changes in lateral subsurface flow chemistry. In humid regions, evidence of solute flushing has been observed as the soils become wetter. However, changes in lateral subsurface flow chemistry appear to be much greater in semiarid environments. Studies in humid environments have shown changes in chloride concentrations of the order of a few milligrams per liter [e.g., *DeWalle and Pionke*, 1994; *Mulholland et al.*, 1990], whereas the flushing that occurs at or near saturation in semiarid environments produces changes of the order of 30–40 mg/L. Changes in organic carbon concentrations at the ponderosa pine site are even greater than those observed for chloride, increasing over 500 mg/L; these changes are much larger than those observed during the humid-zone Walker Branch study [*Jardine et al.*, 1990]. Chloride and organic carbon concentrations at the semiarid Onkaparinga site showed some temporal variation [*Chittleborough et al.*, 1992; *Leaney et al.*, 1993] but not as much as seen in this study. One explanation for this difference is that the very wet conditions seen during the ponderosa pine study did not occur while the Onkaparinga data were being collected [*Leaney et al.*, 1993]. The large changes in chloride and organic carbon concentrations that occurred at the ponderosa pine site were caused by the tremendous salt and carbon enrichment that occurs during extended dry periods, when lateral subsurface flow is restricted to the macropores. With no mechanism for their removal, soluble species build up in the soil matrix and are released in large quantities when saturated conditions are approached.

5. Summary and Conclusions

Stable isotope and chloride tracer results show that lateral subsurface flow in a semiarid ponderosa pine hillslope in New Mexico is largely controlled by preferential flow processes, which not only influence water movement, but dramatically affect soil water chemistry. Most of the lateral subsurface flow is generated in the B horizon and travels mainly via macropores, which can result in extremely rapid water movement even in soils having very low bulk hydraulic conductivities. Throughout most of the year, the flow system has two domains:

a macropore domain, in which water can move relatively rapidly and in which evapotranspiration has a minor effect, and a matrix domain, in which water movement is extremely slow and transpiration has a major effect, resulting in substantial water loss and increased salt concentrations. When the soils are at or near saturation (greater than $\sim 33\%$ volumetric water content) during snowmelt periods, a connection between the two domains is established, and concentrations of chloride, organic carbon, and other aqueous species in lateral subsurface flow rise dramatically. Under these conditions, very large volumes of lateral subsurface flow can be produced.

In addition to the temporal changes in lateral subsurface flow chemistry and volumes at the ponderosa pine site, old/new water percentages also change. These variations point out the need for monitoring over a wide range of events and conditions. In semiarid systems, monitoring a few events over a short duration is not likely to capture the episodic and variable nature of the lateral subsurface flow system.

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