

## Snowmelt-driven macropore flow and soil saturation in a semiarid forest

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### Abstract

Lateral subsurface flow is generally assumed to occur as a result of the development of a saturated zone above a low-permeability interface such as at the soil–bedrock contact, and it is often augmented by macropore flow. Our objective was to evaluate the development of lateral subsurface flow and soil saturation at a semiarid ponderosa pine forest in New Mexico with respect to the conceptual model of saturation building above the soil–bedrock contact. At this site, we have long-term observations of the water budget components, including lateral flow. A 1.5 m deep by 7 m long trench was constructed to observe lateral subsurface flow and development of saturation directly. Our observations are based on flow resulting from a melting snowdrift. The edge of the drift was about 7 m upslope from the trench. Lateral subsurface flow only occurred from root macropores in the Bt soil horizon. Saturation developed and grew outward from flowing root macropores, rather than growing upward from the soil–bedrock interface. This macropore-centred saturation resulted in a highly heterogeneous distribution of water content until enough macropores began flowing and individual macropore saturated zones grew large enough to coalesce and saturate large volumes of the soil. Our observations are based on one snowmelt event and a relatively short hillslope flow path, and thus do not represent a full range of hydrologic conditions. Nevertheless, the observed behaviour did not conform to the traditional model of soil–bedrock control of saturation and lateral flow. Copyright © 2004 John Wiley & Sons, Ltd.

### Introduction

Since 1993, we have been studying the mechanisms by which runoff is generated from a semiarid ponderosa pine forest in New Mexico (Wilcox *et al.*, 1997; Wilcox and Breshears, 1997; Newman *et al.*, 1998; Brandes and Wilcox, 2000). Our studies indicate that lateral subsurface flow is an important mechanism of runoff generation—particularly during the spring, as the soils wet up from melting snow or rain-on-snow events. Small amounts of lateral subsurface flow can also be generated during other seasons.

Wilcox *et al.* (1997) observed that, during periods of substantial lateral subsurface flow (which occurs dominantly in the Bt horizon), the soil profile was saturated, or nearly so, whereas the underlying weathered bedrock remained comparatively dry. Subsequently, Newman *et al.* (1998), using natural tracers, confirmed that macropore flow was controlling lateral subsurface flow. The earlier observations of a fully saturated soil profile above unsaturated bedrock during large spring

lateral flow events appeared to be consistent with proposed mechanisms for lateral subsurface flow generation in other forested landscapes (Bonell, 1993). During periods of high water input, a perched saturated zone may develop over an impermeable (or low permeability) layer, forcing lateral flow from within the saturated zone (Hornberger *et al.*, 1990; Wilson *et al.*, 1990; Turton *et al.*, 1995; Freer *et al.*, 2002).

Vertical bypassing of the unsaturated soil matrix via macropores can facilitate rapid development of a perched saturated zone (Beven and Germann, 1982; McDonnell, 1990). We refer to this concept as the 'impermeable-layer model'.

The collection system of Wilcox *et al.* (1997) and Newman *et al.* (1998) precluded direct observation of lateral subsurface flow, and thus it was impossible to verify directly that the impermeable layer model is representative of the hillslope. A concern was that the tuff bedrock has a relatively high saturated conductivity (e.g.  $10^{-4}$  cm s<sup>-1</sup>; Rogers and Gallaher, 1995); thus, it was unclear why water would perch on the bedrock. Therefore, one of the main objectives of this study was to test whether the impermeable layer model was representative of the site. In order to achieve this objective, we used direct observation and measurements of flow through an open trench face during spring snowmelt. In addition, we wanted to determine what types of macropore were important and quantify individual macropore flow rates. Our study is limited in scope, in that we studied one snowmelt event over a relatively small area. Thus, the data and observations do not represent a wide range of conditions. Nevertheless, this study does provide interesting insights about the hydrologic behaviour of hillslopes.

### Study area and methods

The study site is located in northern New Mexico, in ponderosa pine forest within the Los Alamos National Laboratory, and is adjacent to the experimental hillslope where we have detailed hydrometric (e.g. lateral subsurface flow, and water content), and water chemistry information (Wilcox *et al.*, 1997; Newman *et al.*, 1998).

The site's elevation is around 2315 m and its slope about 6%. Annual precipitation averages 500 mm, of which about 45% occurs in the summer months (July, August, and September). Soils at the site are

Vertic Paleustalfs, generally about 1.2 to 1.5 m thick. These soils have a silt loam A horizon overlying a sandy loam E horizon, clayey and sandy clay loam Bt horizons, a sandy loam CB horizon, above a Cr or R horizon of Bandelier Tuff bedrock.

To observe the processes of lateral subsurface flow and the development of saturation directly, we dug a 7 m long and 1.5 m deep trench across a section of the hillslope. Excavated adjacent to the enclosed trench described in previous studies, the new trench was left open to enable continuous viewing and measurement of lateral flow and soil wetting (the trench was covered with a tarpaulin to prevent entry of rain or snow). A depth of 1.5 m was sufficient to expose the entire soil profile and the upper few centimetres of the tuff bedrock.

The morphological and physical properties of the soil profile (e.g. horizon type and thickness, texture, and structure) were described via standard soil analysis methods (Schoeneberger *et al.*, 1998). At the pit face, the A horizon (0.44 m thick) has clay contents that range from 5 to 13% and sand contents of 35 to 51%. The Bt horizon (0.37 m thick) has 58% clay and 25% sand, and when dry it has shrinkage cracks up to 10 mm wide separating coarse, angular, blocky structural units. The transitional CB horizon (0.45 m thick) consists of 64 to 80% sand and 9 to 27% clay. The Bandelier Tuff forms the bedrock contact. Hydrologic properties of the soils were reported previously (Daniel B. Stephens & Associates, 1993; Wilcox *et al.*, 1997).

Root densities and distributions were determined by means of a point-count frame (20 × 50 cm), and the diameters of roots intersecting the trench wall were classified as <1 mm, 1–2 mm, 2–5 mm, 5–10 mm, or >10 mm. One vertical transect was analysed at the middle of the trench. Each horizon was analysed separately by placing the frame in the middle of the horizon with the 50 cm length of the frame placed in the horizontal direction.

During one of the days that lateral subsurface flow was being generated, a set of soil samples was collected from the trench face for analysis of gravimetric water content. Gravimetric water content was determined along seven vertical transects 1 m apart, and adjacent to flowing macropores (Gardner, 1986). The gravimetric values were converted to percentage saturation using bulk densities and porosities for the site soils (Daniel B. Stephens & Associates, 1993).

Root macropore flow was measured over a 2 day period in March 1997, shortly after the initiation of lateral subsurface flow. An isolated melting snowdrift was the source of the lateral flow. The entire drift was less than about 15 m upslope from the trench and was surrounded by bare ground (there was about 7 m of bare ground between the drift and the trench at the start of flow). Sections of PVC pipe or rain gutter were gently pressed into the trench face to capture flow from individual root macropores or small groups of root macropores spaced too closely to be sampled individually. This sampling approach is similar to that used by Tsuboyama *et al.* (1994). A bucket was placed at the bottom of each macropore sampler to collect the water (Figure 1). In addition, the time of installation of each sampler and bucket was noted so that flow rates could be calculated. Water was collected for a period of about 12 h from each sampling location, then the samplers were removed and the volume of water in each bucket was measured. The first day of sampling yielded measurements from only three flowing root macropores (some samplers were dislodged when the increasing flow of water caused sloughing of the trench face). Between the first and second days, several more root macropores began flowing, and on the second day we were able to obtain data from four root macropores. However, we were not able to install samplers on every root macropore that was flowing. In a few cases the collectors overflowed, so that flow rates were actually larger than what we were able to measure. To take into account water lost because of occasional sampler failures and because more root macropores were flowing than was possible to monitor, we pumped water out of the trench and added the quantity of water obtained to that collected from the samplers to arrive at an estimate of total flow. Because of the possibility of seepage of water through the trench bottom, the total flow estimate should be considered as a minimum bound. There were no additional water sources other than the root macropores on the upslope trench-face, so the total flow estimates are not overestimates of the macropore flow.

Both soil wetting and flow were visually observed in the trench over an approximately 2 week period in March 1997. This is the only period when flow occurred in the trench, and despite our plans to collect additional data at the site, no lateral flow has



Figure 1. Trench face (left side of photograph) showing the site soil profile and macropore flow collection system. Note the mottled appearance of the trench-face soils that results from the heterogeneous water content distribution

occurred over the subsequent 5 years (which have been dominated by drought conditions).

## Results

The root density data that were compiled for each horizon and size class are shown in Table I. Roots were concentrated in the A and Bt horizons. Only a few roots were found in the CB horizon, and no roots were observed below the CB horizon.

All macropore flow occurred through either live or decayed ponderosa pine root macropores in the Bt horizon. Some root macropores flowed for only a day or two, whereas others flowed for nearly a week. Flow rates of individual root macropores varied with time (Table II). This temporal and spatial variability of

Table I. Root density

Soil horizon	Size class (roots/m <sup>2</sup> )				
	<1 mm	1–2 mm	2–5 mm	5–10 mm	>10 mm
A	414	281	57	19	14
Bt <sup>a</sup>	244	163	89	22	15
C	4	8	0	0	0

<sup>a</sup> Over 90% of the roots in the Bt horizon are in the top 30 cm of the horizon.

macropore flow is consistent with results from other field studies (e.g. Tsuboyama *et al.*, 1994; Uchida *et al.*, 2001). Individual macropore flow rates sometimes exceeded 2 l h<sup>-1</sup>, and the measured flow rates overlap with the low end of the range of pipeflow rates (0.72 to 2 × 10<sup>-5</sup> l h<sup>-1</sup>) reported by Uchida *et al.* (2001) or were substantially below that range. We also observed that, in macropores with live roots, flow occurred through the annular space between the root and the soil. In macropores with decayed roots, flow appeared to occur through decayed root material surrounded by a residual outer sheath of bark. At first, flow was restricted to a few root macropores. By the second day, additional root macropores had begun flowing. In the Bt horizon, flow rates reached over 9 l h<sup>-1</sup> over a trench face area of approximately 2.6 m<sup>2</sup> (the actual combined area of flow generation was substantially smaller).

Lateral subsurface flow at the trench face commenced when the soil was largely unsaturated. Soils were only saturated around the flowing macropores (Table III). The percentage saturation values in Table IV clearly indicate that much of the soil profile was unsaturated, whereas the soil around flowing root macropores was saturated. Saturated halos grew outward with time, sometimes coalescing with other root

halos a few millimetres to centimetres away. Additional roots began flowing and zones of saturation continued to grow during the 2 weeks of lateral subsurface flow generation until a large proportion of the Bt horizon became saturated (in order to eliminate bias from water spilling over the trench face, we excavated a fresh face in the trench to verify that a significant percentage of the Bt horizon had indeed become saturated). Lateral subsurface flow ceased when the snow pack completely melted.

 Table III. Percentage saturation adjacent to flowing root channels<sup>a</sup>

Root no.	Saturation (%)
1	100
3	100
4	100
6	100
7	100

<sup>a</sup> Note that values of samples taken near roots exceeded 100%. This error is attributed to sampling problems resulting from the difficulty in obtaining representative samples from small volumes of soil near flowing root channels, and to possible errors in soil porosity values.

Table IV. Ponderosa soil samples, percentage saturation

Soil horizon	Saturation (%) at vertical transect <sup>a</sup>						
	0	1	2	3	4	5	6
A	52	47	57	42	90	64	48
Bt	100	68	72	100	74	100	76
C	47	54	32	41	37	25	23

<sup>a</sup> Transect number indicates distance of the vertical transect from the south end of the trench (m).

Table II. Ponderosa pine root characteristics and flow rates

	Root 1	Root 2	Root 4	Root 6 <sup>a</sup>	Total flow for all roots in trench face	Sampling date
Root condition	Live	Live	Decomposed	Decomposed		
Root diameter (mm)	40	0.5–2	10	4, 10		
Flow (l h <sup>-1</sup> )	0.97	0.27		0.28	7.1	12 March 1997
Flow (l h <sup>-1</sup> )	1.07	0.0	2.1	0.03	9.6	13 March 1997

<sup>a</sup> Root samplers 2 and 6 contained multiple roots.

## Discussion

Keeping in mind that our observations represent one snowmelt event and a relatively small hillslope area, we found that (1) lateral subsurface flow occurred as flow through root macropores and is restricted mainly to the Bt horizon; (2) a perched saturated zone did not develop up from the soil–bedrock interface; instead, saturated zones developed and spread concentrically from root macropores that were conducting lateral subsurface flow (water moved from the macropores into the soil matrix not *vice versa*); and (3) at the initiation of lateral subsurface flow, it occurred as ‘bypass flow’ through largely unsaturated media, although local saturation occurred around the flowing macropores. In other words, the impermeable layer model is not representative of this event because the development of a perched saturated zone above the bedrock interface did not precede lateral subsurface flow.

On the basis of these observations, in combination with our long-term measurements, we further refine our conceptual model for lateral subsurface flow in these semiarid forests (Newman *et al.*, 1998). Wettest conditions occur during the spring snowmelt in years of above-average winter precipitation. Snow accumulates in drifts, and water inputs are therefore not uniform across the hillslope. Lateral subsurface flow is concentrated in the Bt horizon (Wilcox *et al.*, 1997), which has a high concentration of roots/root macropores. Because the macropores flow at different rates and do not all start flowing at once, the distribution and volume of flow—and thereby the water content of the soil—will vary considerably. The transitional CB horizon has few roots and little lateral subsurface flow. However, on the basis of 8 years of soil water monitoring, we know that during wet conditions this horizon will become saturated or nearly saturated (Brandes and Wilcox, 2000). These same soil moisture measurements indicate that little water moves from the CB horizon into the unweathered tuff. The exact reason for the limited flow into the tuff is unclear. We hypothesize that, because there is only a limited flux of water through the lower soils, there simply is not enough water moving across the soil–tuff interface to create extensive saturation with depth in the tuff. This hypothesis is based on observations of little to no macropore flow below the Bt horizon, low matrix flow rates in the Bt horizon

(from chloride mass-balance flux estimates described by Newman *et al.* (1997)), and a limited water supply that is related to the relatively short duration of wet conditions. Capillary barrier effects may also explain the limited flow into the tuff. Whatever the mechanism, under wet conditions, saturation or near saturation develops above the R horizon; however, it does not develop from the tuff interface upward, as suggested by the impermeable layer model. In other words, the endpoints of the impermeable layer model and the macropore-centred model appear to be the same (i.e. a fully saturated soil profile); however, the spatial and temporal development of soil saturation is quite different in the two models.

We have conceptualized the sequence for soil saturation to occur for snowmelt conditions, highlighting the role of root macropores as a driver for lateral subsurface flow, as well as for the development of soil saturation (Figure 2). The conceptualization is based on a synthesis of data and observations from the trench face, the snowpack area, and previous work (Wilcox *et al.*, 1997; Newman *et al.*, 1998). Hydrostratigraphic characteristics consist of a high-conductivity A horizon (e.g. sandy loam), a low-conductivity Bt horizon with an extensive root macropore network, and a lower (CB) horizon and bedrock that have few roots. A high-conductivity surface horizon is required to enable rapid infiltration and percolation (consistent with observations by Whipkey (1965) and Freeze (1972)) and the lower conductivity, but the macropore-rich B horizon encourages lateral macropore flow and macropore-centred growth of saturation in the horizon. The A horizon is saturated, although it may only be locally saturated, as occurred below the upslope snowpack in this study. At this first stage, for upslope and downslope locations, a few root macropores in the upper Bt horizon begin flowing, and around them thin halos (measuring a few millimetres in diameter) of saturation develop. With the passage of time, and as additional water penetrates the A horizon, more root macropores begin flowing and the saturated halos grow outward (now measuring up to a few centimetres in diameter). Note that this behaviour is consistent with the conceptual model of an expanding macropore network and outward growth of a sheath-like matrix–macropore interaction zone described by Tsuboyama *et al.* (1994). In addition, matrix-flow-driven saturation can extend from the A

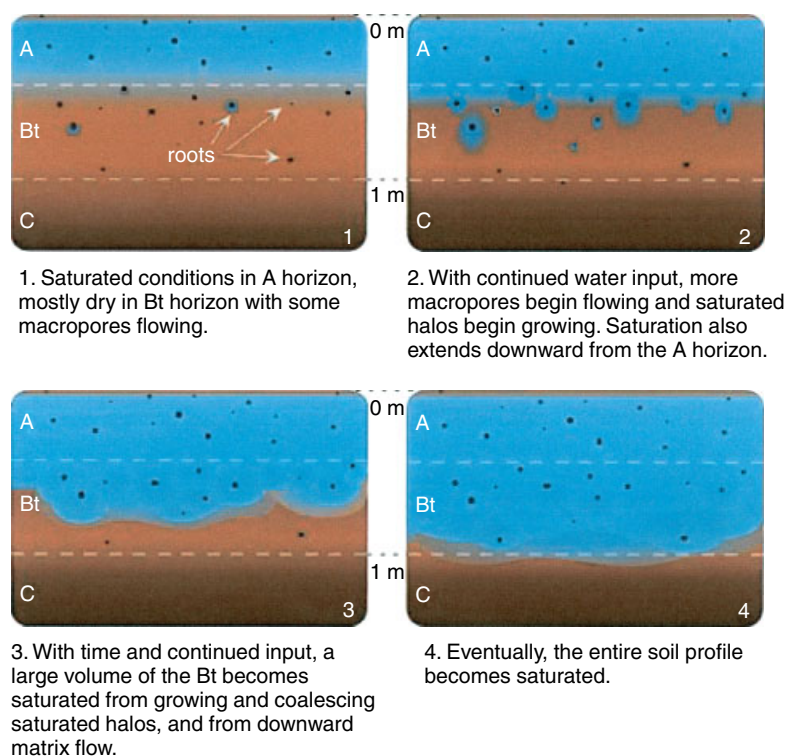


Figure 2. Conceptual model of lateral subsurface flow generation and root-centred development of saturation (light shading indicates saturation, darker shading represents unsaturated conditions)

horizon into the Bt horizon. This type of Bt saturation was not observed in the current study, because the trench was not located at the snowdrift. However, if saturation can extend from macropores, then saturation can also extend downward from a locally saturated A horizon. Most of the Bt and CB horizon soil—the zones not in the immediate vicinity of roots—continues to be relatively dry. The growth of the saturated halos may be controlled by equilibration between saturated soil and adjacent drier soil. However, hydraulic nonequilibrium, where advection in the macropores creates a gradient outward into the soil meso- and micro-porosity, may play an important role (Wilson *et al.*, 1998). At the third stage, many root macropores are flowing, and as their individual saturated halos continue to grow, they begin to coalesce. Matrix-flow-driven saturation also continues to extend deeper into the Bt horizon. Growth of the saturated halos does not have to be extensive before coalescence occurs. Because of the high root density, a few millimetres to centimetres of growth is all that

is required for some coalescence to occur. A substantial volume of the Bt horizon is now saturated. At the fourth stage, given enough water input and time, the Bt and CB horizons become completely saturated, but only a little water moves into the unweathered tuff. Unfortunately, the limited snowmelt supply and the short melt duration were inadequate to saturate the soil fully (i.e. we did not observe Stage 4 conditions in the open trench). However, from previous studies, we know that Stage 4 conditions do occur on the hillslope.

To estimate how long it might take for hillslope conditions to transition from Stage 1 to Stage 4 (fully saturated), we examined volumetric water content data from the large lateral subsurface flow events of 1993 and 1995 described in Wilcox *et al.* (1997) and Newman *et al.* (1998). These data suggest that it can take months to move from Stage 1 conditions to Stage 4 (fully saturated) conditions. For example, in September 1995, volumetric water contents in the Bt horizon were about 30% and only minor amounts

of lateral subsurface flow were generated (Stage 1 conditions). However, in October the water contents began to increase. These eventually peaked at over 40% (fully saturated conditions) in March and April 1995, and extremely large lateral subsurface flow volumes were generated in March and April (Stage 4 conditions). In this case, it took 5 months to shift from Stage 1 to 4. During our 9 years of observing lateral subsurface flow at the adjacent site, Stage-4 conditions have only occurred twice (Wilcox *et al.*, 1997; Newman *et al.*, 1998), which suggests that, in most years, hillslope conditions never move beyond Stages 1 or 2. The relatively infrequent observation of Stage-4 conditions also underscores the need for long-term field monitoring in semiarid environments.

### Summary and conclusions

Our direct observations of snowmelt-driven lateral subsurface flow and soil saturation suggest an alternative conceptual model for how soil saturation can develop at a ponderosa pine hillslope. According to this model, a saturated A horizon (can be localized) feeds zones of saturation that develop around Bt-horizon root macropores that are actively transporting water laterally. Eventually, given sufficient input of water, the entire soil profile can become saturated as an increasing number of root macropores begin flowing, and saturation extends outward from these macropores. Deeper horizons may also become saturated in part by downward matrix flow originating in the A horizon. The combined effects of the hydrologic properties of the soil and the distribution and density of ponderosa pine roots control the generation of lateral subsurface flow and development of saturated zones. The relatively conductive A horizon supplies water to the system of ponderosa-pine-root macropores in the Bt horizon, and the low conductivity of the Bt matrix helps focus flow along the root macropores while limiting downward flow into deeper soil horizons.

Our observations were based on a limited set of conditions, and the applicability of the alternative conceptual model to other conditions or sites is not known. However, we believe that aspects of the alternative conceptual model may apply to other forest environments, particularly those that are water limited. The studies by Aubertin (1971) and Tsuboyama *et al.* (1994) are evidence for possible broader

application of the macropore-centred model. Aubertin (1971) observed root-macropore flow and small-scale wetting around root macropores that was similar to that observed at the ponderosa pine site. He did not observe the development of large-scale saturation resulting from root flow, but we suspect that this was because the experiments were only conducted for a few hours and probably did not have large enough water input or long enough duration for large-scale saturation to develop. Tsuboyama *et al.* (1994) proposed a conceptual model that describes the outward growth of a macropore–matrix interaction zone around an individual macropore that is tied to increasing wetness. Their model is similar to the saturated halo development described here. The heterogeneous and variable saturation and flow characteristics observed at the ponderosa pine site have also been observed at the Hitachi Ota Experimental Watershed (Tsuboyama *et al.*, 1994) and the Panola Mountain site (Freer *et al.*, 2002), although there are some differences in conditions and behaviours between these sites and the ponderosa pine site. Our results also suggest that numerical models of locations that behave similarly to the ponderosa pine site may require an alternative storage–discharge relation (i.e. one that does not rely on depth of saturation above the bedrock interface). Finally, the spatial and temporal variability of lateral flow and soil wetting described here may have important ecological implications, especially in water- and nutrient-limited environments, such as in arid and semiarid ecosystems.

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