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RESEARCH ARTICLE

Lateral water flux in the unsaturated zone: A mechanism for the formation of spatial soil heterogeneity in a headwater catchment

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Abstract

Measurements of soil water potential and water table fluctuations suggest that morphologically distinct soils in a headwater catchment at the Hubbard Brook Experimental Forest in New Hampshire formed as a result of variations in saturated and unsaturated hydrologic fluxes in the mineral soil. Previous work showed that each group of these soils had distinct water table fluctuations in response to precipitation; however, observed variations in soil morphology also occurred above the maximum height of observed saturation. Variations in unsaturated fluxes have been hypothesized to explain differences in soil horizon thickness and presence/absence of specific horizons but have not been explicitly investigated. We examined tensiometer and shallow groundwater well records to identify differences in unsaturated water fluxes among podzols that show distinct morphological and chemical differences. The lack of vertical hydraulic gradients at the study sites suggests that lateral unsaturated flow occurs in several of the soil units. We propose that the variations in soil horizon thickness and presence/absence observed at the site are due in part to slope-parallel water flux in the unsaturated portion of the solum. In addition, unsaturated flow may be involved in the translocation of spodic material that primes those areas to contribute water with distinct chemistry to the stream network and represents a potential source/sink of organometallic compounds in the landscape.

KEYWORDS

hillslope hydrology, hydropedology, pedogenesis, soil science, stream chemistry, unsaturated flow

1 | INTRODUCTION

Variations in thickness and presence/absence of specific soil horizons along topographic and drainage gradients have been described in a variety of landscapes as topo- or hydro-sequence catenas (cf. Jenny, 1946). However, the thickness and sequence of soil horizons that spatially structure soils can vary at a smaller scale than is typical in the catena concept (Bailey, Brousseau, McGuire, & Bullen, 2014; Jankowski, 2013; Sommer, Halm, Weller, Zarei, & Stahr, 2000). In both cases, specific soils grouped by similar horizon thickness and presence/absence have been shown to be indicative of distinct hydrologic (Blumstock, Tetzlaff, Dick, Nuetzmann, & Soulsby, 2016; D'Amore, Edwards, Herendeen, Hood, & Fellman, 2015; Lin, Kogelmann, Walker, & Bruns, 2006) and biogeochemical processes (Laudon et al., 2011; Lucas et al., 2012; Morse et al., 2014). These soil groups have been called hydropedological units (HPUs; Gannon, McGuire, & Bailey, 2014; Tetzlaff, Birkel, Dick, Geris, & Soulsby, 2014), a functional classification that defines HPUs as soil groups relevant to run-off production, biogeochemical processing, and the structure of natural communities.

In some cases, the processes driving the formation of these variations in soil morphology are not well understood. For instance, several studies have identified patterns in variations along hillslopes of the morphology of podzols (Bailey et al., 2014; Jankowski, 2013;

Sommer et al., 2000), which are soils that display moderate expressions of E, Bhs, and Bs horizons (Sauer et al., 2007). These variants are interpreted as lateral podzolization, where the formation of a podzol occurs laterally along a slope instead of only vertically in a profile, which is often the assumption in pedology. The hydrologic processes that drive lateral podzolization are not well understood (Bailey et al., 2014; Jankowski, 2013; Sommer et al., 2000, 2001) but may be the result of differences in the magnitude and/or frequency of water flux. For instance, soil morphology was shown to be influenced by distinct water table regimes, defined by threshold response to catchment storage and frequency and magnitude of water table response (Gannon et al., 2014). However, some soil horizons hypothesized to be developed through lateral translocation and immobilization of spodic materials occurred higher in the soil profiles than water tables were observed (Bailey et al., 2014). Similar sequences in lateral translocation/immobilization have been observed in settings where the presence of water table is unlikely (Jankowski, 2013). One potential explanation of the lateral translocation occurring in these soils is that it is occurring via downslope water flux when groundwater is not present. This flux in the absence of saturation is called lateral (i.e., slope-parallel) unsaturated flow.

Lateral unsaturated flow has been detected in soils in the field (Genereux, Hemond, & Mulholland, 1993; Jackson, 1992; Logsdon, 2007; McCord, Stephens, & Wilson, 1991; Ridolfi, D'odorico, Porporato, & Rodriguez-Iturbe, 2003; Torres, Dietrich, Montgomery, Anderson, & Loague, 1998) and laboratory (Cabral, Garrote, Bras, & Entekhabi, 1992; Lv, Hao, Liu, & Yu, 2013; Sinai & Dirksen, 2006). The resulting unsaturated water fluxes offer a process description for unsaturated soils supplying baseflow to streams (Anderson & Burt, 1978; Hewlett, 1961; Hewlett & Hibbert, 1963) and the variation of soil moisture with topography (Perry & Niemann, 2007). Additionally, lateral unsaturated flow is hypothesized to be responsible for lateral soil development in various landscapes (Jankowski, 2013; McDaniel, 1992; Park & Burt, 2002; Sommer et al., 2000, 2001). However, lateral unsaturated flow has not been measured where lateral podzolization has been documented.

The purpose of this study was to document and examine unsaturated lateral flux at a site with lateral podzolization to address the hypotheses relating the two phenomena. We examined differences in the direction of unsaturated fluxes within forest soils in a steep headwater catchment where lateral podzolization has been documented (Bailey et al., 2014). We used soil descriptions and measurements of saturated and unsaturated soil water dynamics to relate measurements of vertical hydraulic gradients and water table fluctuations to the morphological differences in soils.

2 | SITE DESCRIPTION

This study took place in watershed 3 (WS3) at the Hubbard Brook Experimental Forest (HBEF) near North Woodstock, NH, USA, in the White Mountain National Forest (Figure 1). WS3 is the hydrologic reference watershed for a number of paired watershed studies at HBEF (Hornbeck, 1973; Hornbeck, Pierce, & Federer, 1970; Likens, Bormann, Johnson, Fisher, & Pierce, 1970) and has not been experimentally manipulated. HBEF has a humid continental climate. The site receives 1,400 mm of precipitation annually, a quarter to a third of which falls as snow. Average temperatures are −9 and 18 °C in January and July, respectively (Bailey, Hornbeck, Campbell, & Eager, 2003).

The bedrock in WS3 is the Silurian Rangeley Formation, a sillimanite-grade pelitic schist and calc-silicate granulite. The soil parent materials were deposited during the late Wisconsinan glacial period and are basal and ablation tills of varying thickness and hydraulic conductivity (Bailey et al., 2014). WS3 is steep (20–30%), south-facing, and ranges in elevation from 527 to 732 m. The catchment is forested with mature, northern hardwood species, American beech (*Fagus grandifolia*), sugar maple (*Acer sacharum*), and yellow birch (*Betula alleghaniensis*), with balsam fir (*Abies balsamea*), red spruce (Picea rubens), and white birch (*Betula papyrifera var. cordifolia*) dominating areas with shallow-to-bedrock soils (Likens, 2013).

Despite the previous catchment-wide characterization of soils in WS3 as well-drained Spodosols, Bailey et al. (2014) found distinct variations in morphology and a broad range of drainage classes. These variants of podzols were found to be influenced by distinct shallow groundwater regimes (Gannon et al., 2014) and had substantial variation in carbon accumulation (Bailey et al., 2014), soil chemistry (Bourgault, Ross, Bailey, McGuire, & Gannon, in press), and landscape position (Gillin, Bailey, McGuire, & Prisley, 2015). Due to the functional implications of the distinct hydrologic regimes and carbon accumulation in the podzol variants, they were classified as hydropedological units by Gannon et al. (2014). In this study, we refer to these soils with distinct groundwater regimes and morphology as “soil groups.”

Typical podzols displayed expressions of E, Bhs, and Bs horizons, representative of the central concept of a podzol (Sauer et al., 2007) or Spodosols in the USDA Soil Taxonomy. Mean thickness of the Bhs horizon in typical podzols was 16 cm, and E horizons were relatively thin and discontinuous (Bourgault, Ross, & Bailey, 2015). Typical podzols had moderate amounts of secondary Al, Fe, and organic C associated with spodic materials, reflective of their vertical development and intermediate expression of the spodic horizon (Bourgault et al., in press). An example is the profile K9 in Figure 1. In contrast, some soil groups displayed profiles dominated by one pedogenic horizon (Bailey et al., 2014). Specifically, E, Bhs, and Bh podzols were named for a dominant horizon, reflecting a portion of the podzolization process dominant at that site. E and Bhs podzols (Figure 1: profiles N3 and N4, Figure 2) both have relatively thick E and Bhs horizons, respectively. This observation is hypothesized to be the result of the predominance of lateral eluviation in the E podzol, followed immediately downslope by the predominance of lateral illuviation in the Bhs podzol (Bailey et al., 2014; Sommer et al., 2000). The chemistry of the E and Bhs podzols reflected their morphology and proposed genesis in that E podzols had thick E horizons (usually >15 cm; Bourgault et al., 2015) with very low quantities of secondary Al, Fe, and spodic C (Bourgault et al., in press), and Bhs podzols had relatively thick Bhs horizons (mean thickness: 39 cm; Bourgault et al., 2015) with larger quantities of these elements (Bourgault et al., in press). Bh podzols (Figure 1: profiles K10 and H6, Figure 2), named for their relatively thick Bh horizon (mean thickness: 37 cm; Bourgault et al., 2015), are hypothesized to be zones of accumulation from upslope (Bailey et al., 2014) and had large quantities of secondary

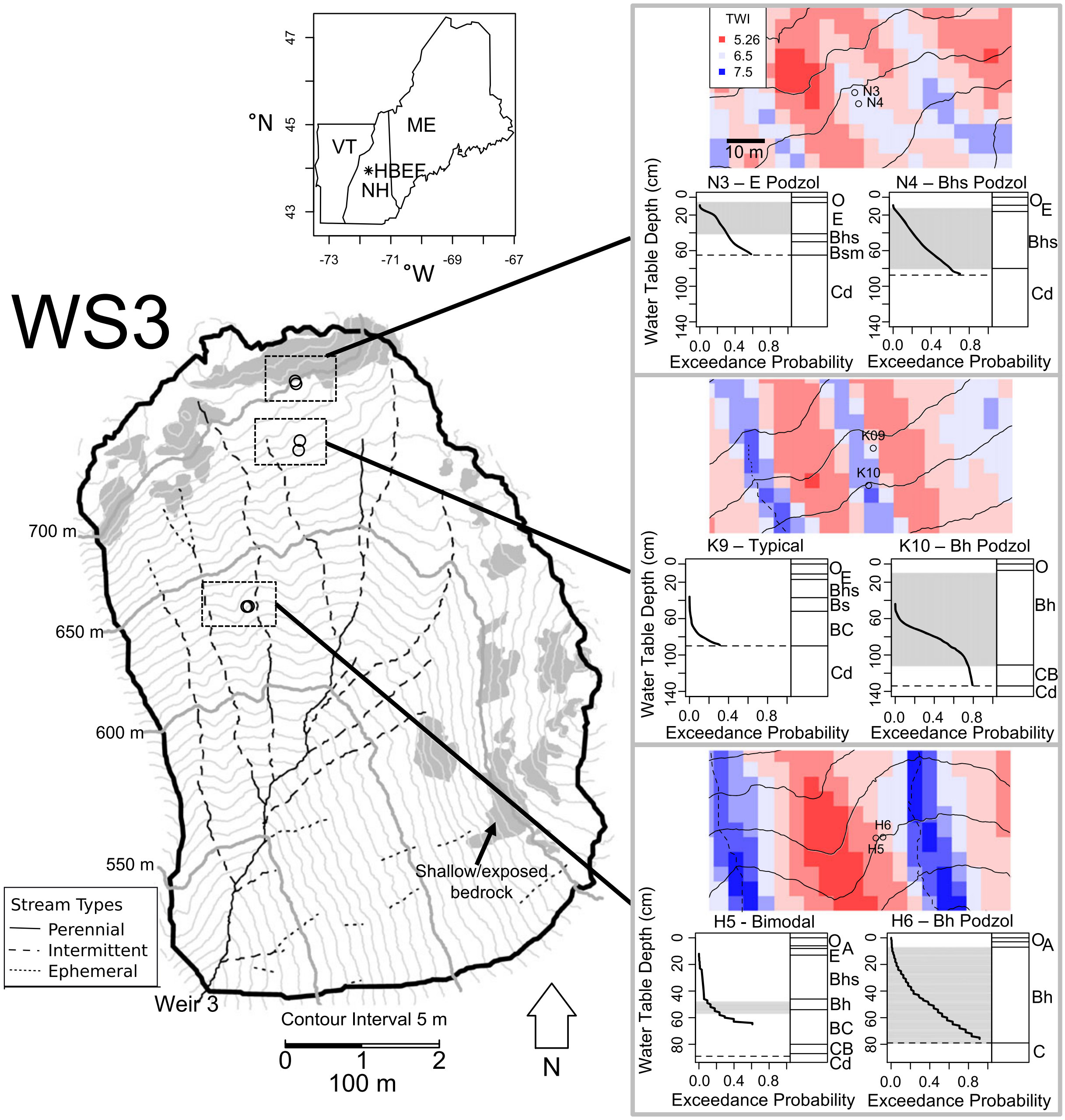

FIGURE 1 Map of watershed 3 (WS3), maps of study sites, study well empirical cumulative density functions (ECDFs), and soil horizons at study sites. An inset map of the location of Hubbard Brook Experimental Forest (HBEF) in northern New England is also included. In WS3, perennial, intermittent, and ephemeral streams are shown by solid, dashed, and dotted lines, respectively. Bedrock outcrops or bedrock under shallow soil are indicated by shaded grey areas. Study sites are indicated by circles on the map. Study areas are shown in detail to the right of the WS3 map. The detailed maps include 5 m contour intervals and downslope topographic wetness index (TWI). Below each of the detailed maps are ECDFs for the water level measurements at each site showing the probability of water levels at the site. The grey shaded portion of the ECDF corresponds with lateral horizons. Attached to the right of each of the ECDFs is the soil horizonation at the corresponding site

Al, Fe, and spodic C to support this hypothesis (Bourgault et al., in press). Gannon et al. (2014) separated Bh podzols into hillslope (Figure 1: profile K10, Figure 2) and near-stream (Figure 1: profile H6, Figure 2) Bh podzols based on distinct variations in water table regimes that corresponded with proximity to the stream network. Bimodal podzols were similar to typical podzols but with an additional Bh horizon at the base of the solum (Figure 1: profile H5, Figure 2). The chemical composition of bimodal podzols was similar to other laterally accumulating podzols (Bhs and Bh podzols; Bourgault et al., in press).

As described above, E, Bhs, Bh, and bimodal podzols were hypothesized by Bailey et al. (2014) to be developed at least partly from lateral podzolization and are therefore called "lateral soil groups" below. Typical podzols, however, were hypothesized to be the result of primarily vertical fluxes. Below, we refer to horizons that Bailey et al. (2014) hypothesized to be formed partly from lateral podzolization as "lateral" horizons. For example, the E horizon in an E podzol would be referred to as a "lateral E horizon." Such horizons are typically disproportionally thick relative to total soil depth compared to vertically developed podzols in the catchment.

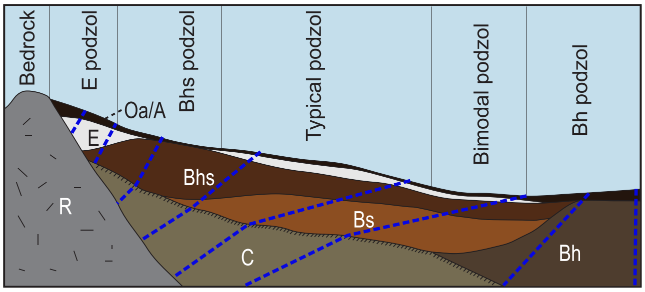

FIGURE 2 Soil schematic conceptual diagram modified from Bailey et al. (2014) showing soil horizonation along a typical sequence of soil groups in watershed 3 in baseflow conditions. Generalized unsaturated flow equipotential lines are shown by blue dashed lines. Moving down the slope, the lines of equipotential move from a condition with entirely lateral flow in the E and Bhs podzols to a primarily vertical flow in the typical podzol and then back to entirely lateral flow in the Bh podzol

3 | METHODS

3.1 | Field methods

This study is based on data collected from three intensive instrumentation sites in WS3 (Figure 1). Sites were chosen to represent characteristic transitions between soil groups in the catchment that we expected were the result of lateral fluxes of water in the solum. The transitions instrumented were an E–Bhs podzol, a typical-hillslope Bh podzol, and a bimodal-near-stream Bh podzol. At each of the three sites, several small reconnaissance pits were excavated by hand in order to locate the transition. Once the transition was located, pits were excavated on either side of the transition to either 10 cm into the C horizon or to bedrock. Pits were characterized based on pedogenic horizons and assigned to a soil group based on horizon type and thickness (Bailey et al., 2014).

After soil profile characterization, eight UMS T4e tensiometers (capable of measuring pressure heads from −8.7 to 10.2 m of H_2O) were installed at each site. Four tensiometers were installed in the two pits at each site: Two were installed just below the O horizon and two were installed near the bottom of the solum. In the bimodal-near-stream Bh and typical-hillslope Bh podzol pits tensiometers were installed into the upslope pit face, and in the E–Bhs podzol pits tensiometers were installed into the pit face orthogonal to the slope, due to a lack of space in the shallower soils. Tensiometers were connected to a Campbell Scientific, Inc. CR1000 datalogger and programmed to record at 10-min intervals. Each T4e recorded and subtracted atmospheric pressure.

At the E–Bhs and the typical-hillslope Bh podzol transitions, wells were installed at each soil pit. Wells were installed 10 cm into the C horizon or on top of bedrock, depending on which was encountered first. Washed, native sand was packed around the well screen, and the previously excavated soil was used to backfill the remainder of the pit. The installed wells were constructed of 3.18-cm SDR 21 PVC pipe and had a 31 cm screen length with 0.025-cm-wide lateral slots spaced 0.32 cm apart. Once installed, the wells were equipped with a 1.5-m Odyssey Water Level Logger, which measured capacitance along a Teflon-coated wire suspended in the well to determine water level. Water level loggers recorded data at 10-min intervals.

At the bimodal-near-stream Bh transition wells were not installed in the soil pits because of proximity to an existing well between the two sites. However, it was found that groundwater regimes often varied greatly between closely spaced wells in different HPUs, necessitating the comparison of water table dynamics at the two pits. Therefore, for the two pits at the bimodal-near-stream Bh site, a water level time series was created using the positive head measurements from the deepest tensiometer at each site. These water table measurements do not include water table that occurs between that tensiometer and the C horizon, but that distance was small (20.1 cm in the typical podzol and 1.85 cm in the near-stream Bh podzol).

The data for this study were collected from July 29, 2011, to April 1, 2012. Four storms were selected for event-based analysis: a summer storm (August 26, 2011), a fall storm (September 29, 2011), a winter storm (December 26, 2011), and a snowmelt event (March 7, 2012). The storms were selected to span a range of antecedent conditions, precipitation intensities/magnitudes, and rainfall/snowmelt combinations. The tensiometer data were used to estimate vertical hydraulic gradients. Water table records were used to compute saturation frequency at different soil depths and to compare water levels to vertical hydraulic gradients.

3.2 | Water table regimes

Water table was measured as depth from the soil surface to water table. Semi-permanent to permanent water tables likely existed deeper in the C horizon in WS3, but for the purposes of examining hydrologic regimes related to soil development, water tables in the C horizon were ignored. To examine the frequency with which water table exceeded certain depths in each of the soils studied, empirical cumulative density functions (ECDFs) were calculated for each well. ECDFs were plotted along with soil horizon depths in order to examine the frequency of saturation of each horizon.

3.3 | Vertical hydraulic gradient

The strength and direction of saturated and unsaturated flow through time determined by the vertical hydraulic gradient at each site as

$$i = -\frac{dh}{dz},$$

where i is the vertical hydraulic gradient and h is the hydraulic head at each tensiometer, calculated as the pressure head plus the elevation head relative to a survey benchmark used to determine the relative elevations of the tensiometers. dz is the vertical distance between the tensiometers. Positive vertical gradients denote an upward gradient, and negative gradients denote a downward gradient.

3.4 | Topography

Several topographic measures were calculated for each of the sites to examine relationships between topography and fluctuations of vertical hydraulic gradients. Topographic measures were calculated from a 5-m resolution, low-pass filtered, LiDAR-derived digital elevation model in

ArcMap Version 10.1 and the System for Automated Geoscientific Analyses (Conrad, 2011). Gillin, Bailey, McGuire, and Gannon (2015) found that the digital elevation model used for this analysis produced values for topographic measures most similar to field measurements. Distance from stream was calculated from a stream network derived from field observations of fluvial channels and streamflow duration (Figure 1) and Euclidean distance was calculated from each point to the nearest channel. Euclidian distance was used because this study focused primarily on subsurface water flow, which may not follow the same path as surface flow. Therefore, the Euclidian distance likely provided a measure with less uncertainty. Additionally, Euclidian distance sufficiently captures the differences in distance to the stream from the focus sites. Slope at each site was calculated using the maximum slope algorithm (Travis, Elsner, Iverson, & Johnson, 1975) and upslope accumulated area (UAA) was calculated with the multiple flow direction algorithm presented in Seibert and McGlynn (2007). Topographic wetness index (TWI) was calculated using the downslope index with d = 5 m and UAA as described in Hjerdt, McDonnell, Seibert, and Rodhe (2004) and shown to predict the locations of soil groups in WS3 by Gillin, Bailey, McGuire, and Prisley (2015). Site distance was the distance between the pit faces of the two pedons at each of the intensive sites and was measured in the field.

4 | RESULTS

4.1 | Topography and site locations

Both the E and Bhs podzols were much closer to exposed bedrock upslope of the sites compared to any other soils in this study at 5 and 12 m, respectively (Table 1). Therefore, a majority of the 6.2 m^2 UAA at the E podzol and 20.2 m^2 UAA at the Bhs podzol was predominantly bedrock outcrop or a region of shallow bedrock covered in thin organic or mineral soil. TWI increased by 1.2 at this site, from 6.7 at the E to 7.9 at the Bhs podzol. These two sites were also the farthest from a stream at 81 m (E podzol) and 74 m (Bhs podzol, Table 1). The depth to the C horizon at the site increased downslope from the E podzol (65 cm) to the Bhs podzol (80 cm).

The typical-hillslope Bh podzol site was much farther downslope from exposed or shallow bedrock at 74 and 83 m, and although closer to the stream network at 36 and 31 m, the site was still out of the influence of the riparian zone. UAA increased from 22 m^2 at the typical podzol to 102 m^2 at the Bh podzol and TWI increased by 1.6 from 7.6 to 9.2. Slope decreased from 0.28 at the typical podzol to 0.25 at the hillslope Bh podzol, and the pedons were 7.8 m apart (Table 1).

The bimodal-near-stream Bh podzol site was farthest from exposed bedrock at 149 and 146 m and closest to the stream network at 15 and 10 m, respectively. The UAA increased downslope from 4.3 to 7.6 m^2, the TWI increased from 5.8 to 6.5, and the slope decreased from 0.33 to 0.29 (Table 1). The two pedons at this site were also the closest to one another at 3 m.

4.2 | Water table regimes

The ECDFs in Figure 1 illustrate the frequency of soil saturation relative to soil profile horizonation. Paired with each ECDF is a description of the instrumented pedon. Horizons hypothesized to be formed by lateral (slope parallel) eluvial or illuvial processes driven by lateral water flux are highlighted. Not one of these highlighted horizons became saturated through the vertical extent of the horizon during the study period. Although the study only spans 2 years, they were the 6th and 9th wettest years in the 58-year precipitation record at HBEF (Campbell, 2016). Water tables were detected in portions of the highlighted horizons: 32% of the time in the E podzol, 65% in the Bhs podzol, 73% and 34% in the two Bh podzols (K10 and H6, respectively), and 10% in the bimodal podzol (Figure 1). However, none of these horizons became entirely saturated during the study period, with the exception of the thin Bh horizon at the bottom of the bimodal podzol. In the hillslope Bh podzol, water table was not observed during the study period in the top 33 cm of the highlighted horizon (Bh horizon, Figure 1).

The typical podzol, a soil developed under unsaturated vertical flow, had the least frequent water table at 40% of total time for the entire pedon. The highest recorded water table in the typical podzol was 40 cm from the surface (Figure 1).

4.3 | Vertical gradients

Figure 3 shows the distribution of vertical gradient for each site over the entire study period. The E–Bhs transition sites, N3 and N4, had the lowest magnitude vertical gradients, with median gradients of −0.11 for each (Figure 3). These two podzols also had gradient values closest to 0.

The bimodal podzol in the bimodal-near-stream Bh podzol transition had the strongest and most persistent downward vertical hydraulic gradient of any of the pits in the study (median = −0.55, standard deviation = 0.09; Figure 3). Three meters downslope in the

TABLE 1 Topographic metrics for each of the profiles at the focus sites

Site	ID	Soil group	Dist between pits (m)	UAA (m^2)	Slope	TWI	Dist to stream (m)	Dist to bedrock (m)
E-Bhs	N3	E	7.1	6.2	0.24	6.7	80.8	5.0
	N4	Bhs	7.1	20.2	0.24	7.9	73.9	12.1
Bimodal-Bh	H5	Bimodal	7.8	4.3	0.33	5.8	15.0	149.2
	H6	Bh	7.8	7.6	0.29	6.5	10.0	146.0
Typical-Bh	K09	Typical	2.9	21.5	0.28	7.6	36.1	74.3
	K10	Bh	2.9	102.0	0.25	9.2	31.6	83.8

Note. Pairs of sites are alternately shaded and unshaded. UAA = upslope accumulated area; slope = surface slope, TWI = topographic wetness index with a d parameter of 5; Dist to stream = Euclidean distance to the nearest stream; Dist to bedrock = Euclidean distance to the nearest upslope bedrock outcrop

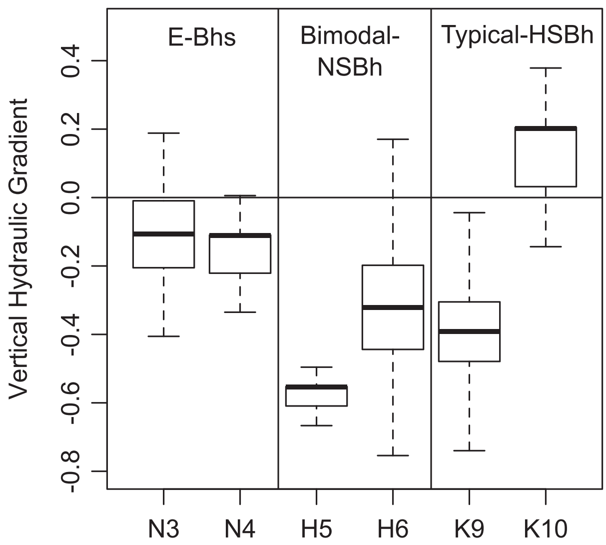

FIGURE 3 Boxplots of vertical hydraulic gradient measurements for the duration of the study period (from July 29, 2011 to April 1, 2012). Soil group names for each site are given at the top of each pair of boxes. Near-stream Bh is abbreviated NSBh, and hillslope Bh is abbreviated HSBh. Negative gradients are downward, positive gradients are upward, and zero indicates an absence of a vertical hydraulic gradient. Each boxplot is data from one pit (named on the *x* axis) and the paired boxes are the three study sites. The line in each box is the median, the top and bottom of the boxes are the boundaries of the interquartile range (IQR), and the whiskers are the first and third quantile plus or minus 1.5 times the IQR. Vertical lines divide study sites, which are labelled at the top of the plot

near-stream Bh podzol, vertical gradients were zero or upward for a small portion of the record and the median vertical gradient was −0.32 (Figure 3).

A downward vertical gradient was measured in the typical podzol in the typical-hillslope Bh podzol pair throughout the majority of the study period (Figure 3, median = −0.39). However, downslope in the hillslope Bh podzol, vertical hydraulic gradients were positive (median = 0.20) indicating an upward flux for a majority of the study period (Figure 3).

Vertical gradients were also shown as time series on an event basis. This was done to examine the consistency of saturated and unsaturated responses, to characterize the vertical fluxes during events, and to examine the interplay between water table fluctuation above the C horizon and vertical gradients. As detailed in Section 3.1, the four events shown were chosen to represent a variety of conditions.

The E and Bhs podzols had consistent vertical gradients just under zero (Figure 4: E–H, M–P). The E podzol vertical gradient remained near zero even when water table rose above the C horizon into the solum (Figure 4: E–H, M–P). Downslope in the Bhs podzol, however, a downward vertical gradient occurred briefly, concurrent with water table rise into the solum (Figure 4: E–H, M–P).

The two Bh podzols had vertical gradients just below or alternating below and above zero (K10; Figure 5: M–P). The vertical gradient observed in the hillslope Bh podzol was consistently close to zero, even when water table rose into the solum (Figure 5: M–P). Brief, weakly negative (downward) vertical gradients preceding water table rise were observed in the summer and winter storms (Figure 4: M and O). In the near-stream Bh podzol vertical gradient was downward before water table rise, briefly strongly negative (downward) concurrent with rise, and then close to zero during water table recession during the summer, fall, and winter storms (Figure 6: M–O). A similar pattern was observed during snowmelt, but the vertical gradient was not as close to zero after water table rise as in the other three storms (Figure 6: P).

The bimodal and typical podzols both had stronger downward vertical gradients, approximately −0.5 (Figure 6: E–H, Figure 5: E–H). The bimodal podzol had a negative (downward) peak in vertical gradient preceding water table rise into the solum for all three events where water table was observed (Figure 6: E–G). The typical podzol had a negative (downward) vertical gradient peak in the summer and fall storms (Figure 5: E and F) but had a small positive (upward) peak preceding the winter storm water table incursion (Figure 5: G).

5 | DISCUSSION

5.1 | Evidence of unsaturated lateral flow

Unsaturated lateral flow has been hypothesized to occur on hillslopes as a result of multiple conditions. For instance, anisotropy or layering of soils with different hydraulic conductivities can refract flow lines away from vertical (Cabral et al., 1992; McCord et al., 1991; Miyazaki, 1988; Zaslavsky & Rogowski, 1969). The hydraulic conditions immediately after cessation of rainfall can also cause lateral unsaturated flow, as a no-flow boundary at the surface results in hydraulic head contours shifting to perpendicular to the surface (Jackson, 1992; Sinai & Dirksen, 2006). Finally, drying of soils can shift flow directions towards lateral, as the lack of input from above causes downward hydraulic gradients to disappear as the soil dries (Lu, Kaya, & Godt, 2011; Lv et al., 2013; Pan, Warrick, & Wierenga, 1997).

Although we did not address the specific cause in this study, we identified periods where lateral unsaturated flow occurred as presented by Weyman (1973): On a hillslope where unsaturated lateral flow was dominant, equipotential contours are oriented perpendicular to the ground surface. Therefore, we considered times when measurements of soil water potential at two depths in the same soil profile were close to or equal and the upper tensiometer position was not saturated to be indicative of lateral unsaturated flow downslope through the soil matrix. Figure 2 illustrates this, showing equipotential lines overlain on the soil catena model developed at this site by Bailey et al. (2014). Therefore, we propose that lateral unsaturated flow occurred frequently in the E–Bhs podzol pair (Figures 2-4) and the hillslope Bh podzol (Figures 2, 3, and 5). This pattern of lateral versus vertical unsaturated flow throughout a hillslope catena is shown in Figure 2.

Despite having similar horizonation to the hillslope Bh podzol, unsaturated lateral flux did not dominate in the near-stream Bh podzol. This site had zero hydraulic gradient for a portion of the record (Figures 3 and 6), but unsaturated lateral flux appeared to be far less prevalent than at the hillslope Bh podzol. We propose that this was caused by the landscape position of near-stream Bh podzols. The hillslope Bh

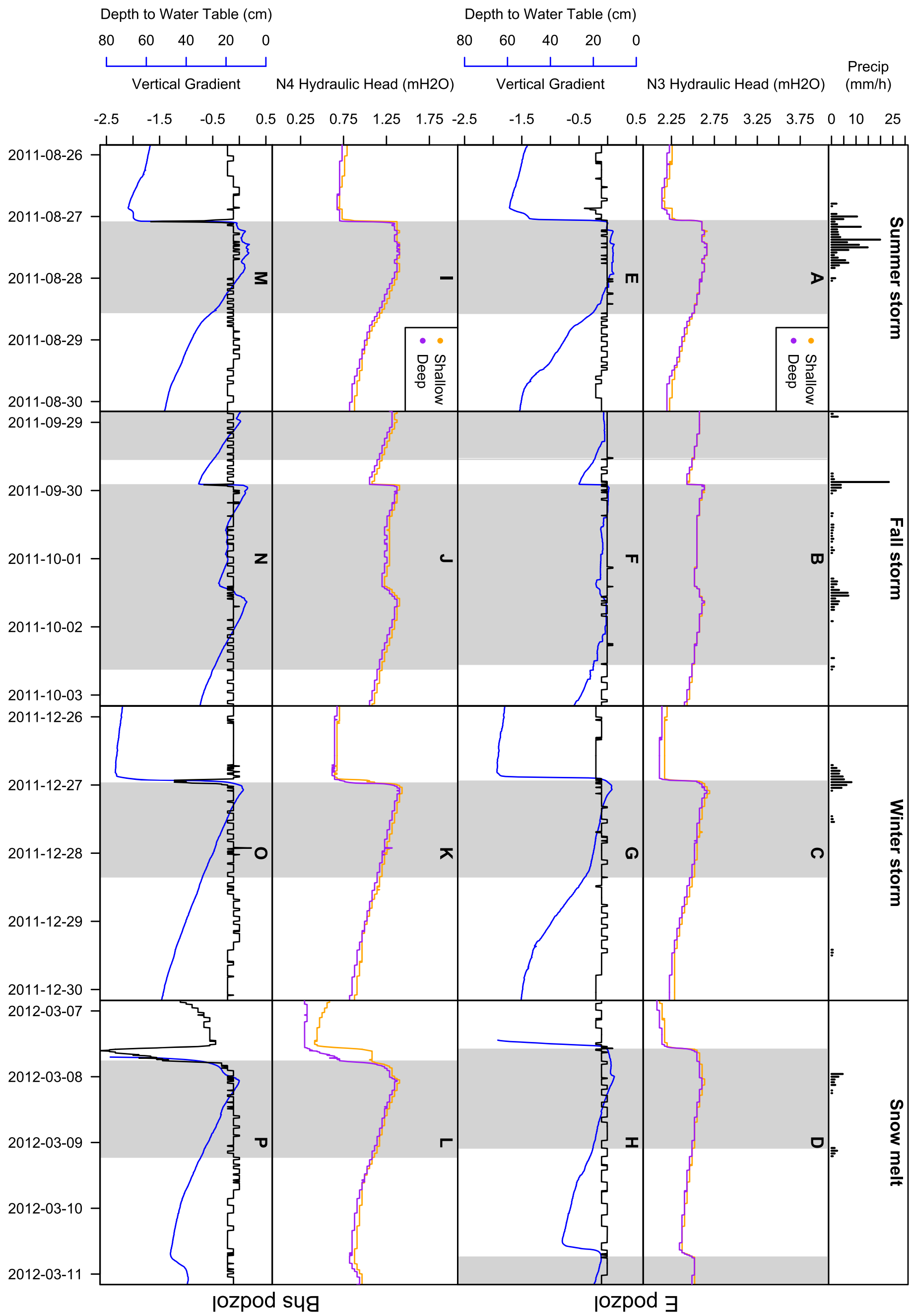

FIGURE 4 Precipitation, total head from tensiometers, vertical hydraulic gradient from tensiometers, and depth to water table are shown for the E (N3)–Bhs (N4) transition site for four events: A summer storm (8/26/2011), a fall storm (9/29/2011), a winter storm (12/26/2011), and snow melt (3/7/2012). The shaded times indicate that the upper tensiometer recorded saturation. In plots showing hydraulic gradient (A–D and I–L), the shallow and deep tensiometer records are coloured orange and purple, respectively. In the plots showing water table and hydraulic gradient (E–H and M–P), the blue line is water table and the black line is vertical gradient

podzol K10 has a UAA of 102 m^2, and the near-stream Bh podzol has a UAA of 7.6 m^2, because it was just below a ridge (Figure 1). Likewise, the smaller contributing area to H6 results in a smaller TWI. Despite being only 10 m from the stream, H6 had a TWI of 6.5 compared to 9.2 at the hillslope Bh podzol K10. The considerably smaller upslope area at H6 may have resulted in lower magnitude hydrologic fluxes from upslope, leading to less unsaturated lateral flux. However, due to its proximity to the stream, the podzol may have had more frequent saturation or wetting from the direction of the stream or down-valley flow. This lack of downslope unsaturated flux from a small upslope area would also explain the lower magnitude gradients in the typical podzol K9 (Figure 3, UAA = 22 m^2) compared to those in the bimodal podzol H5 (Figure 3, UAA = 4.3 m^2).

Other observations from this study also suggest the occurrence of unsaturated lateral fluxes in the soil matrix. Lateral soil horizons, such as unusually thick E, Bhs, (Bailey et al., 2014; Sommer et al., 2000), and Bh horizons (Bailey et al., 2014; Jankowski, 2013), occur above the extent of water table influence most of the time at these sites (Figure 1). Although infrequent events larger than those observed in this study may saturate these horizons, the lack of frequent lateral saturated fluxes suggests that an alternative mechanism is responsible for the formation of these disproportionately thick horizons. Unsaturated

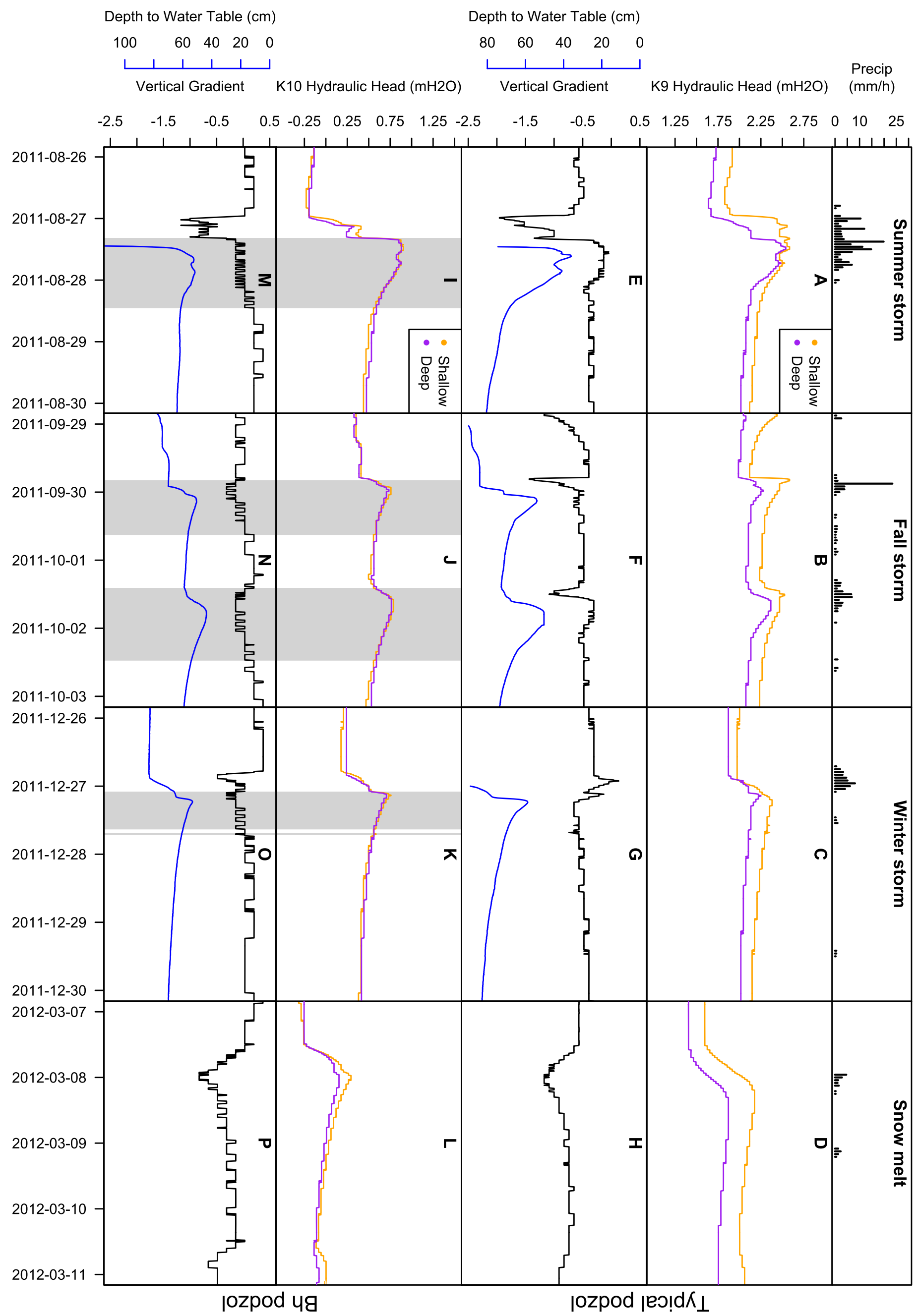

FIGURE 5 Precipitation, total head from tensiometers, vertical hydraulic gradient from tensiometers, and depth to water table are shown for the typical (K9) to Bh (K10) transition site for four events: A summer storm (8/26/2011), a fall storm (9/29/2011), a winter storm (12/26/2011), and snow melt (3/7/2012). The shaded times indicate that the upper tensiometer recorded saturation. In plots showing hydraulic gradient (A–D and I–L), the shallow and deep tensiometer records are coloured orange and purple, respectively. In the plots showing water table and hydraulic gradient (E–H and M–P), the blue line is water table and the black line is vertical gradient

lateral water flux could be partly responsible for the development of these horizons above the influence of frequent saturation. Therefore, anomalously thick E, Bhs, and Bh horizons above the maximum extent of water table in the solum may be an indication of the presence of lateral unsaturated flow.

5.2 | Implications of unsaturated lateral flow: Soil development

Unsaturated lateral flow provides a potential mechanism for the variations in soil formation observed in WS3. Sommer et al. (2000) identified similar patterns in soil formation, where podzol formation occurs laterally along a hillslope instead of vertically, calling it lateral podzolization. The proposed mechanisms for similar patterns are mobilization of spodic material by unsaturated water flux and subsequent downslope immobilization (Do Nascimento et al., 2008; Sommer et al., 2001; Waroszewski et al., 2015). However, this lateral movement of water in the unsaturated zone has not been measured concurrently with lateral podzolization. Bailey et al. (2014) identified the same patterns in WS3 and identified differences in water table regimes that were consistent with some soil groups experiencing greater and more frequent water flux. These differences were found to be consistent

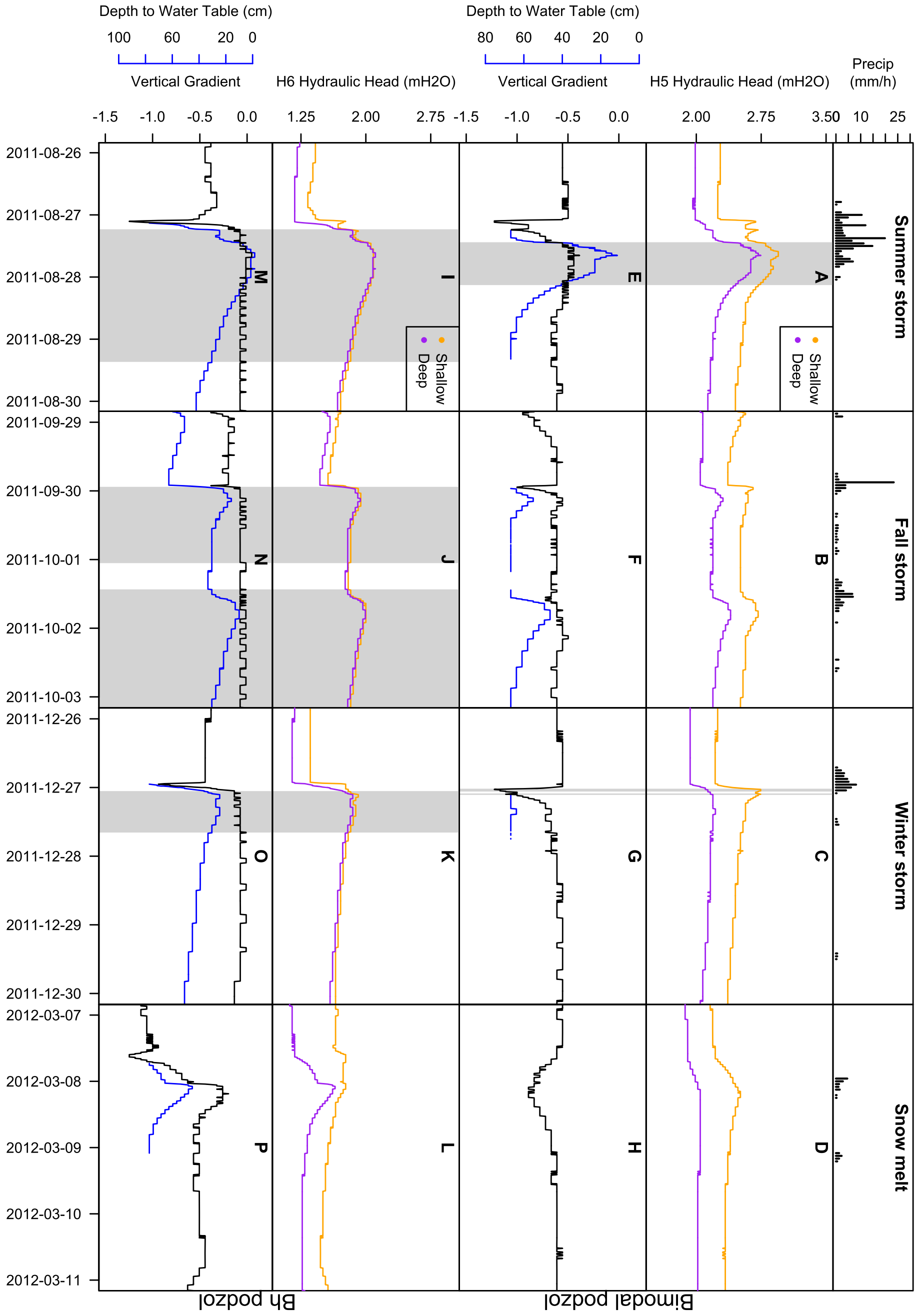

FIGURE 6 Precipitation, total head from tensiometers, vertical hydraulic gradient from tensiometers, and depth to water table (calculated from positive pressure head at tensiometers at this site) are shown for the bimodal (H5) to Bh (H6) transition site for four events: A summer storm (8/26/2011), a fall storm (9/29/2011), a winter storm (12/26/2011), and snow melt (3/7/2012). The shaded times indicate that the upper tensiometer recorded saturation. In plots showing hydraulic gradient (A–D and I–L) the shallow and deep tensiometer records are coloured orange and purple, respectively. In the plots showing water table and hydraulic gradient (E–H and M–P) the blue line is water table and the black line is vertical gradient

among podzols in Gannon et al. (2014). However, as shown in Figure 1, water tables did not occur high enough in soil profiles during this study to explain all observed variations, despite the study taking place in a relatively wet period. Observations of unsaturated lateral flow may provide a way to link the hypotheses of Sommer et al. (2000) with the observed variations in soil morphology in Bailey et al. (2014).

Unsaturated flow may play a role in the lateral development of soils, as described in a companion study by Bourgault et al. (2015). For soils in the same watershed (WS3), scanning electron microscope images of soil thin sections and soil extract chemistry were examined for evidence of vertical and lateral translocation within and between soil groups. Soil thin sections revealed that vertically developed horizons had a crumb-like morphology, with amorphous organometallic complexes (AOCs) forming pellet-like masses, resulting in higher pore space and higher AOC to mineral ratios. Laterally developed horizons, however, had microstructure that was less defined and more in-filled, with less pore space and lower AOC to mineral ratios. AOC in laterally developed horizons were also found to have lower iron and carbon concentrations but higher concentrations of the more mobile aluminium and manganese than the vertically developed horizons.

The detection of lateral unsaturated flow in certain soil groups helps explain the morphological and chemical observations of Bourgault et al. (2015). In the typical-bimodal-Bh podzol transition, Bourgault et al. (2015) proposed that either the transport of soil solution or the physical movement of colloidal AOCs was responsible for the changes in soil chemistry and micro-morphology. This description of lateral translocation is consistent with the occurrence of lateral unsaturated flow, especially in horizons where water table was not detected. Similarly, in the E–Bhs podzol pair, lateral unsaturated fluxes may be responsible for mobilizing AOCs from the O horizon (including areas upslope of the E podzol with bedrock overlain by thin organic horizons) in solution as dissolved organic carbon (DOC) and translocating it downslope to the Bhs podzol (Bourgault et al., 2015). This is consistent with the results from Gannon, Bailey, McGuire, and Shanley (2015), who found the highest DOC concentrations in groundwater and soil water in E and Bhs podzols. In the bimodal-Bh and typical-Bh podzol pairs, lateral unsaturated flow from water draining from upslope typical or bimodal podzols may translocate soluble or solid phase AOCs to Bh podzols.

It is important to consider the possibility that these morphological and chemical characteristics may be relict features that developed in a previous wetter climate that led to more frequent saturation of the soils in WS3. However, similar downslope translocation of AOCs was observed by Jankowski (2013) in a sand dune landscape where water table influence was extremely unlikely, providing further evidence that these processes can occur in the absence of saturation. Therefore, the possibility that these soil-forming processes can occur above observed periodic water tables by way of lateral unsaturated fluxes under current climatic conditions cannot be rejected. Finally, if lateral unsaturated flux was detected only during dry conditions, it would be less likely that it could be a factor in soil formation processes, due to the much lower hydraulic conductivities in drier soil. However, our analysis showed that unsaturated lateral flux occurred during the majority of the monitoring period, across wet and dry conditions, which suggests that these fluxes are more likely to be relevant to pedogenic processes such as lateral podzolization.

5.3 | Implications of unsaturated lateral flow: Stream water chemistry

Unsaturated lateral flow is not a primary stormflow generation mechanism due to the much lower hydraulic conductivities of soils during unsaturated conditions (Anderson & Burt, 1978). Although these flow rates may be unimportant to water transport to the stream network during stormflow, they may be important in explaining the spatial distribution of stream water chemistry. Bishop, Seibert, Köhler, and Laudon (2004) described how solutes can be quickly mobilized to the stream network by water tables rising into the unsaturated zone, mobilizing the water and solutes therein. If unsaturated lateral flows translocate AOCs downslope to zones of accumulation, they may move material to regions that become source areas with the addition of water from event-timescale water table rise. Furthermore, if lateral translocation can move solutes downslope to pedons or horizons that infrequently experience water table, it may be an important mechanism for the storage of elements in the landscape.

These soil-forming processes may therefore offer an explanation for the patterns in stream water chemistry observed in Zimmer, Bailey, McGuire, and Bullen (2013). Once catchment storage exceeds the threshold necessary for water table rise in these podzols (Gannon et al., 2014), the areas close enough to stream channels or in connection with streams through preferential flowpaths will contribute to streamflow while mobilizing unsaturated zone solutes. If hydrologic conditions result in contributing areas expanding into zones of accumulation, stored elements may be mobilized. This could then aid in explaining the varying longitudinal patterns and high concentrations of solutes such as DOC (Gannon et al., 2015) in stream water near sites where such gradients in soils are present.

6 | CONCLUSIONS

In this study, we examined pressure head and water table records for three sites containing six soil groups or hydropedological units in WS3 at the Hubbard Brook Experimental Forest. We inferred both persistent and event-based unsaturated lateral flow in four of six soil groups. These unsaturated lateral flows may be at least partially responsible for soil development contrasts between soil groups, above the highest detected water tables. Furthermore, these unsaturated lateral flows may be partly responsible for concentrating elements in soil groups that act as zones of accumulation. Saturation of these zones may create hotspots that deliver water with distinct chemistry to the stream, whereas lack of saturation of these zones may result in long-term storage of elements in some soil groups.

Although this study examines just WS3 at the Hubbard Brook Experimental Forest, the identification of these processes in other locations suggests that they are more broadly relevant. Villars et al. (2015) documented similar patterns of soil morphology in Vermont, USA, which they interpret as evidence for hydrologically driven lateral soil formation. Other examples, with similar interpretation, have been reported in Germany (Sommer et al., 2000, 2001) and Poland (Jankowski, 2013), although the present study is the only one of these to provide direct hydrologic observations. Strong colour and carbon-content contrasts between soil horizons may aid the detection of this phenomenon in podzolized landscapes. However, this feedback between hillslope hydrologic processes and lateral soil development is likely not limited to podzolized landscapes and potentially occurs in steep upland landscapes where other soil-forming processes are dominant. Future studies might use hydrologic monitoring to test this hypothesis in other regions.

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