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Key Points:

- Soil horization is indicative of distinct water table fluctuations
- Threshold storage-discharge relationships vary among hypopedological soil units
- Hypopedological units describe the spatial distribution of runoff source areas

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Organizing groundwater regimes and response thresholds by soils: A framework for understanding runoff generation in a headwater catchment

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Abstract A network of shallow groundwater wells in a headwater catchment at the Hubbard Brook Experimental Forest in New Hampshire, U.S. was used to investigate the hydrologic behavior of five distinct soil morphological units. The soil morphological units were hypothesized to be indicative of distinct water table regimes. Water table fluctuations in the wells were characterized by their median and interquartile range of depth, proportion of time water table was present in the solum, and storage-discharge behavior of subsurface flow. Statistically significant differences in median, interquartile range, and presence of water table were detected among soil units. Threshold responses were identified in storage-discharge relationships of subsurface flow, with thresholds varying among soil units. These results suggest that soil horization is indicative of distinct groundwater flow regimes. The spatial distribution of water table across the catchment showed variably connected/disconnected active areas of runoff generation in the solum. The spatial distribution of water table and therefore areas contributing to stormflow is complex and changes depending on catchment storage.

1. Introduction

The spatial distribution of soil moisture and depth to water table throughout a catchment are critical components in any attempt to understand streamflow generation [Freeze, 1972; Sidle *et al.*, 2000; Western *et al.*, 1999]. Water table fluctuations are often studied in order to describe runoff generation processes [Bachmair and Weiler, 2012; Sklash and Farvolden, 1979; Tromp-van Meerveld and McDonnell, 2006]. An improved understanding of where and when water tables occur in a headwater catchment would therefore be a valuable tool to help understand runoff generation and transport at the catchment scale.

Authors have posited several controls governing the spatial and temporal distributions of water tables, including riparian morphology and soil hydrologic characteristics [Burt *et al.*, 2002; Buttle *et al.*, 2004; McGlynn *et al.*, 2004], hillslope topography [Anderson and Burt, 1978; Beven and Kirkby, 1979; Detty and McGuire, 2010a; Dhakal and Sullivan, 2014; Penna *et al.*, 2014], and/or the subsurface topography of confining layers such as bedrock [Ali *et al.*, 2011; Freer *et al.*, 2002; Tromp-van Meerveld and McDonnell, 2006], dense glacial till [Hutchinson and Moore, 2000; Rodhe and Seibert, 2011], fragipans [Gburek *et al.*, 2006; McDaniel *et al.*, 2008], or other layers of contrasting conductivities [Rulon *et al.*, 1985]. Mapping the extent of these features may assist in the prediction of potential saturation regions in the subsurface given an amount of antecedent moisture and precipitation. However, bedrock, till, or fragipan hydrogeologic characteristics and topographies are not easily mapped or predicted, making understanding their importance to spatial runoff generation processes challenging.

Even when predictions of saturated regions in a catchment are possible, they indicate little about runoff generation [Bracken and Croke, 2007]. As described in Ambroise [2004], a distinction must be drawn between active and contributing areas. An active area may be any saturated area in the catchment. Contributing areas imply hydrologic connection to the stream with sufficiently high hydraulic conductivity to produce runoff at the catchment outlet at the time scale of storm events. Hydrologic connectivity and flux are higher

in saturated or near-saturated soil than in soil with lower water content. Therefore, while any saturated area may be considered an active area in terms of subsurface flow, if it is not connected hydraulically to the stream at the event time scale, it is not considered a contributing area. Threshold responses (defined as the absence of a response in the dependent variable until a threshold value of the independent variable is exceeded) [Zehe and Sivapalan, 2009] of water table rise in soil profiles to precipitation and antecedent wetness describe the function of distinct hydrologic regimes, such as whether or not areas are likely to be active and/or contributing areas under certain conditions. Threshold responses in catchment discharge have been identified in a variety of landscapes and are a promising tool for deciphering catchment hydrological processes [e.g., Detty and McGuire, 2010b; Penna et al., 2011, 2014]. Additionally, threshold subsurface flow responses have also been identified [Ali et al., 2013]. When compared spatially throughout a catchment, threshold water table responses may offer insight into how water tables develop and contribute to streamflow. This may offer insights into how shallow water tables throughout a catchment relate to discharge and spatial and temporal variations in stream water chemistry.

Spatial and temporal variations in the stream water chemistry of headwater catchments have been observed at a variety of scales [Likens and Buso, 2006; Zimmer et al., 2013]. Contrasting longitudinal patterns in stream water chemistry have been observed within branches of the same stream even in small headwater catchments [Asano et al., 2009; Palmer et al., 2005; Zimmer et al., 2013]. In scenarios where bedrock, soil parent material, and vegetation are similar across the stream network, other factors must be the cause of such variation. One such potential cause of these observed variations is differing spatial distributions of water tables in subcatchments that suggest distinct active flow paths unequally distributed throughout the catchment [O'Loughlin, 1981]. Saturated areas are thought to be hot spots for biogeochemical activity [McClain et al., 2003], regardless of their connection to the stream. Distinct chemical signatures developed in these areas due to variations in redox conditions or water contact time with subsurface materials, may therefore be relevant to stream water chemistry at an event time scale and/or beyond [Zimmer et al., 2013]. Thus, identifying response thresholds, characteristic water table behavior, and the spatial distribution of contributing and noncontributing areas is vital to understanding streamflow generation and regulation of solute composition in headwater catchments.

Several studies have identified hydrological controls on soil development [Bailey et al., 2014; Park and Burt, 2002; Zaslavsky and Rogowski, 1969], expanding the classic soil formation factors of Jenny [1941], which only indirectly identifies hydrologic influences by way of climate and topography. For instance, intermittently saturated soils have been shown to contain redoximorphic features and elevated carbon accumulation [He et al., 2003; Moore et al., 1993; Rabenhorst and Parikh, 2000]. Likewise, several studies have identified lateral throughflow as a control on soil development, detecting patterns of Fe and Mn depletion, and deposition indicative of translocation downslope, not only vertically in a soil profile [McDaniel et al., 1992; Park and Burt, 2002; Sommer et al., 2000].

In this study, we utilized five soil morphological units that have been recognized in watershed 3 (WS3) at the Hubbard Brook Experimental Forest (HBEF), U.S. [Bailey et al., 2014; Zimmer et al., 2013]. Soils were grouped based on the characteristics of the solum. The solum is the soil to the base of the B horizon. Compared to the C horizon, it is relatively weathered, with greater development of soil structure (i.e., particle aggregation), a lower bulk density, and varying carbon accumulation depending on thickness and type of B horizons. Additionally, it is approximately equivalent to the rooting zone. In contrast, the underlying C horizon is less affected by soil forming processes, reflecting geologic properties of relatively unaltered parent material. Varying depths and thicknesses of diagnostic soil horizons in the solum, hypothesized to be the result of differences in hydrologic flow paths, have been identified at HBEF and shown to occur along topographic sequences. Using a well network to monitor groundwater responses in the solum, we compared the water table dynamics and estimated subsurface flow rates under different storage regimes across soil units. The primary questions addressed in this study are: (1) Can soil units defined by morphological differences be used to indicate specific solum groundwater dynamics and/or the spatial distribution of solum groundwater in a headwater catchment? (2) Can insights from examining solum groundwater regimes in different soils provide information about runoff generation and contributing/recharge areas in a catchment?

2. Site Description

This study was carried out at the Hubbard Brook Experimental Forest, in WS3, the hydrologic reference watershed for a series of paired watershed experiments [Hornbeck, 1973, 1975; Hornbeck et al., 1970; Likens

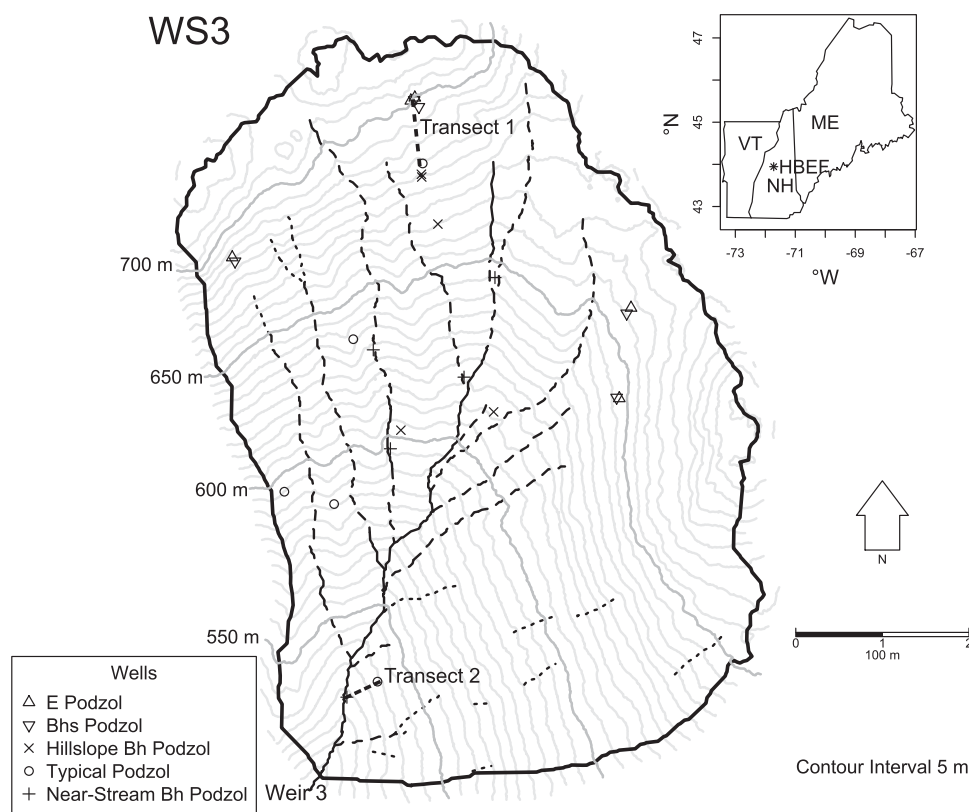


Figure 1. Map of WS3. Perennial, intermittent, and ephemeral streams are shown by solid, dashed, and dotted lines, respectively. Shallow groundwater wells are indicated by symbols on the map. Soil morphological units are indicated by different shaped symbols. Transect 1 (Figure 8) and transect 2 (Figure 9) are shown by bold, dashed lines. The inset map indicates the location of HBEF in northern New England.

et al., 1970] (Figure 1). Hubbard Brook is located near North Woodstock, NH, U.S., in the White Mountain National Forest. The climate is humid continental, with average January and July temperatures of -9°C and 18°C , respectively. Precipitation is evenly distributed throughout the year with about a quarter to a third of the 1400 mm annual precipitation occurring as snow [Bailey et al., 2003].

Watershed 3 is 42 ha, south facing, steep (average slope of 28%), and ranges in elevation from 527 to 732 m [Likens, 2013]. The catchment is forested with mature, northern hardwood species, American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*). On shallow to bedrock areas, balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), and white birch (*Betula papyrifera* var. *cordifolia*) dominate [Likens, 2013].

Watershed 3 is underlain by sillimanite-grade pelitic schist and calc-silicate granulite of the Silurian Rangeley Formation. The soil parent materials are ablation and basal tills of varying thickness, texture, and hydraulic conductivity deposited during the late Wisconsin glacial period [Bailey et al., 2014]. The major soil type is a podzol with a sandy loam texture, which has been characterized as a well-drained Haplorthod with 0.5 m average solum thickness [Likens, 2013]. However, distinct variations of soil horization and a broader range of drainage classes have been identified in WS3, and are hypothesized to be the result of variations in soil forming processes driven by groundwater regime. These variations have been grouped into soil morphological units [Bailey et al., 2014] named according to their dominant pedogenic horizon. For example, the solum of an E podzol is dominated by an E horizon, a leached layer that is highly weathered and has a low carbon content. Bhs and Bh podzols are similarly dominated by Bhs and Bh horizons, respectively, with higher carbon content. The exceptions are the typical podzol, which has horization more typical of the classic concept of a Spodosol, with moderate expression of both E and B horizons, and the bimodal podzol, which is characterized by an anomalous Bh horizon at the base of the solum in an otherwise typical podzol. A conceptual model of these soil units along an idealized hillslope

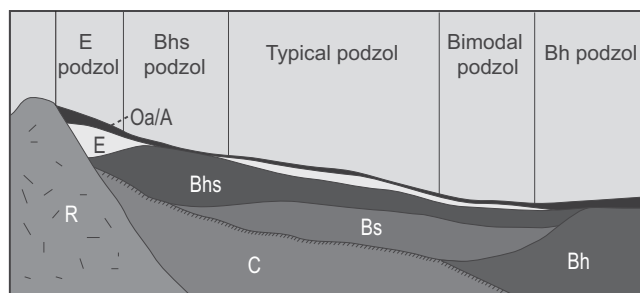


Figure 2. Schematic conceptual diagram showing soil horization along a typical soil unit sequence [Bailey et al., 2014]. Mean depth to C horizon is 70 cm. Vertical scale is exaggerated. E, Bhs, Bh podzols, and the Bh horizon of Bimodal podzols were hypothesized to be indicative of frequent lateral flux in the solum. Typical podzols and the portion of bimodal podzols above the Bh horizon were hypothesized to be indicative of primarily vertical flux.

is shown in Figure 2. E, Bhs, and Bh podzols were hypothesized by Bailey et al. [2014] to be indicative of the lateral translocation of spodic materials downslope (lateral podzolization), a process similar to that identified by Sommer et al. [2000]. Upon initial analysis of existing wells in Bh podzols from Detty and McGuire [2010a] and Bailey et al. [2014], differences were identified in water table fluctuations leading to the separation of Bh podzols into near-stream Bh podzols and hillslope Bh podzols. Bimodal podzols were not included in this analysis as they are considered to be a transi-

tional soil unit between typical podzols and Bh podzols, occupying a small percentage of the catchment compared to other units.

3. Methods

3.1. Well Network

This study is based on data from a shallow groundwater well network spatially distributed throughout WS3 (Figure 1). The network of 25 wells was designed to monitor water table dynamics across different soil units throughout the catchment and is a composite of wells established by previous studies and wells installed specifically for this analysis. Seven wells installed by Detty and McGuire [2010a, 2010b] had soil morphology characterized in adjacent soil pits by Bailey et al. [2014]. An additional seven wells with detailed soil characterization were installed by Bailey et al. [2014] in order to have three wells in each soil unit identified in WS3. In this study, 11 more wells were installed and soils were characterized, in order to bring the total number of wells in each soil unit to five, including five wells each in Bh podzols found in near-stream areas as well as other settings more distant from streams. Wells from previous studies have associated multiyear data sets that were used to test the representativeness of the time period of this study (August 2011 to August 2012).

At each well, a small soil pit was hand excavated to ~10 cm into the C horizon (40–100 cm; 65 cm average) and pedogenic horizons were described. Each soil profile was assigned to one of the categories based on horizon presence and thickness. Wells were constructed of standard dimension ratio (SDR) 21 PVC pipe with a 3.76 cm inner diameter and a 31 cm screen length consisting of 0.025 cm width lateral slots with 0.32 cm spacing between slots. Wells were either installed with a 10 cm hand auger upslope of the characterization pit or in the backfilled pit. The auger was used to bore 10 cm into the C horizon so that the base of the well screen was inserted into the C horizon. Wells were installed on top of bedrock in the cases where a C horizon was not present. Local washed sand was used to backfill to a depth just above the screened interval, and then native soil was backfilled and carefully compacted above the screened interval to the soil surface. Each well was equipped with a 1.5 m Odyssey Water Level Logger that used capacitance measured along a Teflon coated wire suspended in the well to determine water level (Dataflow Systems Pty Ltd) recorded at 10 min intervals. Data were available for the 25 wells used in this study for the period of August 2011 to August 2012; however, several wells had records extending to August 2007. To be sure this data period was not anomalous, and therefore suitable to use to characterize water table regimes in soil units, we compared the water table data from year to year where possible. Because of the large number of water table measurements per year ($n > 50,000$), examining statistical tests for differences in the distributions of water table measurements will always detect differences even when the distributions are very similar [Gardner and Altman, 1986]. Therefore, similar to the analyses used in this study, the median and interquartile range (IQR) was used to examine the water table records for multiple years. The median and IQR were within 1.5 cm of previous years in all seven of the wells with up to 3 years of water table data. This suggests the period of data used in this analysis was not anomalous.

Topographic metrics for each well were derived from a low-pass filtered, 5 m resolution, LiDAR-derived digital elevation model (DEM). This DEM was determined by Gillin [2013] to produce topographic metrics most similar to field-measured values. Upslope accumulated area (UAA) was calculated using a multiple flow direction algorithm defined in Seibert and McGlynn [2007]. The maximum slope algorithm [Travis et al., 1975] was used to calculate slope. Distance from stream was calculated as the Euclidean distance to the nearest intermittent or perennial stream channel on a stream network mapped from observations of streamflow and evidence of fluvial channel development (Figure 1).

3.2. Water Table Dynamics

In an effort to quantify differences observed in the water table dynamics of wells in different soil units, three metrics describing water table fluctuation in the solum were examined: median water level, interquartile range of water level, and percent time water table existed above the C horizon.

The distribution of water level measurements was defined as all data where water level was recorded to be anywhere within the solum. While permanent water tables undoubtedly existed at depth within the C horizon, Detty and McGuire [2010a] found that the upper C horizon saturated quickly following events and saturated hydraulic conductivities above the subsoil were higher. This led to the conclusion that water tables in the solum may develop on top of the C horizon [Detty and McGuire, 2010a]. We acknowledge that solum water tables likely rise up from the C horizon in some settings and perch on top of the C horizon in others. However, because this study focused only on solum water table dynamics, the processes responsible for producing water tables at different sites were not investigated. Therefore, percent time of water table existence was defined as the number of measurements where the record was above the subsoil (i.e., above the top of the C horizon) divided by the total number of measurements in the record times 100. For calculation of the interquartile range and median of each water table record, water table measurements were normalized to range from 0 (ground surface) to 100 (base of solum), in order to more uniformly compare all well records. Records of water level below the C horizon were categorized as nondetects; therefore, a median groundwater level was more appropriate than a mean. Differences between metrics among soil units were tested for statistical significance using the Kruskal-Wallis analysis of variance and Tukey's honestly significant difference test at a significance level of 0.05.

3.3. Groundwater Flux

Groundwater flow was estimated at each well in order to make comparisons among the responses of different soil units. We modeled total catchment storage from 20 February 2011 to 30 June 2012 and evaluated well response for different levels of storage.

The hydrologic lumped, conceptual rainfall runoff model HBV light [Seibert and Vis, 2012; Steele-Dunne et al., 2008; Uhlenbrook et al., 1999], a version of HBV [Bergström, 1995; Lindström et al., 2005], was adapted to MATLAB and used to calculate storage in the catchment and snow melt input. Storage was represented for this analysis by the combination of the soil and groundwater storages from HBV. This combined storage value was intended to represent variation in the overall storage or wetness state of the catchment through time. This model was chosen because it has been shown to perform well in snow-dominated catchments [Bergström, 1995; Seibert, 1997] as well as other catchments around the world [Lidén and Harlin, 2000; Steele-Dunne et al., 2008] and represents catchment storage (as presented in Detty and McGuire [2010b]) well. HBV was calibrated for WS3 by selecting the optimal parameter set from a 100,000 iteration Monte Carlo simulation using streamflow and snow water equivalent by maximizing a multiobjective calibration function:

$$MCE = 0.75 \times NVE + 0.25 \times SE$$

where MCE is the multiobjective function, NVE is the combined Nash-Sutcliffe Efficiency (NSE) [Nash and Sutcliffe, 1970] and relative volume error of discharge following Lindström [1997], and SE is the NSE of snow water equivalent. The values of the function are similar to the Nash-Sutcliffe efficiency, which range from $-\infty$ to 1 [Lindström, 1997]. The same parameters were varied as in Seibert et al. [2000] with the exception of MAXBAS, which is a channel routing parameter that was unnecessary due to the small size of WS3 (Table 1). The multiobjective calibration value for the optimum parameter set was 0.79. The storage dynamics from the optimized model were considered to be representative of actual catchment storage based on a linear relationship we found with storage calculated from measurements in Detty and McGuire [2010b] ($r = 0.95$). The comparison of calculated storage from Detty and McGuire [2010b] and our modeled storage was used to corroborate the model, and was not used for calibration. While magnitudes differed between the two

Table 1. Parameter Ranges and Optimal Values for the HBV Run Used to Provide a Catchment Storage Time Series

Parameter	Meaning	Units	Minimum Value	Maximum Value	Optimal Value
FC	Maximum soil moisture storage	mm	40.0	400.0	90.9
Beta	Shape coefficient determining the fate of water input to soil moisture storage		1.0	6.0	5.5
LP	Wilting point	mm	0.3	1.0	0.4
SFCF	Snowfall correction factor		0.4	1.2	0.6
TT	Threshold temperature	°C	-1.5	1.2	-0.5
CFMAX	Degree-day factor	mm/°C d	1.0	8.0	2.5
k0	Recession constant for near-surface storage	day ⁻¹	0.05	0.50	0.31
k1	Recession constant for upper storage	day ⁻¹	0.01	0.30	0.28
K2	Recession constant for lower storage	day ⁻¹	0.001	0.150	0.140
UZL	Threshold for shallow storage	mm	0.0	70.0	26.4
PERC	Percolation, max flow from upper to lower storage	mm/d	0.0	4.0	0.5

storage values, the strong linear relationship indicated that the model captured the storage temporal dynamics. Therefore, despite the simplicity of the model used, the multiobjective calibration criteria and representativeness of field-measured storage conditions indicate that it provided a suitable synthetic catchment storage time series with which to examine water table behavior.

Following the procedure outlined in *Detty and McGuire* [2010b] for examining threshold changes in catchment discharge, the modeled storage was then added to the daily input, whether it was measured precipitation or model calculated snowmelt input. The resulting data set represented the effective storage in the catchment: catchment storage from HBV plus precipitation and snowmelt inputs on a daily time step.

Subsurface flow within the solum was then calculated for the water level record of every well using Darcy assumptions. The hydraulic gradient at each well was assumed to be parallel to the local, DEM-derived ground surface slope at the well location (i.e., the kinematic approximation), and transmissivity was calculated based on the hydraulic conductivity-depth relationship for WS3 presented in *Detty and McGuire* [2010a]. Subsurface flow (q_{ssf}) above the C horizon (L^2/T) was calculated as

$$q_{ssf} = T(z) \tan b$$

where z is the water table height (L) above the subsoil, b is the local slope, and T is the transmissivity (L^2/T), calculated as:

$$T(z_i) = \int_{z_i}^z \frac{K_0}{f} \{ \exp(-fz_i) - \exp(-fZ) \}$$

where K_0 is the hydraulic conductivity (L/T) at the ground surface, z_i is the initial (highest in the profile) depth to water table, and Z is the depth to C horizon, and f (L^{-1}) is the slope of the line fit to the log transformed hydraulic conductivity-depth relationship [*Detty and McGuire*, 2010b].

Subsurface flow (q_{ssf}) for each well was then examined across all levels of catchment storage. This was done by binning modeled effective storage into 10 mm bins and calculating the mean subsurface flow response for each bin at each well. The result was an estimate of Darcian flow for each effective storage bin, allowing an examination of subsurface flow as a function of the effective catchment storage.

For each bin of effective storage for each well, a Wilcoxon rank sum test was performed to identify bins in which mean discharge was significantly different from zero (significance level of 0.05). The subsurface flow activation threshold for each soil unit was identified as the mean storage level for all wells in the group at which the subsurface flow significantly deviated from zero.

4. Results

4.1. Water Table Dynamics

Water table records from wells in different soil units showed distinct patterns of water table fluctuation (Figure 3). The consistency of these differences among wells in the same soil units over the study period is

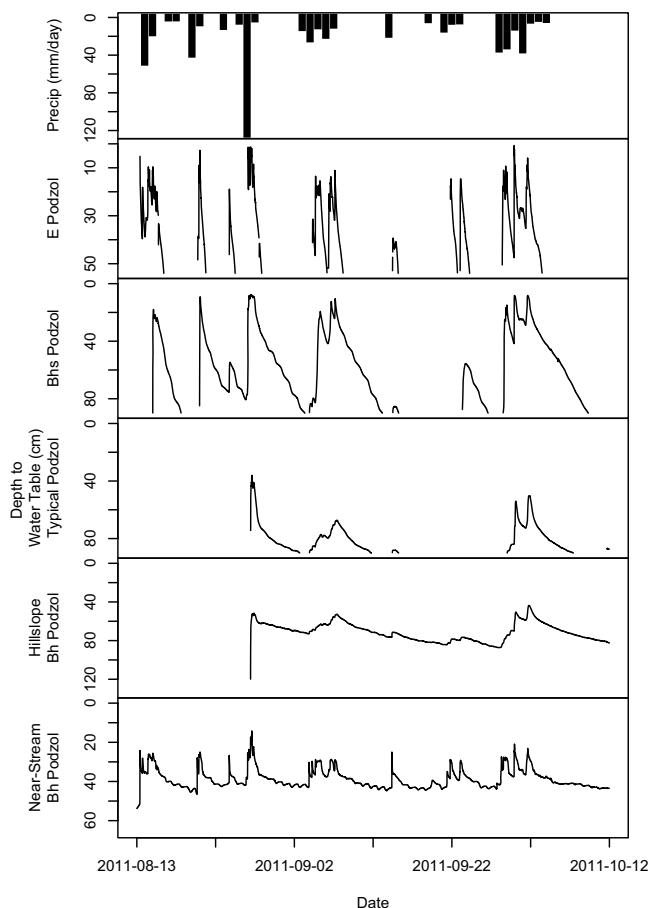


Figure 3. Example time series of precipitation and water table recordings within the solum for one characteristic well in each soil unit. The y axis of each plot extends from the C horizon to the ground surface. Periods without data indicate a lack of water table in the solum at the site. Modified from Bailey et al. [2014].

illustrated further in Figure 4. These two figures exemplify the characteristic differences in water table dynamics among soil units. Transient water table incursions into the solum were very infrequent in typical podzols (Figure 3). Also, water tables seldom rose above the bottom 30% of the soil profile in typical podzols (Figure 4). E and Bhs podzols were shown to have more frequent water table presence (Figure 3) which was also higher into the soil profile (Figure 4). Hillslope and near-stream Bh podzols had higher water tables for longer periods of time (Figure 4). Hillslope Bh podzols, however, had only seasonally persistent water table while near-stream Bh podzols had perennial water table (Figures 3 and 4). Furthermore, hillslope Bh podzols had higher magnitude fluctuations in water level, whereas near-stream Bh podzols had relatively smaller magnitude fluctuations (Figures 3 and 4).

When the distributions of percent profile saturation above the subsoil in each soil unit were compared, statistically significant differences were observed (Figure 5). The presence or absence of water table in wells yielded statistically significant differences among soil units (Figure 5a). Wells in soil units hypothesized to receive groundwater flow from upslope (E, Bhs, hillslope Bh, near-stream Bh) had a significantly higher percentage of their record where water table was observed above the subsoil. Water tables were present in these wells ranging from about 25–100% of the time. Wells in the vertically developed typical podzols detected water table far less frequently, with water table present about 0–10% of the time, with the exception of one well, which had water table just under 40% of the time, but only for a small portion of the solum thickness (Figure 4).

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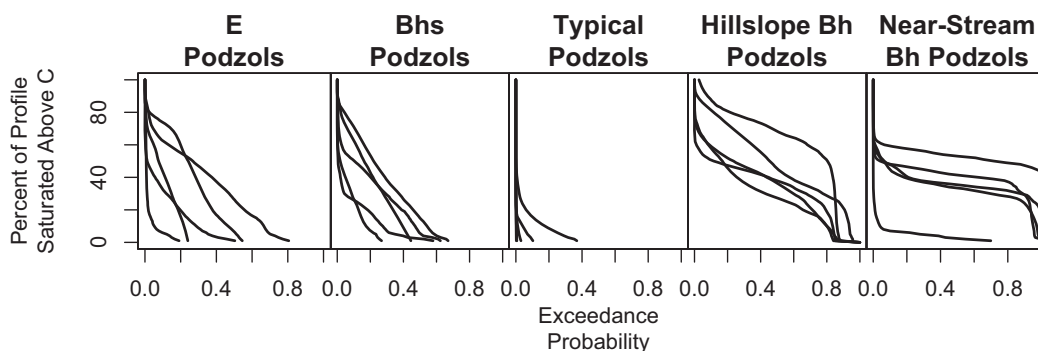


Figure 4. Empirical cumulative density functions (ECDFs) show the probability a water table exists at a given percentage of the total depth of a soil profile. Soil profiles in this figure are considered to begin at the C horizon and extend to the surface. ECDFs were constructed from 1 year of 10 min water level data from all wells in each of the soil units used in this analysis. Each line in each plot represents the water level time series from a well in that soil unit (n = 5 wells per soil unit).

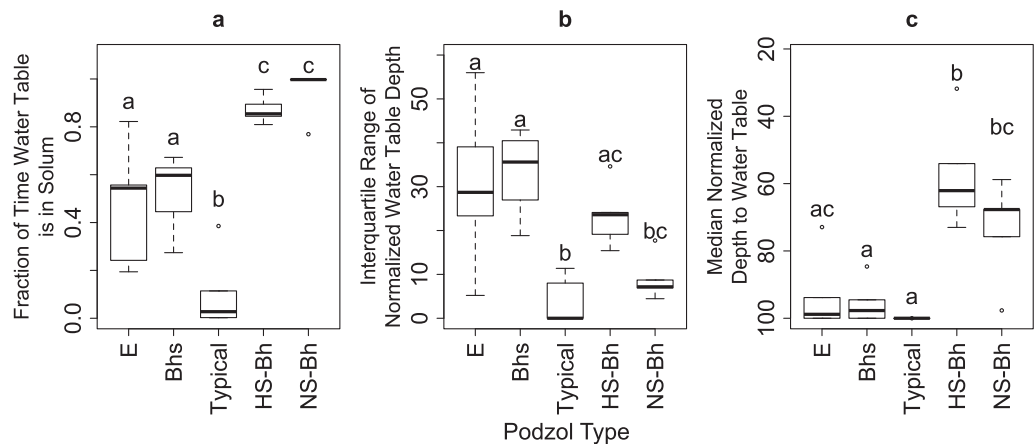


Figure 5. Box plots showing the separation of soil unit water table regimes for different data set measures. Letters above groups indicate statistically significant differences according to a Wilcoxon rank sum test (significance level 0.10). The fraction of total time a water table was detected in the solum is presented in Figure 5a. Water table records were normalized from 0 (ground surface) to 100 (relatively unaltered parent material (top of C Horizon)) for comparison of (b) interquartile range and (c) median depth to water table. The middle line in each box corresponds to the median of the data, the upper and lower bounds of the boxes are of the interquartile range (IQR), the whiskers are the first and third quantiles plus or minus 1.5 times the IQR, and points are outliers beyond the range of the whiskers. The soil types shown are E podzols (E), Bhs podzols (Bhs), typical podzols (Typical), hillslope Bh podzols (HS-Bh), and near-stream Bh podzols (NS-Bh).

The difference in water table fluctuations of the two subsets of Bh podzols can be observed in Figure 3, showing a representative time series of water level data for each soil unit, and Figure 4, showing cumulative density functions of the water table data for each well in each soil unit. Hillslope Bh podzols had persistent water tables only in the nongrowing season and had higher magnitude water table fluctuations than near-stream Bh podzols (Figure 3). The lower slope center portion of the ECDF (Empirical Cumulative Density Function) for near-stream podzols in Figure 4 also shows that water tables were more persistent and fluctuated less. Differences between near-stream and hillslope Bh podzols were also related to the topographic position of the well (Figure 6): Hillslope Bh podzol wells had consistently higher interquartile range of water table recordings, occurred at distances > 10 m from streams, and had upslope accumulated areas (UAA) < 150 m².

Wells in soil units with horizonation hypothesized to be indicative of lateral podzolization processes (E, Bhs, and hillslope Bh podzols) had consistently higher water level than typical podzols. Interquartile ranges of

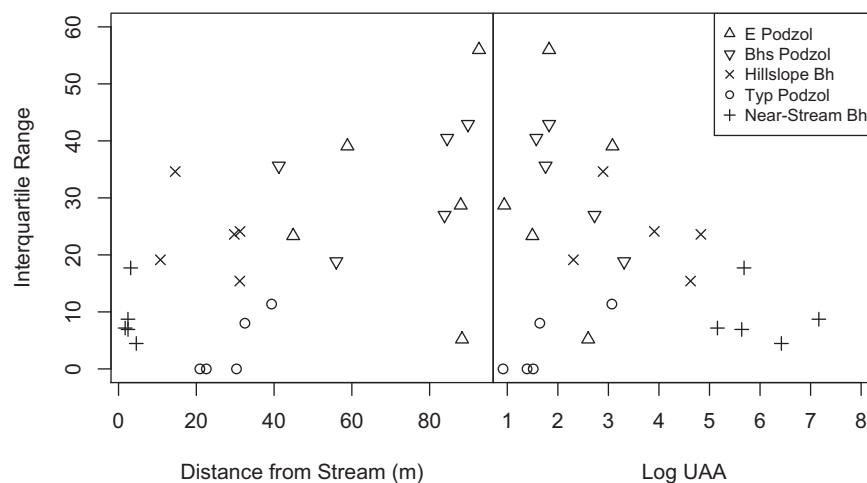


Figure 6. Interquartile range of water table fluctuations in each well plotted against the distance from stream and log upslope accumulated area (UAA). Different symbols indicate the soil unit of each well. With the exception of E and Bhs podzols, soil units separate in this space, illustrating that water table regime is in part related to topographic position.

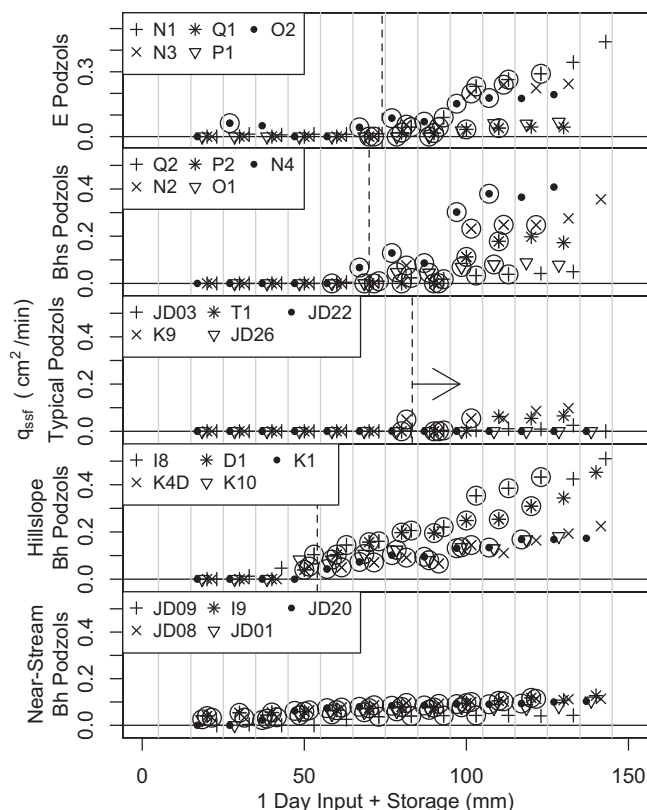


Figure 7. Threshold water table responses for wells in each soil unit. Mean specific discharge (q_{gsf}) is plotted on the y axis in cm^2/min and binned effective storage in mm is plotted on the x axis. Circled symbols denote a statistically significant difference from zero according to a Wilcoxon rank sum test (significance level 0.05). The dashed lines indicate the response threshold for each soil unit, defined as the mean threshold value for all wells in the group. The threshold value for each well was defined as the first storage bin where discharge significantly deviated from zero. The arrow in the typical podzol plot indicates that the mean response threshold for this group is higher than what is plotted because no statistically significant response was detected for two wells in the typical podzol group.

While the podzols hypothesized to be dominated by lateral flow on the hillslope had similar thresholds (E, Bhs, and hillslope Bh), typical podzols, and near-stream Bh podzols had very different responses.

Saturated flow in the solum of typical podzols, where vertical soil development through unsaturated percolation was hypothesized to dominate, showed a very high threshold, requiring over ~ 90 mm of effective storage before a response was observed. For two wells, the responses to precipitation in the solum were too brief and infrequent to elicit any statistically significant response using this analysis. Therefore, the effective storage needed to elicit a detectable response in these two wells is over 140 mm (Figure 7). Furthermore, when typical podzols had measurable discharge, it was of a magnitude not exceeding $0.1 \text{ cm}^2/\text{min}$.

In wells where lateral processes are hypothesized and water table was more frequent, thresholds were substantially lower and discharge much higher. In E and Bhs podzols, the response threshold was in the 70–80 mm storage bin, while in hillslope Bh podzols it was in the 50–60 mm bin (Figure 7). During the growing season, Figure 3 shows E and Bhs podzols responding when Bh podzols did not. Later in the same time series, when vegetation was dormant, hillslope Bh podzols responded with greater magnitude to smaller events, leading to the lower threshold observed for hillslope Bh podzols (Figure 7). Discharge for these podzols was also higher, nearing $0.4 \text{ cm}^2/\text{min}$ for E, Bhs, and hillslope Bh podzols.

Near-stream Bh podzols were observed to have persistent discharge that increased steadily with increased storage, therefore no threshold response was observed. Furthermore, these near-stream soils showed low

these groups, however, did not differ from one another, with the exception of near-stream Bh podzols, which were smaller, indicating less variable water table fluctuations.

Median normalized water level likewise showed differences in well responses (Figure 5c). Hillslope and near-stream Bh podzols were not different from one another as both exhibit persistent saturation for part of the year. E, Bhs, and typical podzols, despite having different dynamics, shown by the percent time and interquartile range metrics, had similar median water levels relative to their respective soil profile depths as their water tables did not persist beyond event responses (Figure 3).

4.2. Storage-Groundwater Flux Relationships

Distinct response thresholds to catchment effective storage, defined in section 3.3, were observed for estimated groundwater flow in the solum for each of the soil units (Figure 7). With increasing storage in the catchment, water table in wells showed no measurable response until a storage threshold was exceeded. This storage threshold differed among wells included in this study. When wells were grouped by soil unit, however, response thresh-

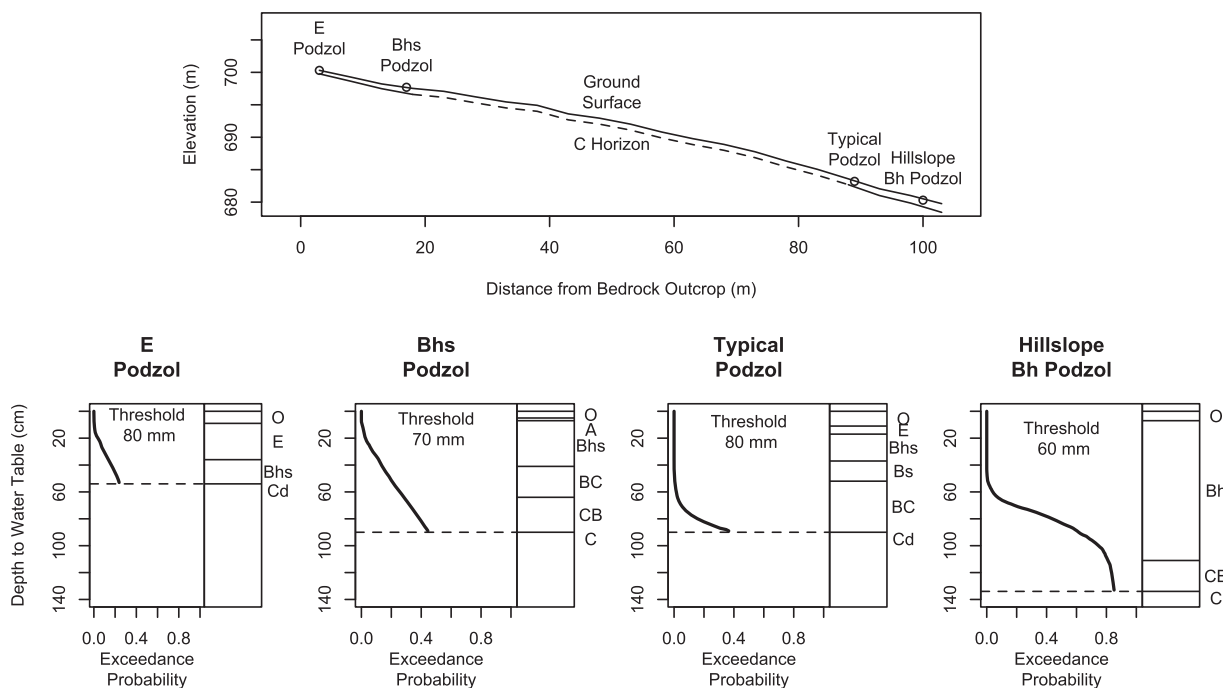


Figure 8. Transect 1 in Figure 1. A transect of wells in soil units along a hillslope beginning at a bedrock outcrop transect in WS3. The top figure shows the ground surface and C horizon as well as the location of the wells. The C horizon depth was interpolated and is dashed where the depth is relatively less certain. The bottom four figures are ECDFs for the wells in the transect with soil horizons shown to the right. The threshold catchment storage for the initiation of water table (corresponding to the beginning of the ECDF line on plot) is shown on each plot.

discharge, whose maximum was about $0.1 \text{ cm}^2/\text{min}$. Differences in response thresholds were not only seen between soil units, but also along transects of wells in a topographic sequence (Figures 8 and 9).

Two common sequences of soil units along transects were examined to serve as examples of the ways thresholds vary along hillslopes in the catchment. In the sequence from E-Bhs-typical podzols, thresholds were lowest in the highest elevation wells, the E and Bhs podzols (Figures 2 and 8). Moving closer to the stream, thresholds increased: E and Bhs podzols had lower thresholds whereas thresholds in typical podzols were higher (Figures 7, 8, and 10b). Conversely, in another common sequence of soil units, typical-hillslope Bh, thresholds changed in the opposite direction (Figure 8). Typical podzols further from the stream had the highest response thresholds, whereas hillslope Bh podzols further downslope required a much lower requisite storage to elicit a response (Figures 8 and 10b). The same pattern is observed in the transition between typical podzols and near-stream Bh podzols (Figure 9).

While response thresholds generally increased with smaller UAA and greater distance from the stream, the relationship was not consistent (Figure 10). For instance E, Bhs, typical, and hillslope Bh podzols, all had overlapping ranges of UAA and distance from the stream; only near-stream Bh podzols separated entirely, with lower response thresholds, lower distance to the stream, and higher UAA (Figures 10a and 10b). While typical podzols only occurred on greater slope gradients and Bh podzols on lesser slope gradients, E and Bhs podzols occurred over almost the entirety of the range observed for wells used in this study (Figure 10c). Finally, the differences between hillslope and near-stream Bh podzols were highlighted when topographic metrics were examined with thresholds. Near-stream Bh podzols not only had the lowest detectable threshold but also the highest upslope accumulated area (Figure 10a) and were the closest to the stream (Figure 10b). Their topographic similarities were in slope, where they occupied the same range (Figure 10c).

5. Discussion

5.1. Soil Horizonation as an Indicator of Complex Water Table Dynamics

Distinct water table regimes, described by the median and interquartile range of water levels and percent time water table exists in the solum, were observed in each soil unit (Table 2). Variations in soil morphology,

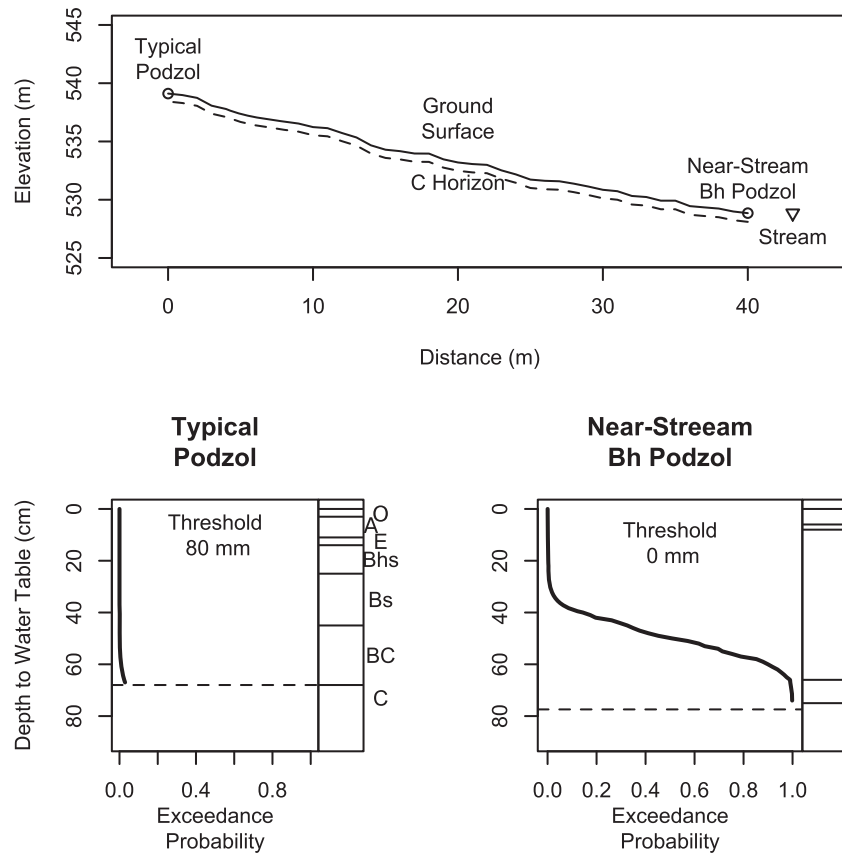


Figure 9. Transect 2 in Figure 1. A near-stream transect of wells in soil units along a hillslope transect in WS3. The top figure shows the ground surface and C horizon as well as the location of the wells. The C horizon depth was interpolated and is dashed where the depth is relatively less certain. The bottom four figures are ECDFs for the wells in the transect with soil horizons shown to the right. The threshold catchment storage for the initiation of water table (corresponding to the beginning of the ECDF line on plot) is shown on each plot.

including the presence of redoximorphic features [He et al., 2003; Rabenhorst and Parikh, 2000] and horizonation [Bailey et al., 2014], have been shown to be indicative of saturation dynamics. Moore et al. [1993] identified relationships between soil properties and topography, hypothesized to be the result of different flow paths and He et al. [2003] and Rabenhorst and Parikh [2000] identified differences based on time of

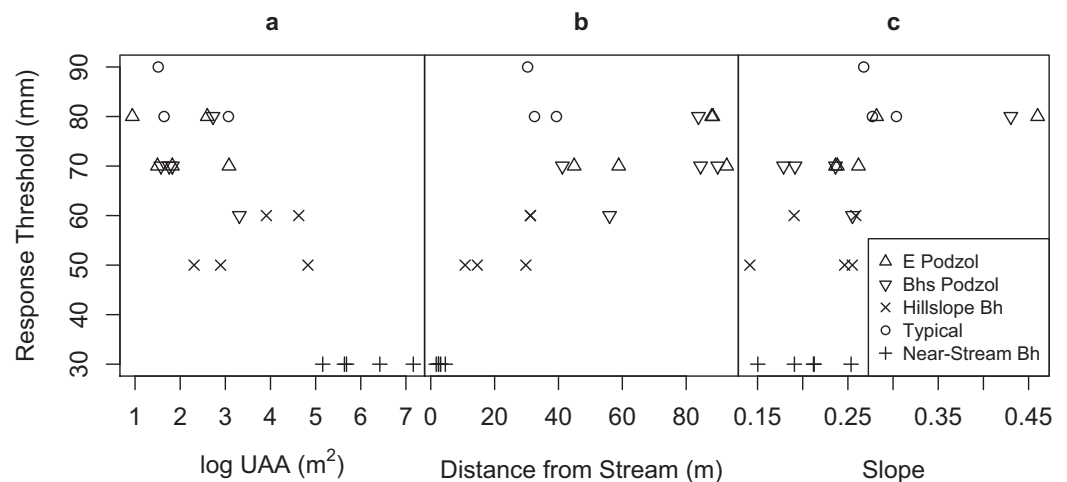


Figure 10. Water table response thresholds plotted against three topographic metrics for the each well. (a) Log UAA (m²), (b) distance from the nearest stream (m), and (c) slope. Different symbols indicate the soil unit of each well.

Table 2. Qualitative Descriptions of the Water Table Regimes for Each Soil Unit (HPU) Based on the Findings of This Study

Soil Unit (HPU)	Water Table Regime Summary
E Podzol	Frequent, near instantaneous response to precipitation and short recession period, nearly entire solum experiences saturation
Bhs Podzol	Frequent, near instantaneous response to precipitation with a longer recession period than E podzols, nearly entire solum experiences saturation
Typical Podzol	Brief, infrequent water tables near the base of the solum, only at high catchment storage
Hillslope Bh Podzol	Seasonally persistent, lower magnitude event responses than E and Bhs podzols, nearly entire solum experiences saturation
Near-stream Bh Podzol	Perennially persistent, lower magnitude event responses than hillslope Bh podzol, rarely if ever experience full solum saturation

saturation. However, in this study, soil units were defined by characteristic horizonation throughout the entire profile, rather than discrete features or horizons within the solum [Bailey et al., 2014]. Furthermore, the differences observed in water table regimes across soil units in WS3 were compared to water table dynamics having to do with the fluctuation, flow magnitude, and duration of flow occurring in a soil unit. This suggests soil units observed in WS3 can be used to understand solum flow dynamics and water table regimes in a catchment.

E and Bhs podzols have shallow profile depths and a large proportion of shallow or exposed bedrock in contributing areas (Figure 2). E podzols were characterized by a soil profile dominated by a thick E horizon and occur in complexes with bare bedrock outcrops and organic horizons directly on bedrock. Bhs podzols were likewise characterized by a thick Bhs horizon, and occurred immediately downslope of E podzols. This sequence of podzols therefore appears to have formed as a result of frequent periods of downslope saturated water flux, driven by vertical flow constriction due to shallow bedrock, creating the eluviated E podzols upslope of the depositional Bhs podzols [Bailey et al., 2014; Sommer et al., 2000]. The result is two pedons in a sequence on a hillslope that show downslope soil forming properties generally seen vertically within a single pedon [Sommer et al., 2000]. This is supported by the frequent incursion of water table into the solum, high interquartile ranges of water levels, and low median water level (Figure 5). Additionally, the threshold storage required to elicit a response in these soil units was lower than typical podzols (Figure 7).

Typical podzols were characterized by a thin E horizon over moderately thick spodic horizons, indicating vertical leaching and immobilization of spodic (Bhs and Bs) materials downward through the soil profile [Lundström et al., 2000; Sauer et al., 2007]. The existence of this horizonation in typical podzols would require a relatively inactive water table regime consisting primarily of unsaturated vertical fluxes, with only brief periods of water table incursion into the solum during extreme events. Indeed, our analysis showed these podzols were saturated very infrequently, with low interquartile ranges of water table measurements, never more than about 1/3 of the profile saturated (Figure 4), and a median water table that was without exception equal to the depth of the top of the parent material C horizon (Figure 5). Activation thresholds for these wells were likewise the highest of all soil units, with the lowest magnitude discharge (Figure 7). These conditions could result from a combination of small contributing area, C horizon topography steep enough to permit drainage, and/or a more permeable C horizon, any of which could create the drainage conditions necessary for limited water table incursion into the solum of typical podzols. Bailey et al. [2014] showed that typical podzols are the most commonly encountered soils in the catchment. Furthermore, Gillin [2013] suggested that the typical podzol was the dominant soil unit in the catchment at approximately 50% of the area, which suggests that no more than 50% of the catchment is active within the solum in all but the most extreme precipitation events.

Two soil units that were typically found lower on hillslopes and with higher upslope accumulated areas were also found to be indicative of frequent incursions of groundwater into the solum: hillslope and near-stream Bh podzols. Both podzols were characterized based on a profile dominated by a thick Bh horizon, hypothesized to be formed by frequent saturation leading to lateral transport of spodic materials [Bailey et al., 2014]. This saturation was likely a result of flow path convergence and/or from water rise originating in the deeper C horizon. Both podzols had the highest median water levels and were the most frequently saturated (Figure 5). The difference in hydrologic response between these soil units was likely related to a combination of topographic variables. Near-stream Bh podzols were closer to streams and had higher upslope accumulated areas (Figures 5 and 8). They also exhibited lower interquartile ranges of water level,

presumably because of higher conductivity soil in the near-stream zone that likely resulted from glacial lag deposits and alluvial material [Detty and McGuire, 2010b]. The higher conductivity in near-stream areas provides a transmissivity feedback [Bishop et al., 2004], limiting water table rise in relation to overall flux magnitude [Detty and McGuire, 2010b]. This transmissivity feedback is also responsible for the low magnitude discharge observed in near-stream Bh podzols in Figure 7.

Several authors have proposed that topography is not a suitable predictor of water table behavior along a hillslope [Devito et al., 2005; Haught and van Meerveld, 2011; Penna et al., 2014; Tromp-van Meerveld and McDonnell, 2006; Western et al., 1999]. Soil thickness [Buttle et al., 2004], bedrock topography [Freer et al., 2002; Tromp-van Meerveld and McDonnell, 2006], and confining layer topography [Hutchinson and Moore, 2000] are all identified as controls on water table dynamics potentially more important than surface topography. Furthermore, the need for characteristics that are capable of acting as surrogates for the integration of these controls has been acknowledged [Graham et al., 2010; Zehe et al., 2005]. We found no one surface topographic metric was able to consistently predict soil units (Figure 10). Water table regimes at well sites in WS3 are controlled by surface and C horizon topography, hydraulic properties, bedrock topography, portion of upslope area that is bedrock outcrop, and surface slope. Yet soil horization is a robust predictor of water table dynamics. We therefore propose that soil units in WS3 act as a suitable characteristic describing the many controls on water table fluctuations, integrating their myriad hydrologic effects.

5.2. Soil Units as Hydropedological Units

Bailey et al. [2014] identified the soil units in WS3 because they observed variations in soil horizon presence/absence and thickness beyond the ranges of recognized soil series in the region. These variations occurred at a fine spatial scale and were therefore not included in medium intensity soil surveys where they would have been excluded by minimum map unit/polygon area requirements. However, Bailey et al. [2014] found differences in carbon pools in soil units as well as evidence for varying hydrologic regimes, hypothesizing that these soil units are indicative of distinct hydrologic and biogeochemical conditions. Our analysis has shown that these soil units are indicative of distinct water table regimes and threshold water table responses to relative catchment wetness consistent with the conditions hypothesized to create individual soil units (Table 2). The soil units are therefore indicative not only of variations in soil horization, but the coupling of biogeochemical processes and hydrologic regimes. Our work suggests there are feedbacks between water table regime and soil formation, the understanding of which may lead to new insights into critical zone processes concerning the structure and function of ecosystems [Chorover et al., 2011]. The term "hydropedological unit" has been used to describe similar feedbacks elsewhere [Tetzlaff et al., 2014], but has not been previously defined. Following our investigation, we propose defining the term "hydropedological unit" as a grouping of variations in soil morphology that directly relate influence of water table regime, flow paths, and saturation to soil development.

A hydropedological unit is therefore a functional grouping of soils by hydrologic behavior and indicating potential implications for biogeochemical processing, runoff production, and the structuring of natural communities. This system of grouping soils may be most useful in catchment or other studies of similar scale where local differences in water movement outweigh the role of varying vegetation or other soil forming factors on local gradients in soil morphology and chemistry. In contrast, the theory of Jenny [1941] only implicitly considers the role of water as a soil forming factor within the context of climate, which explains patterns of soil distribution at much broader scales than considered here. The role of the other soil forming factors of parent material, relief, time, and organisms in influencing water movement is even less explicit, although all of the soil forming factors may differentiate soils by affecting hydrologic properties. Thus, the concept of a hydropedologic unit may provide an alternative perspective to soil taxonomy that centers on the interactions of hydrologic and pedologic processes.

5.3. Implications for Runoff Generation

The highest threshold responses observed in this study were in midslope positions, while the lowest occurred near the top and bottom of hillslopes. Typical podzols, which had the highest response thresholds, dominated the catchment, accounting for an estimated 50% of the catchment area [Gillin, 2013] and primarily occurred along midslope positions. While E and Bhs podzols almost always occurred together on the landscape, they were also almost always separated from hillslope Bh podzols by typical podzols (Figure 2). Hillslope and near-stream Bh podzols were likewise sometimes separated from each other by typical

podzols. This paints a picture of stormflow generation via a spatial patchwork of water table occurrence within the solum, and therefore lateral subsurface flow in the solum of the catchment, rather than an uninterrupted saturated area extending up from streams. A system such as this highlights the importance of the active versus contributing areas of *Ambroise* [2004]. For example, water tables occurred in E and Bh podzols far from the stream at frequently exceeded thresholds of catchment storage necessary for water table occurrence. Furthermore, there are large areas of the catchment separating E and Bh podzols from the stream that only had water tables in the solum during extreme events (typical podzols). While portions of E and Bh podzol areas may connect with intermittent or ephemeral channels, in many cases water tables occur upslope and infiltrate to deeper storage before the areas of saturation reach a stream channel. When water from these soils does enter stream channels, it often flows into portions of the stream network where the stream is surrounded by typical podzols, likely indicating the stream is losing water to surrounding soils. During larger events, when thresholds are exceeded in typical podzols, E and Bh podzols are more likely to connect to the stream (Figure 1). Therefore, if water tables connected to the stream channel generate stormflow, there are active areas in the catchment that are not contributing areas unless a high threshold of catchment storage is exceeded. However, water in these areas is moving further downward into the C horizon.

Water in the C horizon may take one of several paths to the stream network. While generally lower conductivity [Detty and McGuire, 2010b], the C horizon in WS3 has been shown to be heterogeneous, with lenses of higher conductivity material [Bailey et al., 2014]. Furthermore, preliminary ground penetrating radar results have shown the C horizon to be 0–9 m thick. Therefore, most water entering the C horizon will take a slower flow path to the stream, recharging the larger C horizon groundwater reservoir. However, as high conductivity areas of till are present throughout the catchment, there also exists the possibility of groundwater following such a pathway to the stream. Some water moving from water tables in E and Bh podzols into the C horizon may contribute flow to streams in this way.

Other authors have discussed discontinuous active areas on hillslopes [McNamara et al., 2005; Spence, 2010; Stieglitz et al., 2003]. Furthermore, as distance from the stream increases, some authors have found a decreased correlation of groundwater levels with streamflow [Haught and van Meerveld, 2011; Penna et al., 2014; Seibert et al., 2003]. The spatial patchwork of solum water table occurrence in WS3 is consistent with the behavior presented in these other studies. However, we have identified an integrative characteristic (i.e., hydrogeological unit) that is consistently indicative of water table behavior. Looking at the catchment through this lens provides a framework for mapping continuous/discontinuous water table occurrence in the solum of the catchment through time. As mentioned above, the role of discontinuous water tables in generating streamflow is currently unknown, as is their potential influence on stream chemistry. However, the insights offered in this study may provide an approach to more closely investigate the effects of patchy regions of subsurface saturation located throughout a catchment.

In addition to being a useful tool for examining the role of discontinuous solum water tables, our findings may be useful for examining the evolution of contributing area throughout events. Our observations are consistent with others suggesting distinct hydrologic regimes in near-stream areas [Cirno and McDonnell, 1997; McGlynn and Seibert, 2003; Ocampo et al., 2006]. We detected persistent water tables in near-stream Bh podzols with lower magnitude water fluctuations, presumably the result of higher saturated hydraulic conductivity in the near-stream zone [Detty and McGuire, 2010b]. Upslope of these soils was almost always typical podzols, which our threshold analysis has shown to have very infrequent water table incursion into the solum. Therefore, the observation of persistent water tables in the near-stream zone and typical podzols immediately upslope is consistent with the majority of event water being mobilized from the near-stream zone [McGlynn and McDonnell, 2003]. A direct connection between hillslope groundwater and the stream likely only occurs during large events, where water tables occur in the lower portion of typical podzol profiles. The discontinuities evident from our analysis suggest most hillslope water takes longer, deeper flow paths to the stream, likely through the glacial parent material of the C-horizon.

6. Conclusions

We have shown that variations in soil horization across the landscape in WS3 at the Hubbard Brook Experimental Forest were indicative of specific water table regimes. Descriptors of water table regime that

can be determined by examining soil horization include percent time a water table exists, median water level, interquartile range of water level fluctuations, and the threshold storage at which a water table will occur in the solum. The water table regimes associated with soil units across the landscape were consistent with the hypothesized flow regimes necessary to create the observed soil horization. As a result, we introduced the term hydrogeopedological unit to describe variations in soil horizon presence/absence and thickness that correspond to the hydrologic behavior of a soil.

We used a technique where catchment storage levels were compared to water table occurrence in the solum to determine storage thresholds for the generation of subsurface flow above the parent material. This method revealed isolated areas where water table occurred at lower storage thresholds than areas closer to the stream with larger contributing areas, painting a picture of a spatially disconnected patchwork of water table occurrence in the solum of the catchment. Response thresholds were related to soil horization: an integrator of several surface and subsurface properties including topography, rather than distance from the stream or contributing area.

Soil horization is therefore a useful tool for examining water table dynamics throughout a catchment. Upon characterizing the flow regimes associated with different soil morphologies in a catchment, different soil groups (hydrogeopedological units) may be used as an indicator to predict regions of the catchment where water tables are likely to occur. Additionally, we have shown these hydrogeopedological units to be indicative of distinct and consistent water table regimes. This framework, where distinct soil units indicative of hydrologic regimes and biogeochemical processes are identified, may be a useful tool for examining runoff generation processes and patterns in surface water chemistry in headwater catchments.

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