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THE EFFECT OF SPATIAL PATTERNS OF SOIL HYDRAULIC CONDUCTIVITY AND DEPTH ON LOCAL AND HILLSLOPE SCALE SHALLOW WATER TABLE DYNAMICS

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THE EFFECT OF SPATIAL PATTERNS OF SOIL HYDRAULIC CONDUCTIVITY AND DEPTH ON LOCAL AND HILLSLOPE SCALE SHALLOW WATER TABLE DYNAMICS

By

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Chairperson: Dr. Kelsey Jencso

ABSTRACT

Much research in forested headwater catchments has focused on the role of topography for organizing subsurface flow and the hydrologic connectivity of upland flow paths to stream networks. However, little work has been conducted to evaluate how localized and hillslope scale patterns of hydraulic conductivity and soil depth contribute to spatial patterns of water table duration, magnitude, and connectivity. I monitored shallow groundwater dynamics in wells distributed across a 1st order hillslope in the Lubrecht Experimental Forest, Montana. Additionally, I collected *in-situ* measurements of soil saturated hydraulic conductivity and soil depth at 10m intervals across the study hillslope and compared these values to the well hydrologic response. Similar to previous studies, my results indicated that upslope accumulated area was a first-order control on the duration of soil saturation. However, I found that local soil hydraulic properties modulate hillslope scale controls on the duration, magnitude, and extent of groundwater development. Generally, local contributing areas with higher saturated hydraulic conductivity values exhibited lower magnitudes of water table depth and variability in water table depths, lower median water table height, and less cumulative duration of hydrologic connectivity with upslope landscape positions. Additionally, areas with more variable bedrock topography required higher antecedent wetness conditions for the development of transient water tables. These results demonstrate not only the importance of hillslope scale topography for controlling hillslope water table dynamics, but the need to also consider local patterns of soils characteristics and bedrock topography. This study advances the science of hydrology by addressing previously unresolved questions regarding the relative roles of spatial patterns in topography, hydraulic conductivity and soil depth on local and hillslope scale shallow water table dynamics. A better understanding of these local and nonlocal processes may contribute to improved conceptualizations of factors affecting runoff generation and the degree of watershed scale hydrologic connectivity that influences discharge dynamics in forested mountain watersheds.

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Chapter 1: Introduction

1.1 Introduction

Watershed structure and organization plays an important role in conversion of rainfall to runoff across watersheds. Several mechanisms of runoff generation (e.g. infiltration excess surface runoff, saturation excess runoff, and subsurface flows) have been identified (Horton, 1933; Hewlett and Hibbert, 1967; Freeze, 1974), and many studies have focused on attributes of watershed structure that organize their spatial occurrence. One or more of these mechanisms of runoff generation are often simultaneously present in a particular watershed; for example, a number of researchers (e.g. Pilgrim, Huff, and Steele, 1978; Jordan, 1994; Perrin, Michel, and Andréassian*,* 2001; Wetzel, 2003; Godsey, Elsenbeer, and Stallard, 2004) report that the spatial heterogeneity in the landscape allows for all of the above-mentioned mechanisms to be present in a particular watershed at the same time; however, depending on the hydrologic characteristics of a watershed, one or more of the mechanisms may dominate.

In forested mountain catchments with shallow soils (1-2m) and relatively impermeable bedrock, shallow subsurface flow is often the dominant runoff generation mechanism. During periods of high antecedent moisture, the soil pore volume is often exceeded and subsurface flow may lead to hydrologic connectivity of upslope and downslope runoff contributing areas (McGlynn and McDonnel, 2003; Jencso *et al.,* 2009); hydrologic connectivity refers to water movement from one location to another on the landscape either by surface or subsurface flow (Bracken and Croke, 2007). Empirical and theoretical studies have suggested that watershed topographic, soil, vegetation, and bedrock characteristics are important controls on the spatial variability of hydrologic connectivity between hillslopes and streams (Jencso and McGlynn, 2011). However, few studies have explored how these characteristics lead to patterns of connectivity between areas of runoff generation within hillslopes.

At the scale of individual hillslopes previous studies have highlighted the important role of both surface and bedrock topography for subsurface flow dynamics. For example, in their formative study Beven and Kirkby (1979) found that for hillslopes with relatively shallow soils, and where bedrock topography is assumed to be parallel to the soil surface, the first order controls for subsurface flow response were surface topography (hillslope contributing area and local slope) and differences in soil profile transmissivity (the product of soil depth and horizontal hydraulic conductivity).

More recent work has shown that bedrock topography can partially control spatial patterns of subsurface stormflow initiation (Noguchi *et al.*, 2001; Freer *et al.*, 2002; McGlynn, McDonnell, and Brammer, 2002; Tromp Van-Meerveld and McDonnell, 2006c; Graham, Woods, and McDonnell, 2010). Work by Freer *et al.* (2002) indicated that bedrock surface topography was a critical factor in the spatial dynamics of soil profile saturation for a single slope at the Panola Mountain Research Watershed in Georgia. Further, in their 2002 study, Freer *et al.* concluded that patterns of water table development were generally governed by the bedrock topography, with surface topography being an overall poor predictor of subsurface flow patterns. Further work at the same research site by Tromp-Van Meerveld and McDonnell (2006b) revealed that soil moisture was not well correlated with any topographic variables considered in the study, suggesting that soil depth is a first-order control on subsurface stormflow during dry antecedent moisture conditions, with the role of bedrock topography being more pronounced during wet antecedent moisture conditions. While these studies highlighted the need to consider bedrock topography, the studies did not integrate analysis of local patterns of soil hydraulic properties on the effect of subsurface flow dynamics.

Sherlock, Chappell, and McDonnell (2000) suggested that predictions of runoff generation rely on accurate measurements of hydraulic gradients and field-state hydraulic conductivity (K). Further, they emphasized that saturated hydraulic conductivity (Ksat) is a critical hillslope hydrological parameter which should be accurately characterized in studies that attempt to elucidate hillslope scale runoff dynamics. If the cross sectional area, slope, and hydraulic conductivity are known, Darcy’s Law (1856) enables the calculation of flow through a porous medium. Thus, estimation of hydraulic conductivity is important for hillslope hydrology studies, especially modeling efforts, as it represents the ability of the soil to transmit water. However, most hillslope scale studies often do not characterize spatial patterns of hydraulic conductivity which may lead to "markedly inaccurate process inference" (Anderson and Burt, 1978) and a disconnect between the role of upslope topography and local soil characteristics for hillslope runoff generation.

Previous work by Grayson, Western, Chiew, and Blöschl (1997) identified preferred states in spatial soil moisture patterns, differentiating between local and nonlocal controls. Local controls often become more prominent during dry soil states, with vertical fluxes being the dominant form of hydrologic flow, and soil properties and local terrain influencing spatial patterns of soil moisture. Furthermore, the authors identify nonlocal controls as occurring during wet soil states, with primarily lateral movement of water through the soils, and catchment terrain primarily influencing the organization of areas with high soil moisture. These previous studies provided significant first steps in identifying preferred states and drivers of runoff generation. However, the study focused on surficial soil water content (% mass balance) to assess hydrologic redistribution; thus, the study did not directly quantify how local soil characteristics modulated topographic controls on lateral water redistribution.

Many studies have suggested that runoff generation is spatially and temporally variable, and hydrologic connectivity of runoff generation areas is important for overall hillslope (Jencso *et al.*, 2009; Detty and McGuire, 2010) and catchment scale response (Jencso et al., 2009; Jencso and McGlynn, 2011). However, there has not been significant work to evaluate how local soil characteristics may modulate spatial patterns of hydrologic connectivity in a downslope direction and the emergence of hydrologic connectivity at the hillslope scale. Knowledge of the physical processes involved in the development of shallow water table dynamics may be further improved through analysis of the spatial organization of soil depth and hydraulic conductivity which may lead to emergent patterns of hillslope scale hydrologic connectivity. Here, I improve upon previous hillslope investigations by identifying the presence of potentially concurrent effects of local (soil characteristics) and non-local (topography) upon the organization of subsurface flow and hydrologic connectivity of flowpaths along a hillslope. I address this objective by testing the following hypotheses:

1.2 Research Objectives

Objective: Evaluate the role of spatial patterns in topography, hydraulic conductivity and soil depth on local and hillslope scale shallow water table dynamics.

H1. Local spatial patterns of Ksat modulate upslope topographic controls (upslope accumulated area) on the duration and magnitude of soil saturation.

H2. Well contributing areas with greater Ksat have decreased connectivity to upslope well positions relative to those with low Ksat due to enhanced drainage in a downslope direction.

H3. Well contributing areas with larger proportions of high Ksat soils and those with more variability in bedrock topography have a higher antecedent moisture threshold for water table development relative to those with low Ksat because of enhanced vertical and downslope drainage.

Chapter 2: Methods

2.1 Site Description

This study was conducted at the University of Montana’s Lubrecht Experimental Forest, which has an area of 113 km^2 and is located 56 kilometers east of Missoula, Montana (Figure 1). The elevation of Lubrecht Experimental Forest ranges from 1082m to 1920m above mean sea level, with 75% of the forest having elevations between 1220 – 1524m (Nimlos, 1986). Lubrecht was established in 1937 after 77 km^2 were donated to the state of Montana by the Anaconda Mining Company, with a subsequent gift of 5 km^2 from the Northern Pacific Railroad, and additional land acquisitions from private owners. Lubrecht is managed by the University of Montana for “natural resource study, demonstration, and learning, and public use in a forest setting” (Keyes and Perry, 2010).

Vegetation at Lubrecht is dominated by western larch and douglas-fir on north-facing slopes, ponderosa pine on south-facing slopes, and lodgepole pine throughout the eastern portion of the forest. Much of the vegetation is second-growth, a result of extensive logging and slash burning activities in the early 1900s (College of Forestry and Conservation, n.d.).

The geology of Lubrecht primarily consists of Belt supergroup bedrock and quartz monzonite (granite). Other parent materials present include limestone, Tertiary rock, lamprophyre, and alluvium (Nimlos, 1986). The study hillslope is located in an area with Belt bedrock. Soils in Lubrecht are primarily (86%) inceptisols with tertiary substrate, with some alfisols, mollisols, and entisols present (Nimlos, 1986). The soil profile of the study hillslope has been classified as Winkler gravelly loam: a loamy-skeletal, mixed, frigid Udic Ustochrept (USDA *et al.*, 1995). The Winkler series contain six key soil horizons: An O horizon from 0-5cm consisting of undecomposed and slightly decomposed forest litter, an A horizon from 5-13cm consisting of grayish brown very gravelly sandy loam, an E horizon from 13-69cm consisting of pinkish gray very gravelly sandy loam, an E and Bt horizon from 69-112cm consisting of pinkish gray extremely gravelly sandy loam, and a C horizon from 112-152cm consisting of pinkish gray extremely gravelly sandy loam, below which lies Belt bedrock (USDA, 2008).

Mean annual precipitation is approximately 457mm, with 44% of annual precipitation arriving during the winter (November through March), and only 24% falling during the summer months of June, July, and August (Nimlos, 1986). The areas of higher elevation in Lubrecht receive an average of 508 to 762 millimeters of precipitation annually (Ross and Hunter, 1976).

This study utilizes a north aspect hillslope in the Cap Wallace watershed of Lubrecht. The hillslope has an area of 32,200m^2, average slope of 14 degrees with a standard deviation of 6.76. The elevation ranges from 1348m at Cap Wallace Creek to 1534m at the upslope ridgeline. Cap Wallace Road crosses the hillslope at 1430 meters elevation. A convergent hollow, or gulley, runs southwest-northeast approximately 150 meters from the lower Cap Wallace Road to Cap Wallace Creek. The hillslope study area is separated from the surrounding hillslopes by divergent topography in the form of gentle ridgelines. The study plot, below Cap Wallace Road, has an area of 6,700 m^2 (Figure 2).

2.2 Site Selection

Installation locations for groundwater wells were chosen so that four wells would be installed within the convergent hollow, spaced as evenly as possible along the study area, with two sets of two side slope wells installed on opposing sides of the convergent hollow. Sampling sites for SWE, Ksat, and soil depth were generated through the fishnet feature in ArcGIS 10.2. Physical measuring locations were verified on-site through the combined use of a Trimble GeoXT GPS unit, pin flags, and 100m surveying measuring tape. SWE was sampled on a 20x20m grid across the entire hillslope, including upslope of the study area, while soil depth and Ksat were sampled on a 10m grid within the study area. Sampling points were also included outside of the study area boundary to maximize the accuracy of interpolation. Because the goal of the study was to investigate non-local contributing area controls versus local soil characteristics, and to determine which is more important at different spatial and temporal scales, I discovered to focus this study on the area below Cap Wallace Road. Cap Wallace Road acts as an area of zero soil depth, effectively precluding groundwater connectivity along the hillslope.

2.3 Well Installation and Water Table Dynamics

I installed shallow groundwater monitoring wells at eight locations across the study hillslope. Four wells were installed within the convergent hollow, and four wells were installed in planar side slopes that drain to the main axis of the hollow. The well boreholes were augured to bedrock using a gas-powered auger. 5cm diameter PVC was screened with narrow slits at 1cm increments, and pounded to the bottom of the augured well hole until refusal using a sledgehammer and solid steel rod. To ensure that recorded measurements represented groundwater levels, bentonite clay was used during installation of 1m capped PVC risers to prevent surface water from running down the sides of the installed PVC and into the well. To record water levels in each well I installed water level meters (TruTrack WT-HR Water Height Data Logger), which recorded water table height (1mm resolution) and water temperature (0.1°C resolution) at 30 minute intervals from March 4th to September 12th, 2014. The resulting water table height data was analyzed to determine cumulative duration of water table persistence, duration of hydrologic connectivity with neighboring wells, lag time between snowmelt and presence of water within each well, as well as summary statistics such as maximum water table height, mean and median values. In order to quantify the cumulative duration of saturation for each water table monitoring well, I analyzed the data collected from the TruTrack data loggers, identifying periods of saturation, defined as a detectible column of water present in the well (>1cm). By multiplying the total number of saturated timestamps by the recording interval (0.5 hours), I calculated the cumulative duration of saturation, in hours, for each water table monitoring well.

2.4 Snow Water Equivalent

At the Lubrecht Experimental Forest, annual hydrologic contributions are dominated by the effect of snow melting and subsequent subsurface runoff generation. To measure the amount of potential snowmelt water contribution to spatial locations across my study hillslope I calculated peak snow water equivalent (SWE) during the point of maximum annual snowpack. SWE was calculated by manually measuring snow depth (h_s) and local bulk density (ρ_b) at pre-selected sampling locations using a snow sampling tube and hanging scale (Rickly Hydrological Company). Local bulk density is calculated as

$$\rho_b = \frac{M_s}{V_s}$$

where M_s is the mass of the snow core (g), and V_s is the volume of the snow core (cm^3). Total available SWE (cm) is then calculated as

$$SWE = h_s \frac{\rho_b}{\rho_w}$$

where ρ_w is the density of water (1 g cm^{-3}), and all other terms are as previously defined. (Sturm *et al.,* 2010).

2.5 Calculation of an Antecedent Moisture Index

Previous studies have highlighted the importance of antecedent soil wetness for hillslope subsurface flow generation in semiarid environments (Karnieli and Ben-Asher, 1993; Ceballos and Schnabel, 1998; Fitzjohn, Ternan, and Williams, 1998). To determine the antecedent moisture conditions necessary for groundwater response, I calculated a daily antecedent precipitation index (API) for the study hillslope using precipitation data from the nearby Lubrecht Flume SNOTEL station. The API is calculated as:

$$API_t = (API_{t-\Delta t} \times C) + I_t$$

where API_t is the antecedent wetness index at time *t* (cm), $API_{t-\Delta t}$ is the time interval of input observations, C is a temporal decay of coefficient for antecedent moisture, and I_t is the precipitation that occurs from $t - \Delta t$ (cm). I determined a decay coefficient C of 0.96 based upon a best-fit linear relationship (R^2=0.73) between the calculated API and discharge values from the stilling well in Cap Wallace Creek at the base of the hillslope (s*ensu* McGlynn and McDonnell, 2003; Jencso and McGlynn, in review).

2.6 Soil Depth

Soil depth was measured at 88 pre-selected sampling locations on a 10x10m grid along the study hillslope. Each measurement was conducted using a sledgehammer to drive a 140cm steel rod into the soil to the point of refusal. At some sampling locations, the ability to measure the depth of the complete soil profile was limited to the length of the available steel rod. At these locations, I recorded a total depth of greater than 130cm, and used a value of 130.01cm for data analysis.

2.7 Saturated Hydraulic Conductivity

I used a compact constant-head permeameter (Amoozegar, 1989a) to determine hydraulic conductivity at 88 pre-selected sampling locations on a 10x10m grid within the hillslope. Amoozegar (1992) describes the compact constant head permeameter as being “composed of four constant-head tubes, a 4-L water reservoir, a 1-L flow measuring reservoir, a water dissipating unit, and a base with a three-way valve. The four constant-head tubes are used to maintain a constant level of water in an auger hole up to 2m below the surface” (Figure 3).

I used a hand auger to create an access hole (r =3 cm) to 40cm depth, within the E soil horizon, that allowed for the measurement of the steady-state rate of water flow (Q) into the soil. I chose a constant head (H) such that 15cm<H<20cm, and such that $H/r \geq 5$, allowing for the use of the Glover solution to calculate Ksat. I used the Glover solution to calculate saturated hydraulic conductivity based on the gravitational flow from a cylindrical hole (Amoozegar, 1989b):

$$K_{sat} = CQ/(2\pi H^2)$$

Where

$$C = sinh^{-1}(H/r) - (r^2/H^2 + 1)^{1/2} + r/H$$

At some measurement locations, the Ksat value of the soil was high enough that the infiltration rate equaled or exceeded that of the dispersion rate of the Amoozemeter. In other words, head recovery was too rapid to allow for measurement. For these locations where I was unable to achieve the required *H/r* ratio of greater than or equal to 5, Ksat values are reported as being greater than 20cm/hour, which was the highest reasonable rate of Ksat I observed, above which the soil infiltration rate exceeded the Amoozemeter maximum flow rate and measurement values could not be calculated; therefore, a Ksat value of 20.01cm/hr was used for data analysis. In addition, multiple measurements were taken during different days at a single location in order to determine a measurement error; these measurements had a range of 0.93cm/hr, a standard deviation of 0.42cm/hr, and a standard error of 0.24cm/hr.

2.8 Geographic Information Systems

Surface topography data was obtained from a 10m Digital Elevation Model (DEM) provided by the University of Montana School of Forestry Geographic Information System Program. Areas of hydrologic contribution, or upslope accumulated area, for each well were derived using a combination of the Flow Accumulation tool within ArcGIS 10 and the Upslope Area tool within the Terrain Analysis module of SAGA GIS 2.1 Additional delineations within SAGA GIS 2.1 allowed me to specifically identify the local contributing area to each well, which I define as the area of land which drains to a particular well on the hillslope, yet does not contribute to a neighboring upslope well (sensu Jencso *et al.,* 2009).

SWE, Ksat, and soil depth measurement data were interpolated across the study hillslope using ordinary kriging within ArcGIS 10 software. Ordinary kriging is an interpolation technique that estimates a given Z value at an unobserved location based upon regression against observed Z values of surrounding data points. Ordinary kriging has been shown to be an effective tool for interpolating soil depth (Knotters, Brus and Oude Voshaar, 1995; Penížek and Borůvka, 2006; Almasi, Jalalian and Toomanian, 2014), Ksat (Gallichand, Prasher, Broughton, and Marcotte, 1991; Hosseini, Gallichand, and Caron, 1993; Moradi, Ghonchehpour, Majidi, and Nejad, 2012), and SWE (Carroll, Carroll, and Poston, 1999; Pulliainen, 2006).

I used a Root Mean Square Error (RMSE) analysis to determine the optimal raster cell sizes at which to interpolate SWE, Ksat, and soil depth values. RMSE is a function of the difference between the estimated Z values and the observed values.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[z(x_i) - \hat{z}(x_i)]^2}$$

where $\hat{z}(x_i)$ is the predicted value, $z(x_i)$ is the observed value, and N is the number of values in the dataset (Robinson and Metternicht, 2006).

For each dataset, I calculated the RMSE and the correlation of coefficient (R^2) value for different interpolation approaches (Tables 1-3). Based upon RMSE analysis, I determined to interpolate SWE and soil depth at a 2m cell resolution, and Ksat at 1m (Figure 4b,c,d).

Chapter 3: Results

3.1 Hydrologic Inputs

To examine hydrologic inputs for the study hillslope, I utilized data from the nearby Lubrecht Flume SNOTEL station (distance: 3.16 kilometers, elevation: 1426m). The watershed received 526mm of precipitation during water year 2014. The maximum snowpack depth of 102cm occurred on February 25th, with peak SWE of 21.6cm occurring on March 6th, 2014. Locally on my hillslope the measured SWE values for the entire hillslope were centered around 14-17cm depth, with one value of zero (no visible snow present at sampling location), and one value >30cm (Table 4). Much less variation in SWE values were observed within the study area of the hillslope (Table 5), where values ranged from 15-16.78cm, and higher values generally occurred in areas of topographic convergence (Figure 4b). Rapid snowmelt began on March 24th, 2014, and by April 18th, the snowpack had completely melted (Figure 5a). The average daily melt intensity was 0.51cm. Following the snowmelt period, additional hydrologic input occurred as rain on 28 separate days between April 18th and September 19th (the day the period of record ends) for a cumulative total of 193mm. Large rainstorms occurred during the periods of June 17th – 19th, August 14th – 16th, and August 21st – 24th, delivering precipitation totals of 35.6mm, 40.6mm, and 38.1mm, respectively.

3.2 Landscape and Spatial Analysis

UAA increased in a downslope direction, with the largest areas of UAA occurring in convergent areas towards the base of the hillslope. (Table 6) (Figure 4a). Wells 1, 2, 3, 4, 5, and 8 show a clear progression of greater UAA towards the base of the hillslope, near well 8. Wells 6 and 7 have comparatively lower UAA, as they are located on steep side slopes of the gulley which contribute rather than receive lateral flow from the convergent area.

Ksat values ranged from 0.15 to >20cm/hour across the hillslope, with a standard deviation of 7.59cm/hour (Table 7). The overall spatial pattern of Ksat across the hillslope was highly spatially heterogeneous, with two areas of high conductivity occurring along the side slopes of the gulley, and other high Ksat values being dispersed throughout the study area. Wells 1, 4, and 5 were located in areas of high conductivity, whereas wells 2, 3, 6, 7, and 8 had noticeably lower conductivity values at well locations. In particular, the area surrounding wells 6, 7, and 8 had an overall pattern of low conductivity, with no high Ksat values recorded in that area (Figure 4c).

Depth-to-bedrock measurements ranged from 61.5cm to >137cm with a standard deviation of 19.83cm (Table 8). The largest soil depths were recorded in the convergent gulley near wells 1 and 2. Overall soil depth appeared to be a function of landscape position. Soil depth was the lowest in the south-east corner of the hillslope near the Cap Wallace Road, with a transition towards greater soil depths occurring in and at the bottom of the gulley (Figure 4d).

To determine the degree of spatial autocorrelation within the SWE, Ksat, and soil depth datasets, I used the Spatial Autocorrelation tool within ArcGIS 10.1 to calculate Moran's I. I used inverse distance as conceptualization of spatial relationships and the Euclidean distance method since these were the most appropriate choice for continuous data. The default neighborhood search threshold was the distance to include two adjacent neighboring observations – 30 meters for Ksat and soil depth, and 60m for SWE. Moran's I values were 0.034 for SWE, 0.030 for Ksat, and 0.012 for soil depth (Table 9). These values indicate that at these resolutions of measurement, these variables do not appear to exhibit significant spatial autocorrelation.

3.3 Hillslope Water Table Dynamics

In order to quantify hillslope water table responses, I analyzed the data collected from the TruTrack data loggers (Figure 5a). Groundwater responses were never observed at two of the eight groundwater monitoring wells during the period of record; well 3, located on a side slope near the top of the study area, and well 4, located in the middle at the gulley, did not record any water table development. The reason for this lack of measured groundwater response is likely due to the fact that these wells were difficult to complete to bedrock, and often required multiple attempts to install each well. Large rocky debris is present towards the bottom of the soil profile, and it is possible that wells

3 and 4 were installed on top of large rocks, effectively raising the completed depth to above the maximum water table extent at that location. While six of the eight wells have a complete period of record, wells 6 and 7 did not record water table data between the dates of May 21st and August 1st, 2014 due to equipment malfunction.

I observed a range of well dynamics from transient to more persistent depending upon the landscape position across the hillslope (Figure 5a,b). The duration of groundwater response increased in areas with a larger upslope accumulated area. For wells 1, 2, 5, 6, 7, and 8, water tables tended to develop extremely rapidly, usually transitioning from absence of water to maximum height within only a few hours. Once present, water dissipated quickly (hourly scale) in most wells, with well 2 (high side slope) and well 8 (downslope in hollow) displaying a more gradual water level drawdown over a period of weeks. While not all wells wet up during each event, four main hillslope responses are evident within the time series. In March, five wells (1, 2, 5, 6, 8) displayed a presence of water, with the largest response recorded in well 8 near the bottom of the gulley. All six wells recorded extremely-quickly developing water tables in mid-April corresponding with rapid snowmelt. Heavy precipitation events in June and August both produced well responses from wells 1, 2, and 8.

3.4 Non-local Controls on the Duration of Saturation

To examine the relationship between the duration of well saturation and total upslope area, I compared UAA to the cumulative duration of saturation. I found a significant exponential relationship (R^2=0.67, p=0.047) between UAA and the cumulative duration of saturation within the water table monitoring wells (Figure 6). Total cumulative duration of saturation ranged from 263.5 hours at well 7, which is located on a small sideslope, to 1888.5 hours at well 8, located at the bottom of the hillslope in the center of the gulley. Generally, wells located towards the bottom of the hillslope and in convergent areas with higher UAA had greater cumulative duration of saturation.

3.5 Local Soil Characteristics Modulate Topographic Controls on Water Table Dynamics

To better understand the effect of local soil characteristics on the relationship between UAA and cumulative duration of saturation, I compared local mean Ksat to the residuals from the analysis of UAA versus cumulative duration of saturation. Local mean Ksat was a strong predictor ($R^2=0.77$, $p=0.034$) for explaining the variance from the expected duration of saturation (Figure 7). Wells with higher local Ksat had less duration of saturation than expected, and wells with lower local Ksat had longer periods of saturation than predicted based solely upon UAA.

In order to assay the relationship between water table magnitude and variability, I compared water table height values to interpolated Ksat values at well locations. Figure 8 shows all recorded non-zero water table height values for the period of record plotted as boxplots. There is weak evidence ($R^2=0.57$, $p=0.082$) that wells with lower Ksat values have larger variability in water table heights, and higher overall mean water table heights. Including all zero values for water table height within the dataset results in moderately strong evidence ($R^2=0.80$, $p=0.017$) that median water table heights are lower for areas with higher Ksat values at well locations (Figure 9).

3.6 Local Spatial Patterns of Ksat May Affect Hydrologic Connectivity between Wells

I investigated the controls on the spatial variability of hydrologic connectivity between adjacent landscape positions by quantifying the cumulative duration of concurrent saturation between adjacent hillslope wells. Of the upslope-downslope well locations where at least one well responded (wells 2, 5, 6, 7, 8), four pairs of wells recorded concurrent saturation in both upslope and downslope positions (wells 1&2, 5&6, 5&7, as well as 5&8) (Figure 10). The smallest duration of connectivity was between wells 4&5 (0 hours). The largest duration of connectivity was at the bottom of the convergent gulley, between wells 5&8 (850.5 hours). Of these 5 pairs, local mean Ksat served as a predictor variable ($R^2=0.68$, $p=0.085$) for the cumulative duration of hydrologic connectivity with the upslope well, with an exponentially decreasing relationship; areas with larger mean Ksat values had overall lower durations of hydrologic connectivity to upslope positions.

3.7 Initiation of Well Saturation as a Function of Antecedent Wetness and Variability in Bedrock

In order to determine if contributing areas with larger proportions of high Ksat soils require higher antecedent moisture thresholds for water table development, I compared the derived API for the calendar day each well recorded water table development with interpolated Ksat values at well locations (Figure 11). Since some small snowmelt events began before all the data loggers were installed, and wells 6 and 7 were not recording data during June precipitation events, I chose to utilize the well responses driven by large August precipitation events (where a full data set exists) to analyze this relationship. I observed a positive trend (Figure 11) that would suggest that higher Ksat values at well locations may result in higher API values at wet up; however, since only 4 wells responded, this relationship is not significant enough to make any strong claims as to whether Ksat is a clear predictor variable for this relationship (R^2=0.5686, p=0.25).

To examine the relationship between antecedent moisture thresholds for water table development and variability of bedrock topography, I compared the derived API for the calendar day each well recorded water table development with the standard deviation for the interpolated soil depths within each well's local contributing area (Figure 12). I observe a strong positive linear trend (R^2=0.922, p=0.04) indicating that areas with more variability in bedrock topography required higher antecedent wetness conditions for water table development. Wells 7 and 8, with highly planar bedrock topography within the local contributing area (standard deviations of 2.1 and 1.5cm, respectively) required low antecedent moisture conditions for water table development (API=4.3cm). Alternatively, wells with significant variability in bedrock depth, such as wells 1 and 2 (standard deviations of 5.8 and 8cm, respectively) required a significant amount of soil moisture for water table development to occur (API=5.5cm).

Chapter 4: Discussion

4.1 Do Local Soil Patterns of Ksat Modulate Upslope Topographic Controls on the Duration and Magnitude of Soil Saturation?

My results confirm that nonlocal topographic controls are a first order control on the duration of soil saturation for the study hillslope; a significant exponential relationship (p=0.047) exists between the cumulative duration of saturation and hillslope UAA (Figure 6). These results are consistent with previous hillslope hydrology studies that discovered a relationship between nonlocal topographic controls and subsequent hillslope water table response within the Tenderfoot Creek Experimental Forest, MT (Grabs, Seibert, Jencso, and McGlynn, 2009; Jencso *et al.,* 2009; Jencso and McGlynn, 2011; Pacific, McGlynn, Riveros-Iregui, Welsh, and Epstein, 2011), and within Hubbard Brook Experimental Forest, NH (Detty and McGuire, 2010). When considered in the context of previous studies, these highly similar results from the Lubrecht Experimental Forest suggest the presence of transferrable nonlocal controls on the duration of soil saturation that have now been observed in multiple catchments with diverse ecological settings and climatic regimes. Further, the work presented here builds upon previous studies on this topic that have not considered the potential effects of soil attributes on plot-scale water table magnitude, duration, and connectivity.

While non-local topography has a clear signature in the cumulative duration of water table development, research has also shown the importance of local soil characteristics, specifically hydraulic conductivity, on water table development (Smith *et al.,* 2013), and runoff generation (Niehoff, Fritsch, and Bronstert, 2002). My study reveals that while there exists a significant exponential relationship between duration of saturation and UAA, variance from the predicted relationship may be further explained by examining local patterns of Ksat. Wells with high local mean Ksat values, such as wells 5 and 7, exhibited less cumulative duration of saturation than the predictive model suggests. Conversely, wells with lower mean Ksat values, such as wells 1, 6 and 8, tended to display longer cumulative duration values than the predictive model suggests. Hydraulic conductivity is defined “the rate at which water moves through a porous medium under a unit potential-energy gradient” (Dingman, 2002), thus, areas with larger local mean

Ksat values are able to transmit water downhill more rapidly, resulting in a faster transition from a state of saturation to non-saturation.

This study both supports and builds upon previous arguments emphasizing the importance of characterizing spatial patterns of Ksat in studies which attempt to elucidate hillslope flow behavior; for example, in their 1978 study in Somerset, England, Anderson and Burt utilized measurements of key soil parameters, including field-state hydraulic conductivity, and showed that accurate determinations of hydraulic conductivity over different types of hillslope topography were essential to a more complete understanding of hillslope throughflow processes and hillslope-channel hydrology relationships. Further, these authors demonstrated that “the consequences of ignoring hydrologic conductivity in such investigations can lead to markedly inaccurate process inference”. Similarly, in this study, I discovered that saturated hydraulic conductivity was critical in modulating upslope topographic controls; although total upslope area was a first-order control on the cumulative amount of time landscape positions were saturated, local patterns of Ksat were a significant explanatory variable for deviation from the predicted relationship for UAA versus duration of saturation (Figure 7). These results demonstrate that hydraulic conductivity is an important control for local and hillslope scale hydrologic processes.

In addition to local soil hydraulic characteristics influencing the duration of saturation, this study also identifies local patterns of Ksat as influential to both the variability and magnitude of local water table development. Wells located in areas with high Ksat values displayed less variability in water table heights over time, and lower overall magnitudes of saturation (Figure 8). The median water table height for all wells which recorded a groundwater response also showed an exponentially decaying relationship as a function of Ksat at the well location (Figure 9). I hypothesize that this relationship is due to the fact that as local hydraulic conductivity increases, so too does the rate at which the soils are able to transmit water downslope. With higher hydraulic conductivity values, we expect these areas to transmit and disperse water very quickly, resulting in less water accumulating in these areas. Other studies have also identified larger magnitudes of water table variability in areas of higher hydraulic conductivity. For example, Whittington and Price (2006) in their study Canada also discovered water table fluctuations to be highly controlled by the local hydraulic conductivity, with areas of lower hydraulic conductivity resulting in increased water table fluctuations.

These results support the hypothesis that local patterns of soil hydraulic properties modulate upslope topographic controls on the duration and magnitude of water table responses and have interesting broader implications. While modeling efforts, such as TOPMODEL (Beven and Kirkby, 1979) have had some success in predicting patterns of saturation in different studies (*e.g.* Ambroise, Bevan, and Freer, 1996; Pinol, Bevan, and Freer, 1997), it was noted that “the use of spatial data in model calibration and confirmation is not straightforward”, and “how to do this should be the subject of future work (Bevan, 1997). While significant advances have since been made regarding model sophistication, such as accounting for differences in vertical Ksat (Rupp and Selker, 2005 & 2006), recent research has identified that there is still a need to account for spatial and areal differences in the different vertical distributions of Ksat (Fu, Chen, Zhang, Nie, and Wang, 2015).

The results from this study provide novel insight into how non-local controls are modulated by local patterns of soil hydraulic properties, and highlight the importance for future studies to consider local controls on the movement of water through the soil profile for physically-based hillslope scale studies and modelling efforts.

4.2 Do Well Contributing Areas with Greater Ksat Values Have Decreased Connectivity to Upslope Well Positions Relative to Those with Low Ksat?

UAA has been identified as an important control on hillslope hydrologic connectivity (Jencso *et al.,* 2009; Jencso and McGlynn, 2011); however, I found that local controls also affect the dynamics of hillslope water table development. The results from this study indicate that water table connectivity between adjacent landscape positions may exponentially decrease as a function of higher local median Ksat; however, these results are not as statistically significant as was predicted (Figure 10; $p=0.085$). Since two of the eight wells did not record water table development, this analysis is limited to five data points (wells 2, 5, 6, 7, and 8). The three wells that recorded the highest connectivity with upslope wells (wells 2, 6, and 8, all connected to upslope landscape positions for greater than 350 hours) were highly variable in space and associated UAA, which may suggest that, for this relatively small study plot, local spatial patterns of soil characteristics are a stronger predictor variable than UAA for hydrologic connectivity. Although it was assumed that concurrent saturation at adjacent wells indicated a connected groundwater table between the two locations, an alternative explanation for these results is that we are not observing a spatially continuous groundwater layer between wells, but rather isolated zones of saturation; previous research has noted that for small semiarid basins with shallow soils, the saturated zone can exist as a series of disconnected or only partially connected zones of saturation of limited spatial extent (Maneta, Schnabel and Jetten, 2008; Van Schaik, 2010).

When determining the implication of these results, another important consideration is the relatively small size of the study hillslope. This research study was conducted on a small hillslope study plot of 6,700m^2. Research has shown that the duration of hydrologic connectivity increases with larger values of UAA (Jencso *et al.,* 2009; Jencso and McGlynn 2011; Jencso and McGlynn, in review); these studies found significant relationships when considering hillslopes with UAA values spanning a broader range from 600m^2 to 50,000m^2, a maximum area almost an order of magnitude larger than the study plot considered in this research. In essence, while the scale of this project does not enable us to obtain a macroscopic perspective on the hillslope scale hydrologic processes at work, it does allow for a detailed analysis of local controls at the plot scale.

4.3 Do Well Contributing Areas with Larger Proportions of High Ksat Soils and Those with More Variability in Bedrock Topography Have a Higher Antecedent Moisture Threshold for Water Table Development?

Four hillslope wells responded to large August precipitation events (wells 1, 2, 7, and 8). While I initially hypothesized that well contributing areas with larger proportions of high Ksat soils require higher antecedent moisture thresholds for water table development, I did not observe a significant relationship (p=0.25) between the API required for well response and the Ksat at the well location (Figure 11). There was, however, a trend suggesting that wells with higher Ksat values may require higher antecedent wetness values in order for wells to respond. This indicates that as antecedent wetness values increase and the soil profile nears saturation, areas with relatively higher Ksat values will more rapidly disperse water from the near-saturated areas, subsequently requiring relatively more hydrologic input in comparison with low Ksat areas to achieve saturation. This is supported by Grayson *et al.,* (1997), who describe a dry state where soils are not fully saturated, in which state local controls (*i.e.* local patterns of Ksat) and vertical fluxes are the dominate drivers of hydrologic redistribution. All of this considered together indicates that more research is needed in this area in order to determine the complex, dynamic relationship between local patterns of Ksat and antecedent moisture thresholds for water table development. Future researchers should pay especial attention to the work of Haga *et al.*, (2005) who suggest that rainfall amount and intensity may also be critical factors in rainfall-runoff response lag times and subsurface water movement above the soil-bedrock interface.

I observed a significant linear relationship (p=0.04) between the API at the time the wells responded and variability in the bedrock profile. Wells with highly planar bedrock topography within the local contributing area required low antecedent moisture conditions for water table development in comparison to wells with significant bedrock variability. Areas with high variability in bedrock topography suggest the presence of bedrock depressions in which water will collect until the depth of water accumulated on the bedrock surface exceeds the depth of the bedrock depression, at which point the water will overflow the depression and drain downslope, creating a “fill and spill” process described by Tromp van-Meerveld and McDonnell (2006c). I propose that this “fill and spill” process explains the observation that well contributing areas with greater variability in bedrock topography required higher antecedent moisture thresholds for water table development relative to those with less variability in bedrock topography

In order to fully understand these results, however, we must orient them in the context of watershed scale and the literature describing the relationship between antecedent moisture thresholds and bedrock topography. According to Freer *et al.,* (2002) who analyzed this process on a 20x48m trenched hillslope in the Panola Mountain Research

Watershed in Georgia, the bedrock surface was important for spatial dynamics of hillslope wetting, water table development, and generation of lateral flow. Similarly, Weiler and McDonnell (2004) incorporated soil depth variability into a numerical model of subsurface flow for the Panola hillslope and identified depth-to-bedrock variability as a dominate control on both the spatial variation of subsurface flow and the total subsurface flow volume produced. Taken together with our research results, this indicates that bedrock topography is an important physical parameter of interest when investigating antecedent moisture thresholds required for subsurface flow generation at the hillslope scale. At the very least, more research is needed on the topic of watershed scale and its relationship to antecedent moisture thresholds for water table development and bedrock topography.

4.4 Conceptual Model of Hillslope Flow Processes

This study contributes to our understanding of local versus nonlocal controls on hillslope shallow water table behavior. Through increasing our knowledge of how the spatial organization of local soil characteristics and hydraulic properties lead to emergent patterns of hillslope scale hydrologic connectivity and modulate upslope topographic controls, we gain novel insight into how local processes affect hillslope scale water table response. For example, this study demonstrated that while nonlocal controls such as UAA serve as primary controls on the hillslope scale water table dynamics, local physical and soil characteristics such as Ksat and bedrock topography further impact local water table dynamics across hillslopes. Finally, if we orient these local controls into a larger picture of wetness states, runoff, and streamflow we see that at different moisture states, both local and nonlocal controls may have potentially significant impacts on the timing of subsurface runoff to streams.

During times when the hillslope maintains low levels of soil moisture and the hillslope is in a dry state, local soil characteristics and bedrock topography play an especially important role (Figure 13a). Since soils are not fully saturated, the subsurface flow regime is dominated by vertical flows, and landscape positions are hydrologically disconnected. With rates of evapotranspiration which exceed those of precipitation, soil moisture decreases across the hillslope, and landscape positions become hydrologically disconnected. We would not expect to see significant lateral flow until a transition in the hillslope moisture state occurs.

This transition in moisture state is often driven by snowmelt or large precipitation events which will dramatically increase soil moisture content across the watershed. As antecedent moisture increases, further precipitation inputs result in a wet watershed state where soils are near-saturated, and non-local controls are the primary driver for the downslope routing of water as landscapes positions become more hydrologically connected (Figure 13b). Further, as soil becomes saturated, the variability of bedrock topography will play a role in the timing of the delivery of water to streams, with bedrock depressions requiring time to reach capacity and overflow. Although local soil hydraulic properties and bedrock topography are not first-order controls on the timing of the subsurface through flow at this moisture state, they modulate upslope topographic controls, further affecting the timing, and possibly preferential flow routes, of water being delivered downslope to streams (Figure 14).

4.5 Opportunities for Future Research

This study utilized eight shallow groundwater monitoring wells that were installed across a single hillslope. Of these eight wells, six recorded the presence of water table development. In addition, two wells temporarily experienced equipment malfunction during the observation period. While this study provides interesting preliminary insight into how local soil attributes affect temporal and spatial patterns of groundwater development, this study had a small sample size of six spatial observations of groundwater development. This may have impacted our ability to accurately determine initiation of well saturation as a function of antecedent wetness and variability in bedrock. Future studies should work to incorporate more water table monitoring wells, and in doing so may provide a more complete picture of the interactions between shallow water table dynamics and local soil attributes.

This study examined water table development, including hydrologic connectivity, on one hillslope with a relatively small slope contributing area. Previous research has shown that the duration of hydrologic connectivity increases with larger upslope contributing areas (Jencso *et al.,* 2009; Jencso and McGlynn 2011; Jencso and McGlynn, in review). By employing similar techniques utilized in this study across several hillslopes with larger and varying upslope contributing areas, researchers could gain additional insight into complex interplay between topography and local soil characteristics, and the resulting effect on hillslope water table development and water table connectivity.

In addition, this study normalized the depth of Ksat measurements, relying on one measurement at a normalized depth for each measurement location. However, previous research has discovered that effective Ksat is a function of depth (e.g. Kendall, Shanley, and McDonnell, 1999; Brooks, Boll, and McDaniel*,* 2004), and previous studies have improved their analyses by making multiple measurements at different depths (e.g. Smith *et al.,* 2013). Measuring at only one point in the soil profile may give an intermediate value, based on patterns of conductivity above and below the sample point.

I measured Ksat values in the E horizon which was the most hydrologically relevant location in the soil column for lateral flow development; however, previous studies have shown that Ksat measurements are highly spatially variable (e.g. Nielsen, Biggar, and Erh, 1973; Bjerg, Hinsby, Christensen, and Gravesen*,* 1992; Logsdon and Jaynes, 1996; Sobieraj, Elsenbeer, Coelho, and Newton*,* 2002; Deb and Shukla, 2012), and also highly sensitive to measurement error and the uncertainties associated with the measurement technique utilized (Sherlock, Chappel and McDonnell, 2000). This suggests that outside of a highly controlled experimental environment, point measurements of Ksat may not be the most reliable indicator of soil conductivity properties at the watershed scale. The Ksat values obtained in this research project affirm and build upon these previous results; while they are highly spatially heterogeneous and do not generalize across the entire study area, they do provide insight into local soil controls on the overall magnitude and variability of water table development, duration of hydrologic connectivity with upslope well locations, and variance in the relationship between upslope accumulated area and cumulative duration of saturation within landscape positions.

4.6 Implications

The results obtained from this study suggest that incorporating measurements of local soil characteristics and bedrock topography can provide insight into many larger patterns and processes – for example, spatial patterns of water table magnitude, variability, extent, duration, and connectivity. Previous research has shown that hillslope hydrologic connectivity can affect a range of ecological processes, including downslope nutrient transport, carbon/nitrogen cycling, and biological productivity (Stieglitz *et al.,* 2003). Thus, the findings presented here are an important consideration in the context of snowmelt and precipitation-driven water table model development at the hillslope scale, as understanding hillslope processes is critical for scientists and land managers; these processes will affect the timing and magnitude of runoff, and also have implications for the downslope delivery of nutrients to streams. For example, Ocampo, Silvapalan, and Oldham (2006) demonstrated that for their study hillslope in Western Australia, hillslope hydrological connectivity not only resulted in the downslope delivery of fresh water, but was a critical factor in transporting nitrates that had previously accumulated in the upslope zone. It logically follows that given a state where water tables are continuous and connected across a hillslope, rates of hydraulic conductivity will affect the rates of nutrient transport or retention. Previous studies have confirmed this relationship (Morrice, Valett, Dahm, and Campana, 1997; Butturini *et al.,* 2003). Thus, this hydrological effect on nutrient dispersal is critical for the growth of aquatic vegetation and faunal species, and understanding more about the relationship between hillslope form and process, runoff, and available nutrients is critical to the appropriate management of waterways in mountainous ecosystems.

Furthermore this study has implications for current research in the field of terrestrial biology and ecological restoration. This study was conducted on a hillslope which was recently harvested; as such, this study provides important insights into the dynamics of subsurface runoff in areas that have been cleared of large vegetation. This study might thus provide a foundation for future research that examines the role of groundwater development and stream flow in the processes of forest regrowth.

4.7 Summary

My study examined the roles of spatial patterns in topography, hydraulic conductivity, and bedrock topography on local and hillslope scale shallow water table dynamics. By gathering *in-situ* measurements of Ksat, I further explain variance in the relationship between upslope area and duration of saturation within landscape positions. By comparing water table connectivity to local patterns of Ksat, I address how local controls affect the dynamics of hillslope water table developments. Finally, by utilizing data which identify the spatial patterns of Ksat and the variability in bedrock topography, this study evaluates the effects of local soil characteristics on water table development. Together, these approaches help further our understanding of how local slope soil characteristics may modulate upslope topographic controls on shallow water table development, and subsequent hydrologic connectivity at the hillslope scale.

Chapter 5: Conclusion

I measured water table development at eight locations at 30 minute intervals for 193 days between March 4th and September 12th, 2014 across a 6,700m^2 hillslope in Lubrecht Experimental Forest, Montana. I combined spatiotemporal measurements of seasonal water table development with climatic records for the area and *in situ* measurements of the spatial patterns of SWE, Ksat, and depth-to-bedrock across the hillslope to evaluate how local soil hydraulic properties and bedrock topography modulate hillslope-scale controls on shallow water table development and hydrologic connectivity across the hillslope. This analysis revealed explanatory variables which helped us to predict spatial and temporal water table dynamics, including cumulative duration of saturation, water table variability, overall water table magnitudes, and the effects of bedrock topography. My results and analyses provide new and preliminary insights into how hillslope water table dynamics are affected by both hillslope and local patterns of topography, soil characteristics, and bedrock topography.

On the basis of my analysis, I conclude:

1. Upslope accumulated area is a first-order control on the cumulative duration of saturation for landscape positions.
2. The mean Ksat of local contributing areas is a strong predictor for variance in the relationship between upslope accumulated area and cumulative duration of saturation within landscape positions.
3. The Ksat at the water table monitoring well locations is a strong predictor for both the overall magnitude and variability of water table development.
4. The mean Ksat of local contributing areas is a strong predictor for duration of hydrologic connectivity with upslope well locations.
5. More research is required at this site to determine the complex, dynamic relationship between local patterns of Ksat and antecedent moisture thresholds required for water table development.
6. Higher variability in bedrock topography is correlated with larger antecedent moisture thresholds required for water table development.

This study advances the science of hydrology by addressing previously unresolved questions regarding the relative roles of spatial patterns in topography, hydraulic conductivity and soil depth on local and hillslope scale shallow water table dynamics. A better understanding of these local and nonlocal processes and their effect on hillslope throughflow may contribute to the development of better conceptual and predictive models regarding how soil characteristics affect the timing and magnitude of hydrologic response within hillslopes, and subsequent streamflow generation.

Tables and Figures

Table 1. RMSE and coefficient of correlation for SWE interpolation resolution.

SWE	RMSE (cm)	R^2
20m	33.06	0.1151
10m	3.1755	0.1167
5m	3.1783	0.1151
2m	3.1753	0.1168
1m	3.1778	0.0091

Table 2. RMSE and coefficient of correlation for Ksat interpolation resolution.

Ksat	RMSE (cm/hr)	R^2
10m	3.673	0.8127
5m	2.38	0.9478
2m	1.53	0.9859
1m	1.28	0.9915

Table 3. RMSE and coefficient of correlation for soil depth interpolation resolution.

Soil Depth	RMSE (cm)	R^2
10m	18.933	0.0952
5m	18.6516	0.1233
2m	18.7746	0.1118
1m	18.6553	0.1243

Table 4. Summary statistics for SWE measurements across the entire study hillslope, including uphill of study area.

n	Min (cm)	Max (cm)	Mean (cm)	Median (cm)	Std dev. (cm)	Skewness	Kurtosis
103	0	30.74	16.285	16.59	3.7463	-0.40194	6.8991

Table 5. Summary statistics for SWE measurements within the study area.

n	Min (cm)	Max (cm)	Mean (cm)	Median (cm)	Std dev. (cm)	Skewness	Kurtosis
19	15	16.78	16.285	16.0	3.7463	-0.18854	2.3334

Table 6. Upslope accumulated area values for each well.

Well	1	2	3	4	5	6	7	8
UAA (m^2)	2200	2737	3194	4288	5737	219	154	6834

Table 7. Descriptive statistics for saturated hydraulic conductivity measurements. All Ksat measurement units are in units of cm/hr.

	Study Area	1	2	3	4	5	6	7	8
n	82	22	7	4	8	17	2	2	7
Minimum	0.151	0.432	1.267	1.173	0.951	0.778	1.51	2.86	1.247
Maximum	20	20	20	3.459	20	20	3.968	20	20
Mean	6.387	5.277	8.689	2.30	6.753	9.785	2.739	11.435	4.73
Median	9.525	1.624	5.20	2.285	2.903	3.675	2.739	11.435	1.907
Std. Dev.	7.588	6.636	7.958	0.899	7.255	8.662	1.123	8.575	6.313
Well Ksat	----	11.04	4.77	4.03	15.62	9.39	2.01	3.35	1.30

Table 8. Descriptive statistics for depth-to-bedrock measurements. All depth measurements are in units of cm.

	Study Area	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
n	84	22	7	4	9	17	2	2	7
Minimum	61.5	69	93.2	61.5	65.9	81.5	103	111	66.5
Maximum	137	137	135	125	130	130	115	120	130
Mean	108.613	111.732	111.2	96	102.189	110.324	109	115.5	99.529
Median	111	123	109	98.75	102	109	109	115.5	117
Std. Dev.	19.829	20.723	14.134	24.22	20.547	15.014	6	4.5	25.994
Depth at Well	---	116.451	116.657	112.448	113.92	110.918	108.712	108.787	107.964

Table 9. Spatial autocorrelation report of Moran's Index and corresponding z-score and p-values for measured variables.

	Moran's I	**z-score**	**p-value**
SWE	0.034171	1.388951	0.164848
Ksat	0.029566	1.222756	0.221422
Soil Depth	0.012114	0.727710	0.466791

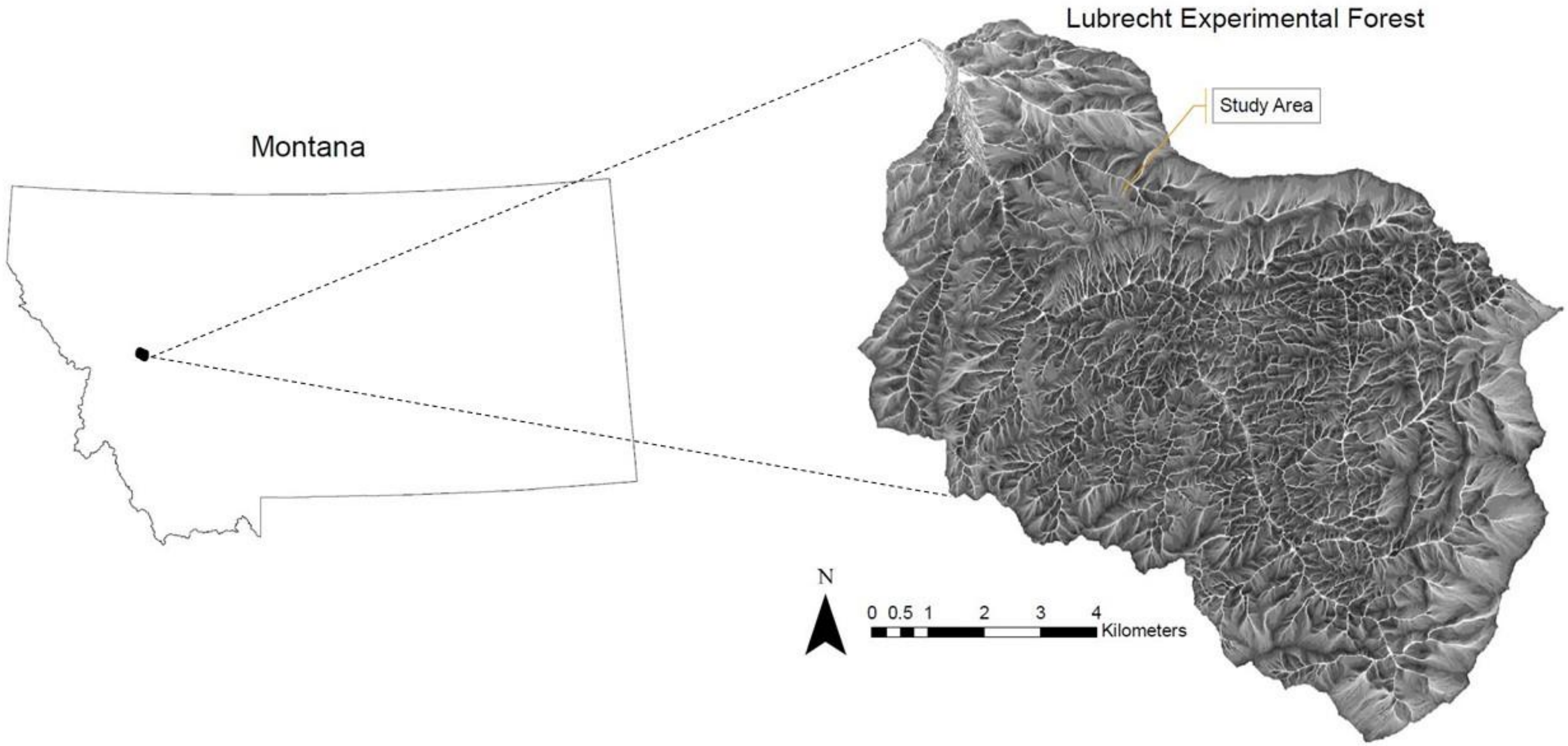

Figure 1. Lubrecht Experimental Forest in western Montana, near Greenough, MT, with study area illustrated in inset map.

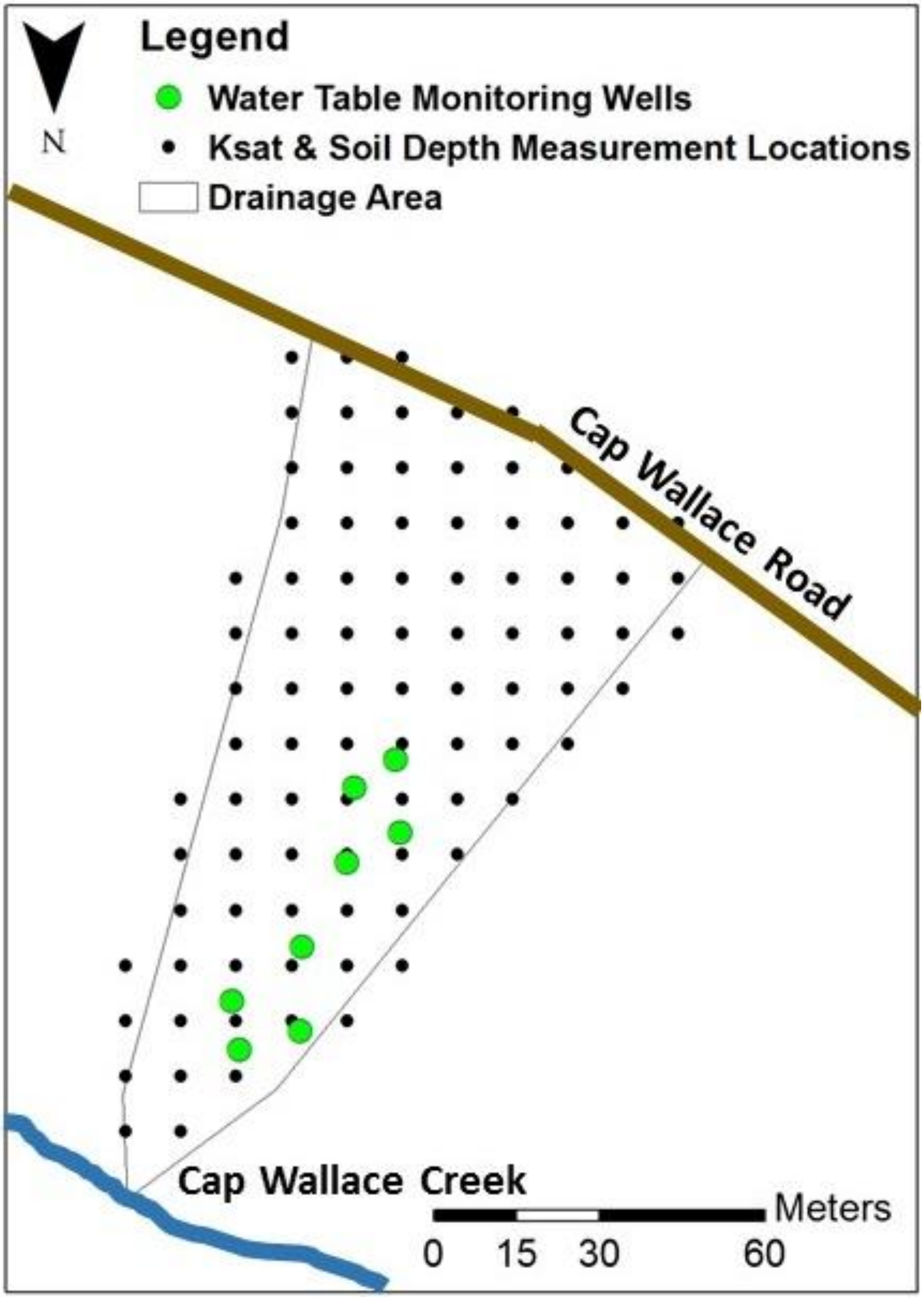

Figure 2. Map of study area illustrating water table monitoring wells and measurement locations for bedrock depth and saturated hydraulic conductivity.

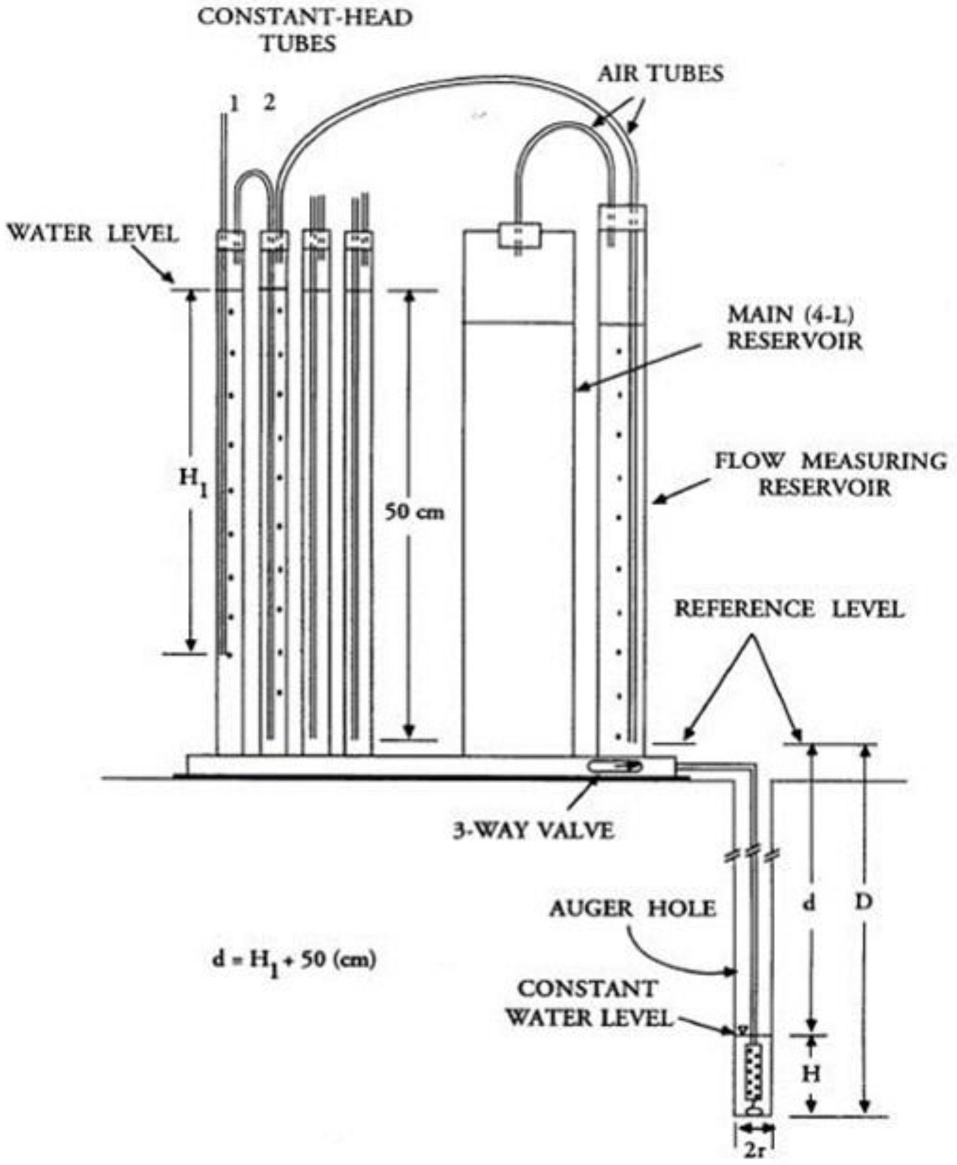

Figure 3. Schematic diagram of the Compact Constant Head Permeameter (Amoozegar, n.d.)

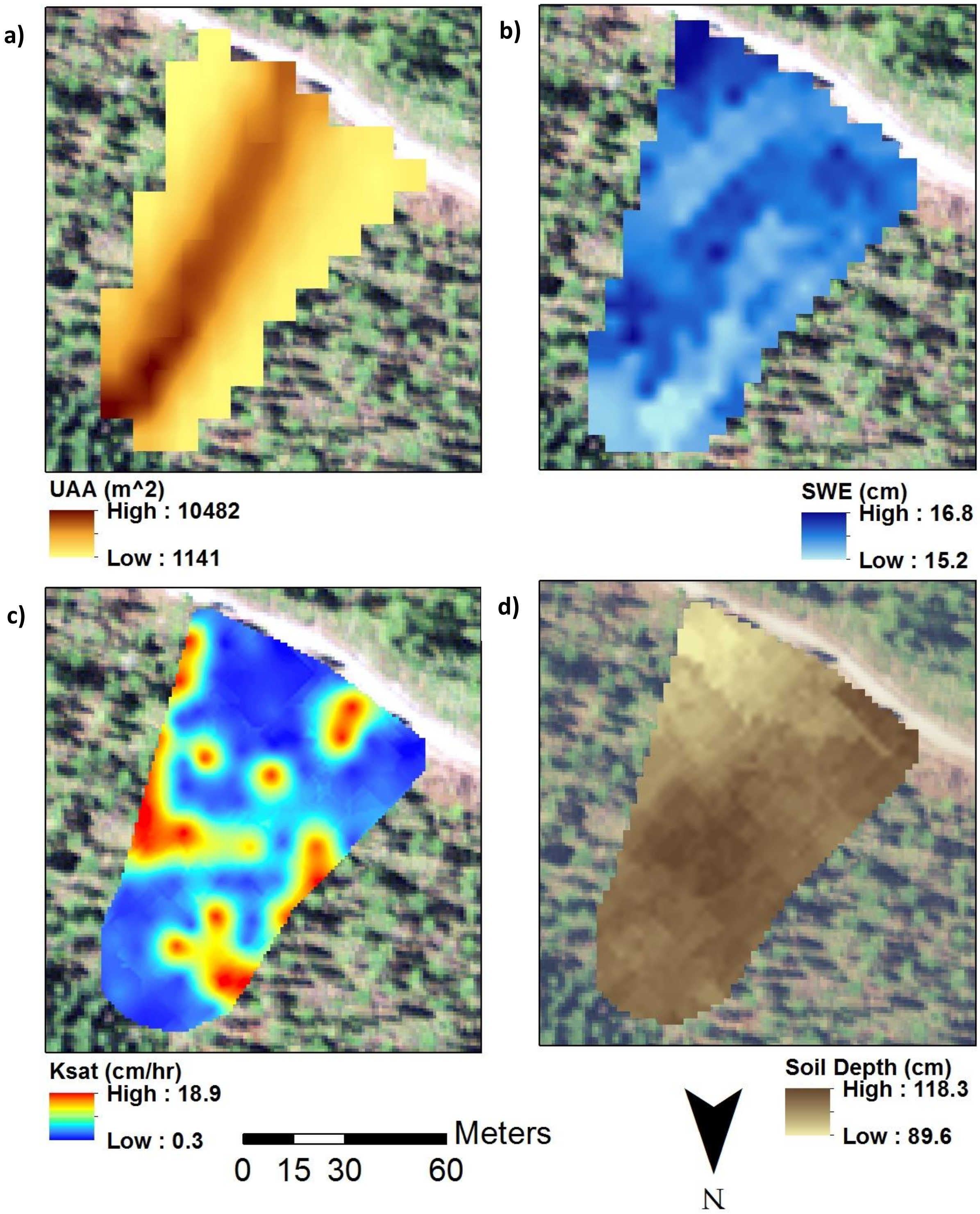

Figure 4. Upslope accumulated area (a), spatial distributions of snow water equivalent (b), saturated hydraulic conductivity (c), and soil depth (d).

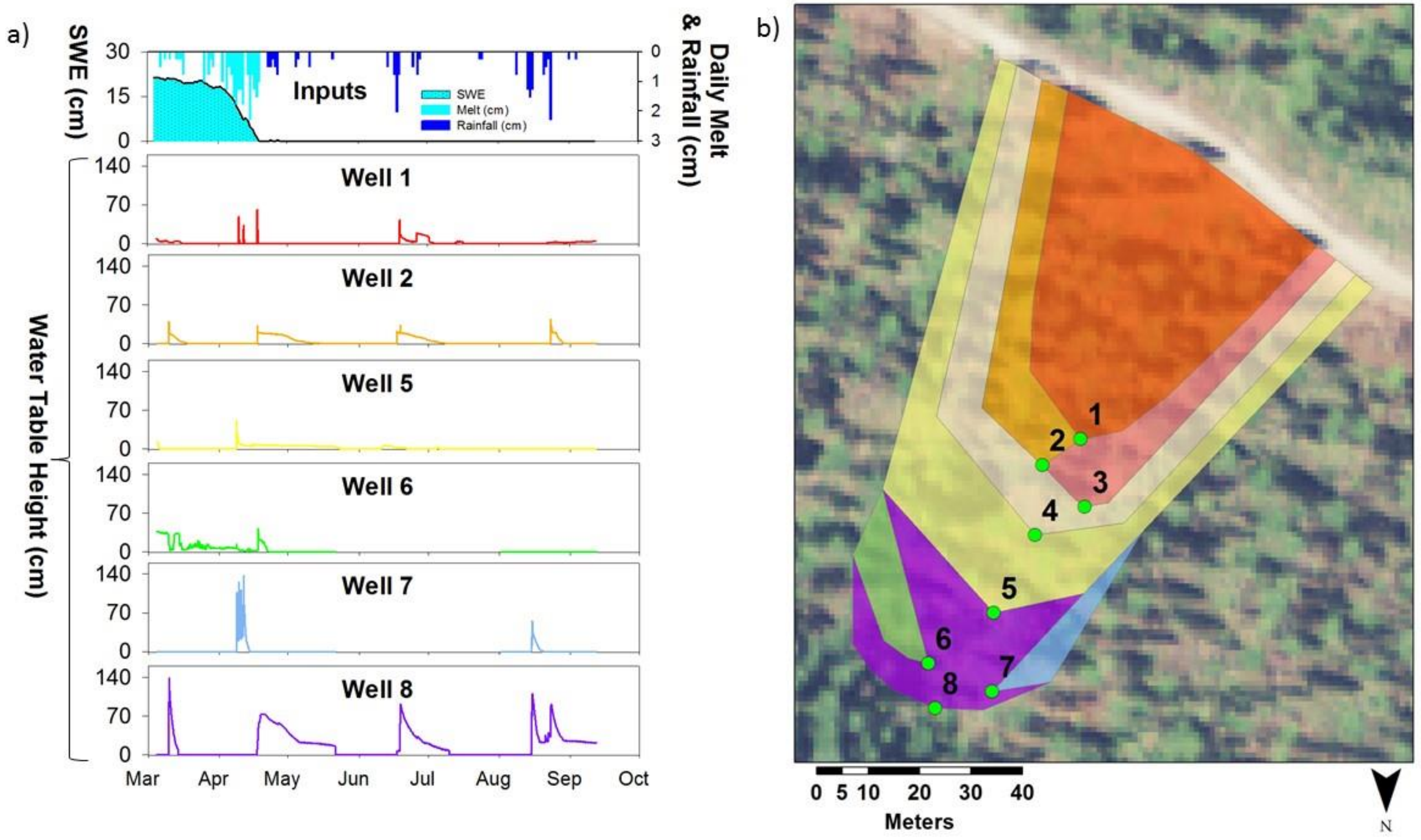

Figure 5. Hydrologic inputs to hillslope (snowmelt & rainfall), and water table height time series for the shallow water table wells which recorded water table development (a), and map of study area indicating local contributing areas (b).

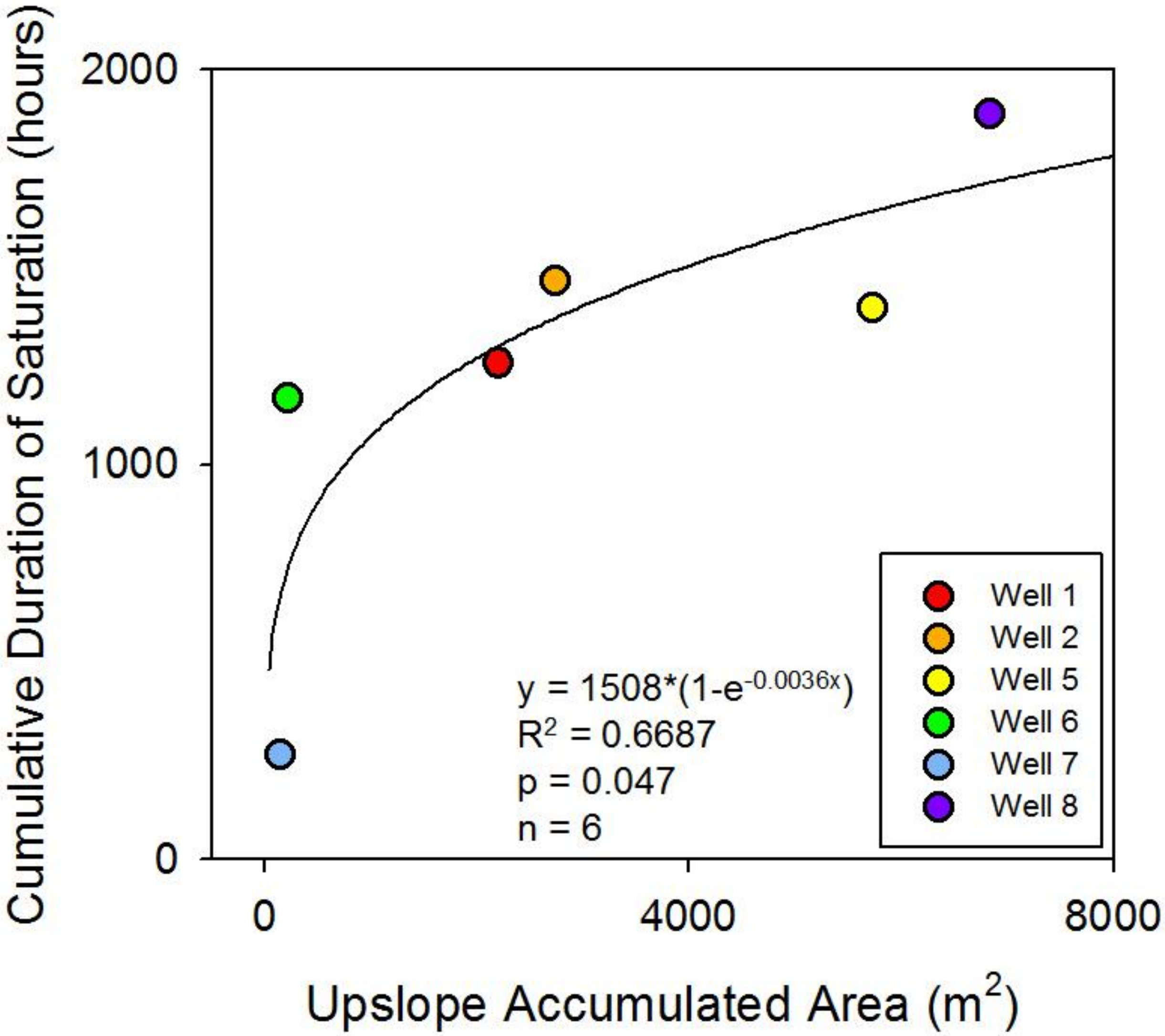

Figure 6. Cumulative duration of saturation as a function of upslope accumulated area. Data points above the line indicate more cumulative saturation than expected by the model, and data points below the line indicate less cumulative saturation than expected.

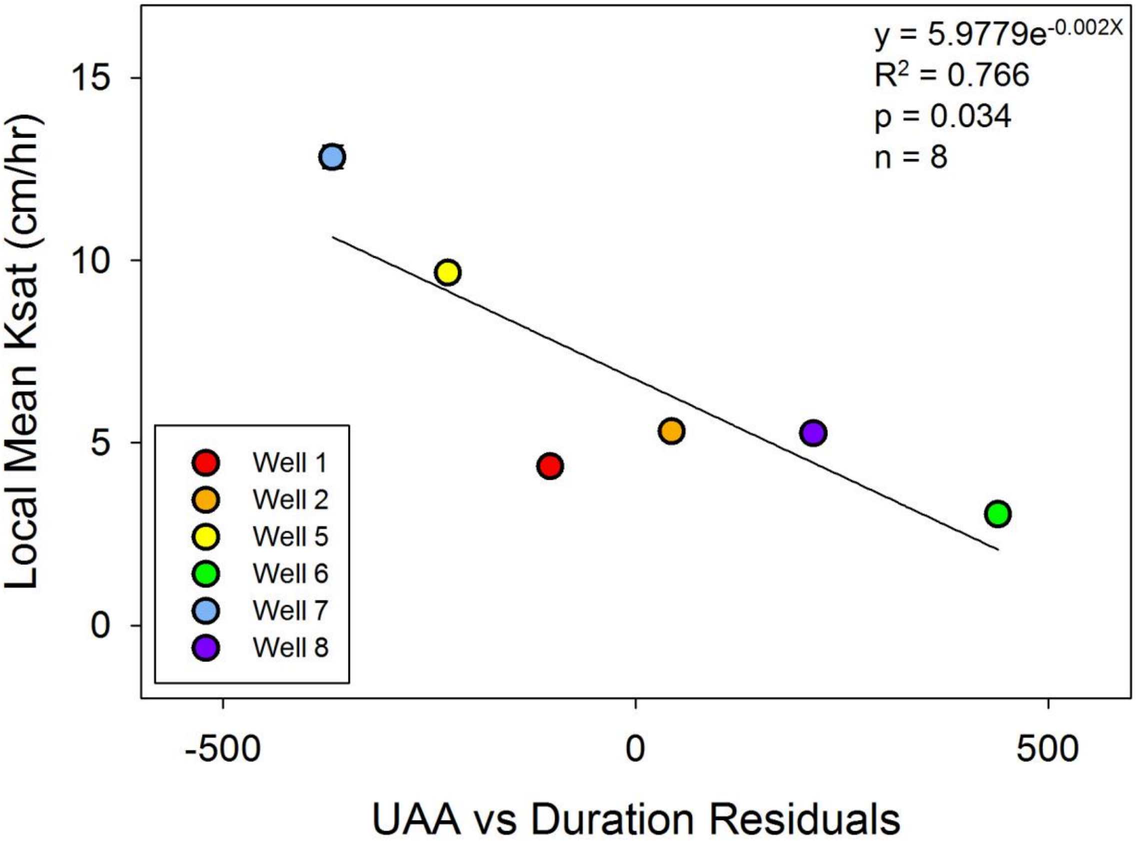

Figure 7. Local mean Ksat plotted as an explanatory variable for the residuals from the previous regression of UAA vs cumulative duration of saturation for each well.

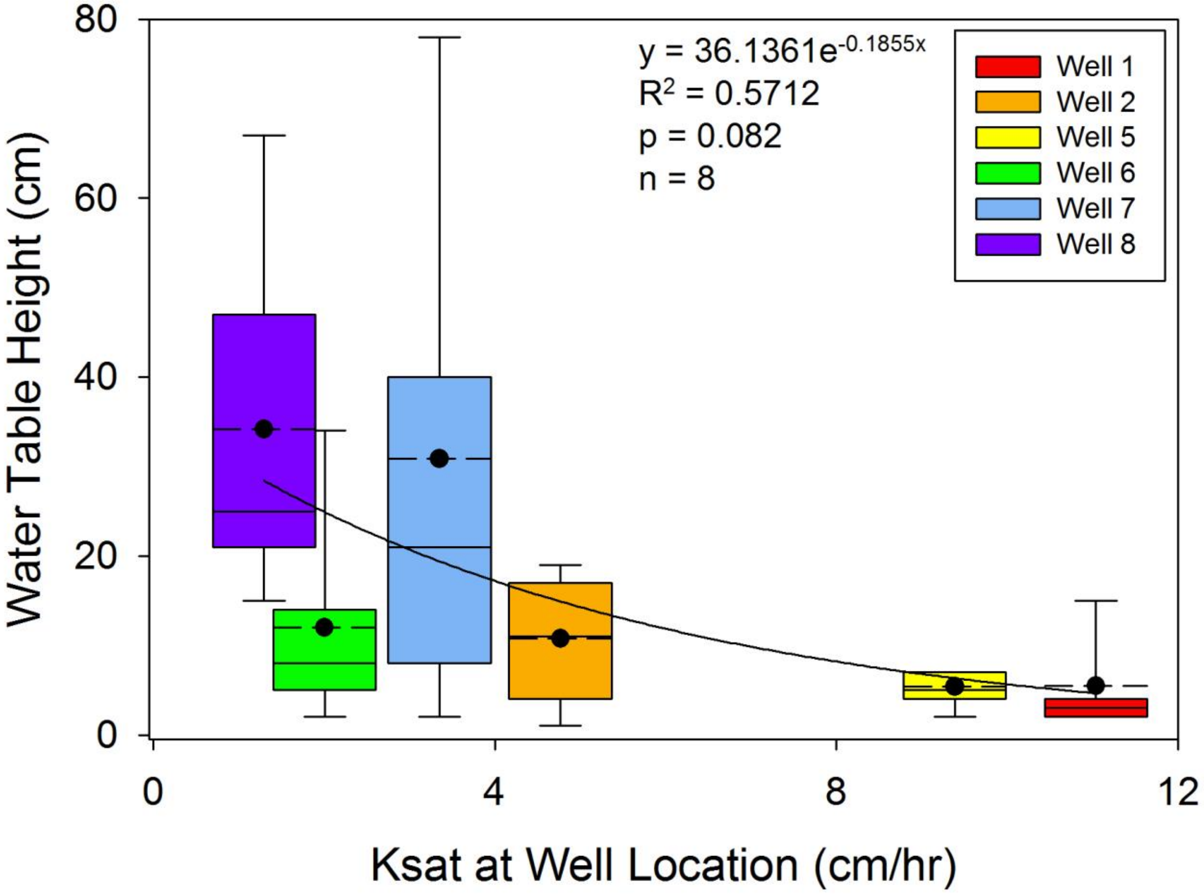

Figure 8. Boxplots of water table height values during periods of saturation as a function of Ksat at each well location. Outliers have been removed to enhance visual clarity. Solid horizontal lines represent median water table height values, and dashed lines represent mean water table height values.

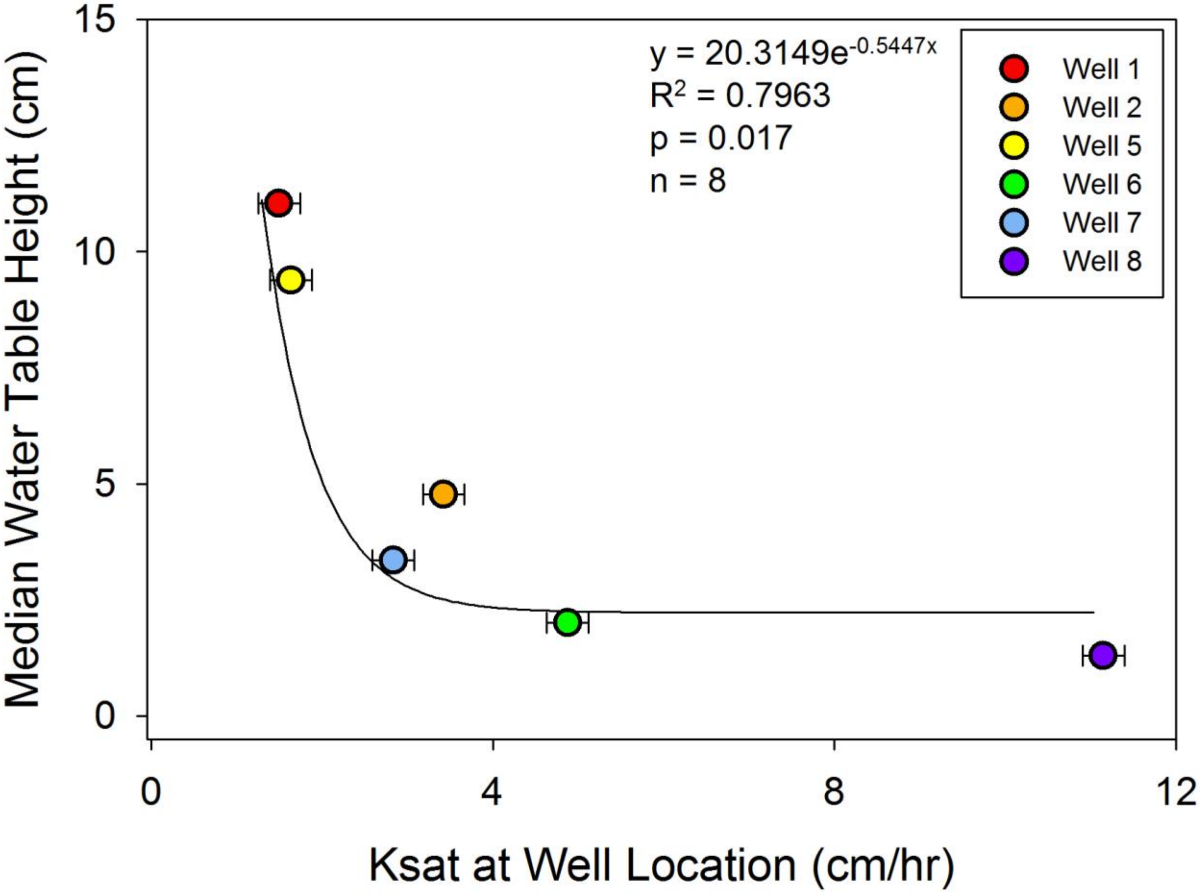

Figure 9. Median water table height for the period of record as a function of Ksat at well locations. Error bars represent standard error.

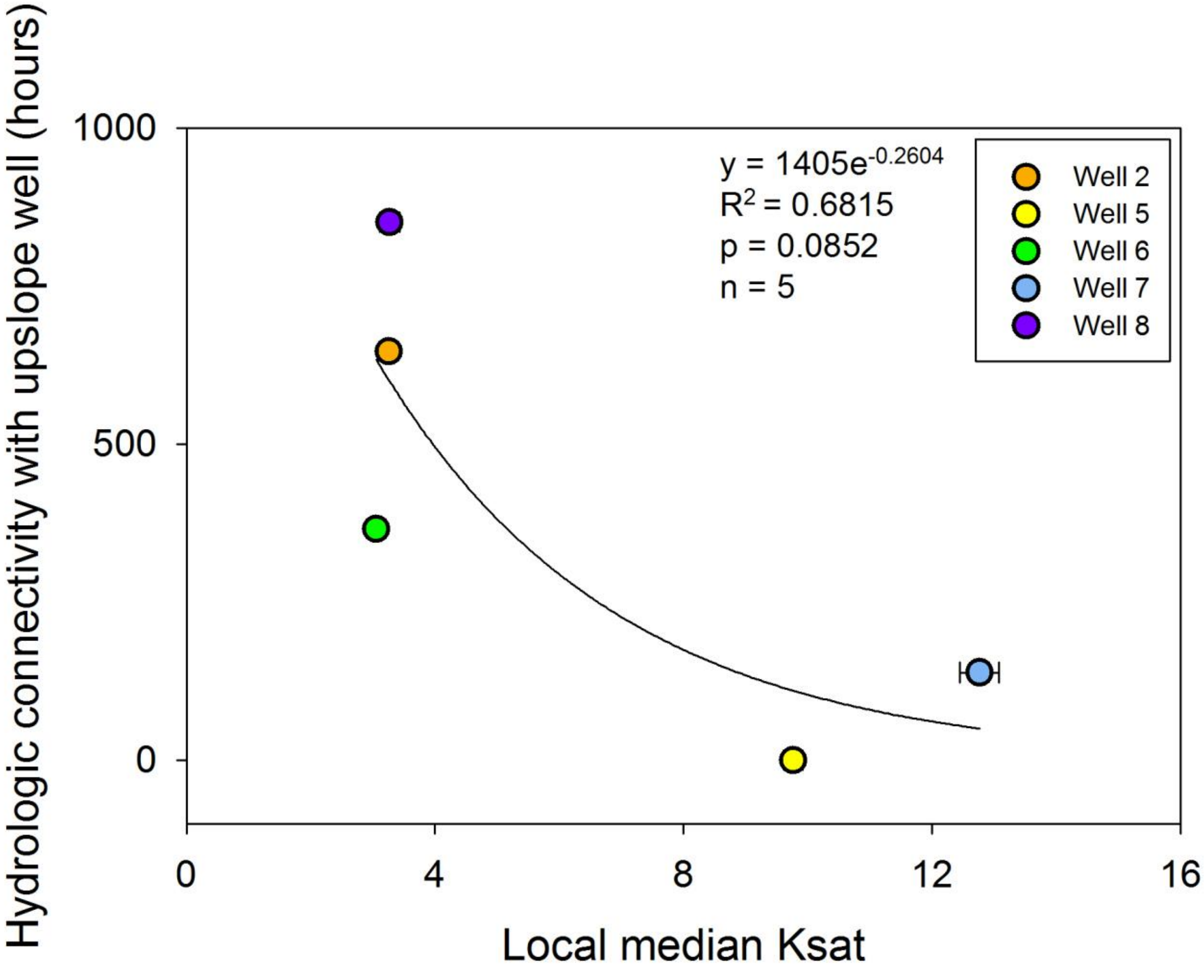

Figure 10. Hydrologic connectivity as a function of local median Ksat. Error bars represent standard error.

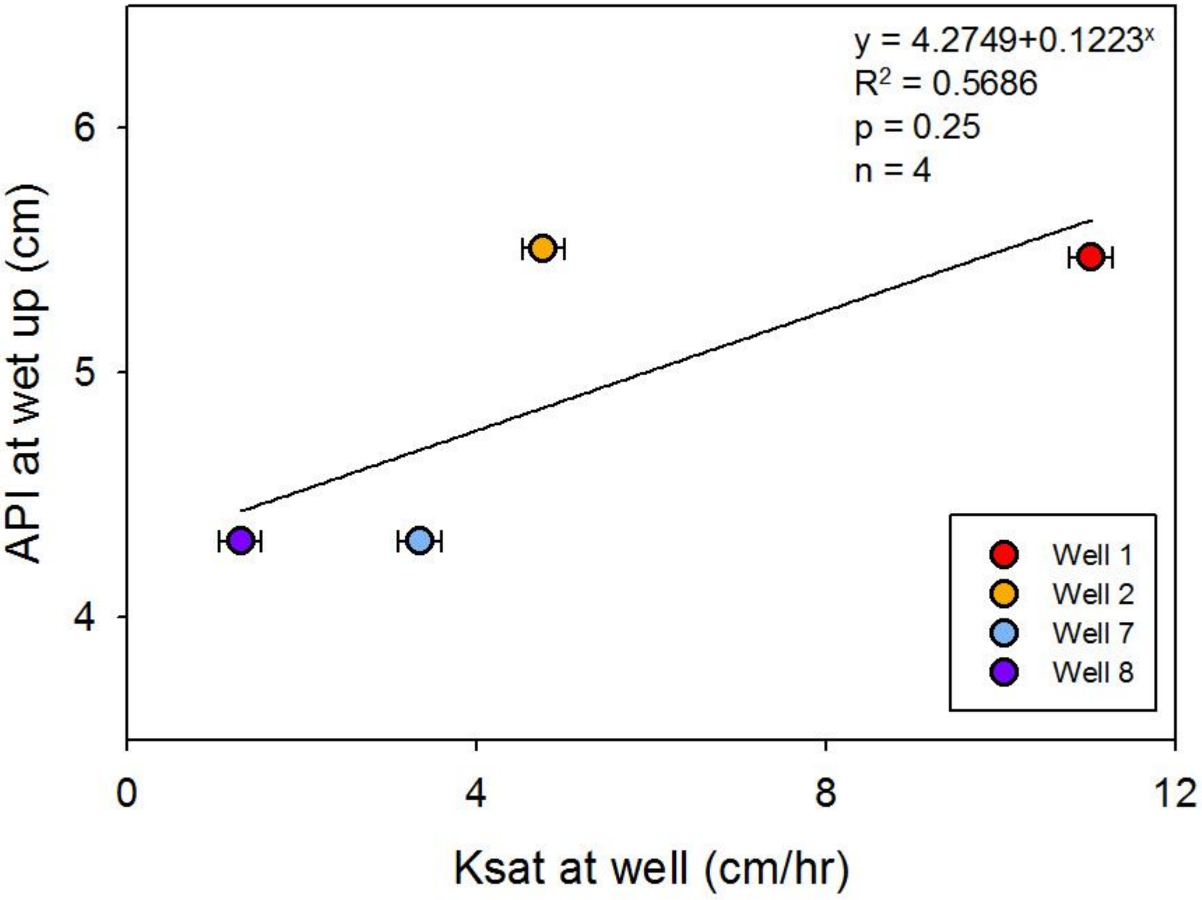

Figure 11. The API on the day each well recorded the presence of water following August precipitation events as a function of the Ksat value at the well location. Error bars represent standard error.

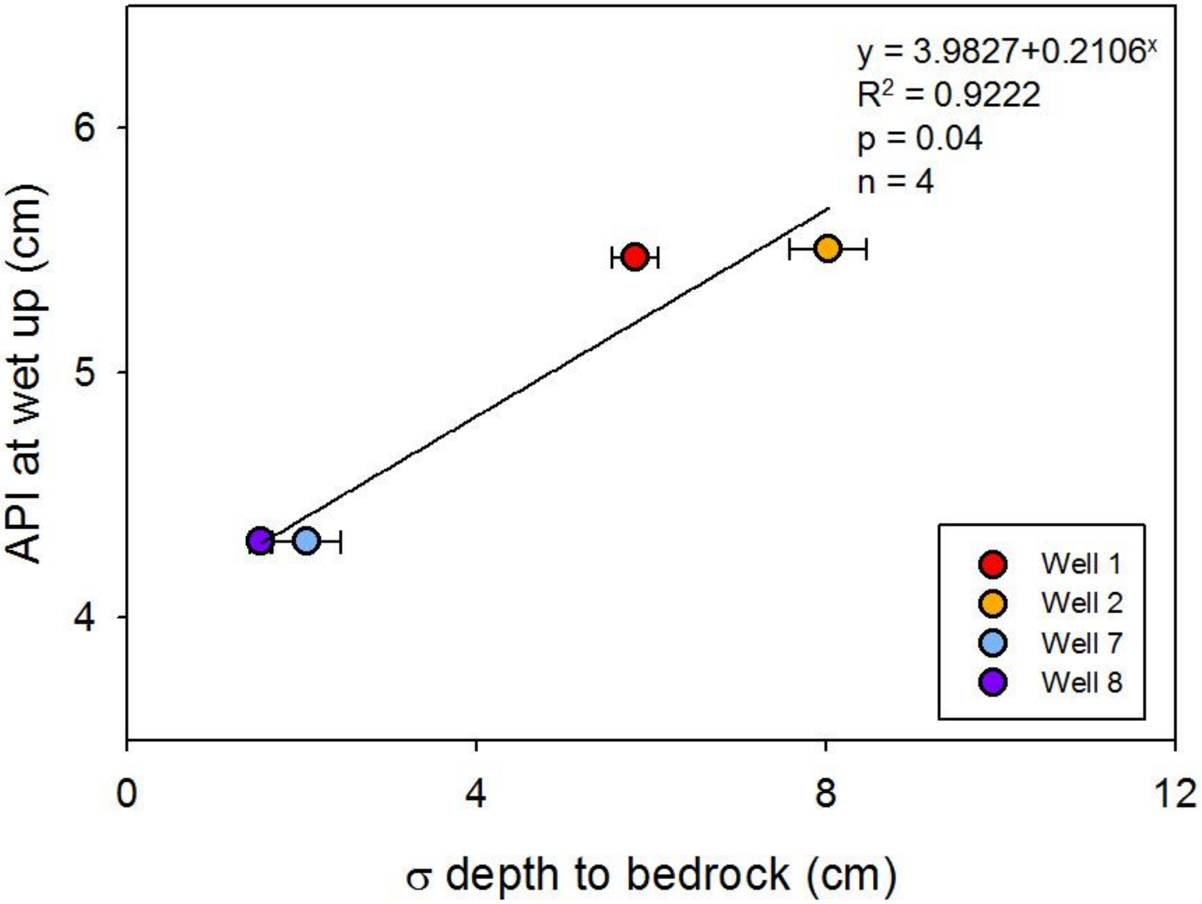

Figure 12. The API on the day each well recorded the presence of water following August precipitation events as a function of the variability of bedrock topography within the local contributing area. Error bars represent standard error.

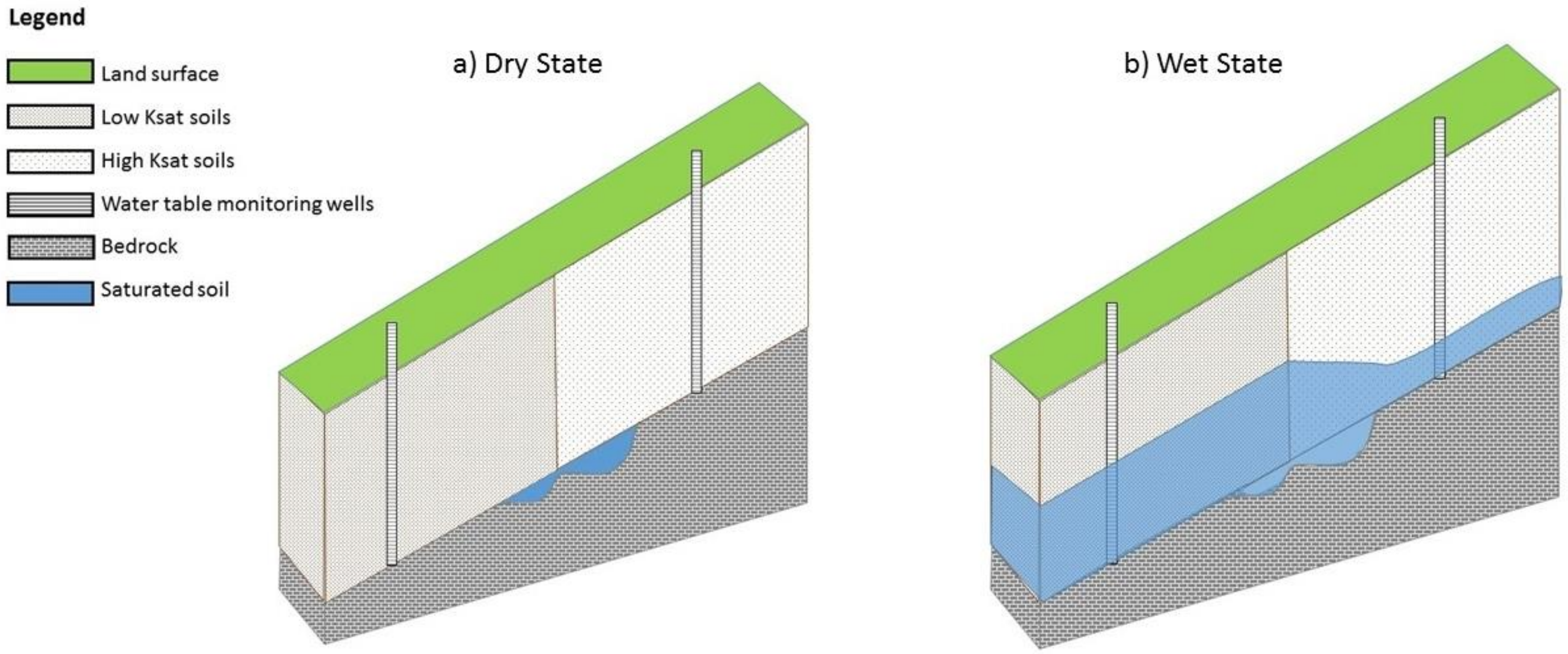

Figure 13. Conceptual diagram of hillslope moisture states. During dry states (a), the subsurface flow regime is dominated by vertical flows, and landscape positions are disconnected. As snowmelt and/or precipitation drive the transition to a wet state where soils are near-saturated (b), non-local controls are the primary driver for the downslope routing of water to streams; however, local soil characteristics also work to influence shallow water table dynamics. Areas with variable bedrock topography force water to collect until the depth of water accumulated on the bedrock surface exceeds the depth of the bedrock depression, thus increasing the required moisture thresholds for water table development and downslope expansion.

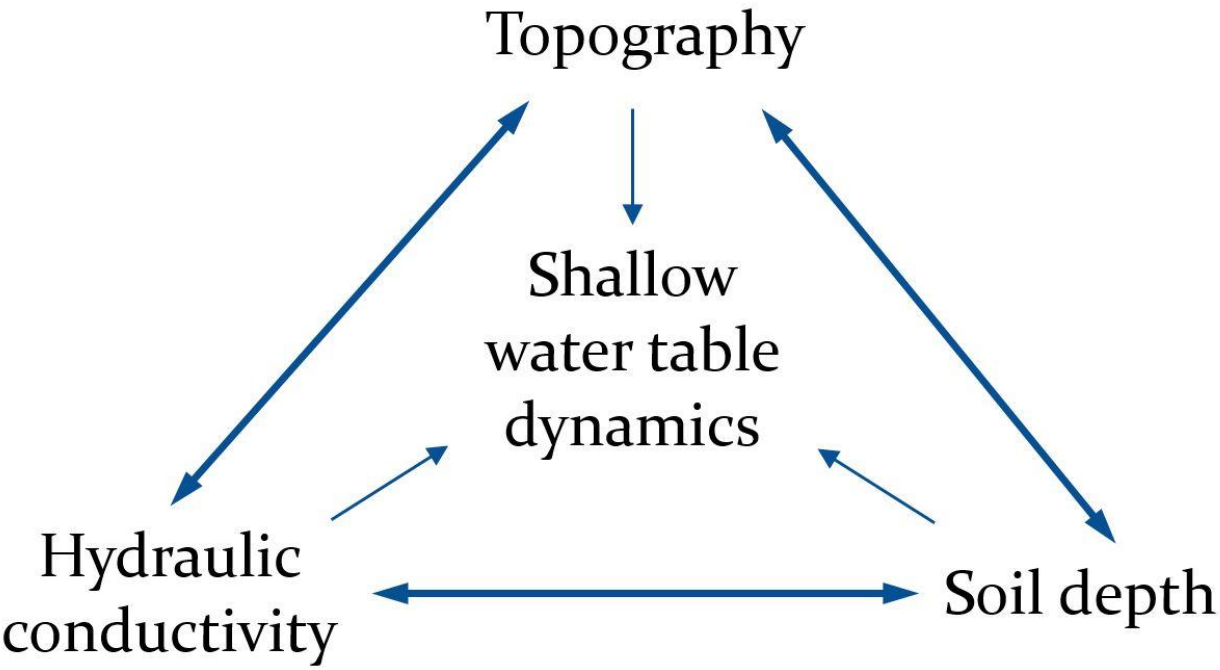

Figure 14. Conceptual framework of influences on flow processes. Nonlocal controls such as topography and total upslope area serve as primary controls on hillslope scale water table dynamics. Local physical and soil characteristics such as hydraulic conductivity and soil depth further impact local water table dynamics across hillslopes.

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Appendix

Raw measurement data for snow water equivalent, saturated hydraulic conductivity, soil depth measurements. ND indicates no data.

Measurement Location	Ksat (cm/hr)	Depth to bedrock (cm)	SWE (cm)
2	ND	88.00	23.00
3	ND	ND	12.50
4	ND	ND	15.79
5	3.87	127.00	14.54
6	0.15	93.20	14.39
7	20.01	103.00	19.09
8	0.61	ND	14.10
9	1.11	98.60	16.42
10	1.54	98.90	16.26
11	1.21	130.01	11.72
12	1.30	98.20	17.77
13	20.01	123.10	16.72
14	ND	ND	10.19
15	8.43	130.01	18.33
16	20.01	127.90	10.92
17	1.19	113.50	14.38
18	2.94	82.50	13.72
19	1.22	69.00	19.13
20	1.15	84.20	17.48
21	1.56	86.50	19.68
22	ND	130.01	14.60
23	1.21	135.00	18.52
24	20.01	130.01	20.05
25	0.43	125.00	30.74
26	0.58	77.00	10.33
27	0.86	130.01	19.09
28	20.00	110.90	15.09
29	2.09	65.90	17.81
30	20.01	94.30	17.51
31	1.64	116.20	20.12
32	3.72	83.00	16.88
33	0.76	92.30	12.16
34	1.49	130.01	18.82
35	20.01	86.10	18.86
36	2.59	130.01	14.53

37	5.20	104.40	18.46
38	0.95	130.01	13.73
39	20.01	93.60	12.21
40	4.05	130.01	16.42
41	3.46	61.50	17.15
42	4.67	120.70	19.28
43	5.87	90.70	18.40
44	1.71	127.70	16.33
45	2.47	127.50	17.87
46	6.49	99.60	16.26
47	20.01	81.50	16.42
48	0.95	108.60	16.59
49	17.93	102.40	19.92
50	1.73	125.10	16.26
51	14.44	130.01	18.81
52	11.67	130.01	16.10
53	20.01	108.70	15.77
54	18.19	130.01	19.86
55	20.01	109.00	20.35
56	2.84	86.50	20.71
57	1.17	111.30	14.06
58	1.73	116.00	17.42
59	2.16	130.01	22.85
60	3.68	105.50	16.23
61	1.76	98.00	17.72
62	20.01	128.20	17.97
63	1.03	124.20	9.58
64	20.01	116.40	16.70
65	0.78	101.90	11.71
66	1.99	129.00	18.16
67	1.51	114.80	22.24
68	2.04	100.00	10.71
69	12.99	98.50	18.68
70	19.21	130.01	13.83
71	1.91	70.00	18.66
72	3.97	102.70	18.91
73	20.01	120.00	12.69
74	20.01	73.20	13.93
75	1.37	121.00	18.37
76	2.58	118.50	13.75
77	4.39	130.01	11.35
78	0.82	85.40	16.12
79	2.86	111.00	20.25

80	1.61	117.00	18.19
81	1.25	66.50	11.07
82	2.57	122.80	21.90
83	0.57	130.01	16.67
84	0.73	137.00	16.05
85	0.83	118.20	19.27
86	1.90	78.00	14.28
87	1.28	122.50	15.46
88	20.01	130.01	13.06
89	ND	ND	16.84
90	ND	ND	10.74
91	ND	ND	17.90
92	ND	ND	16.15
93	ND	ND	17.48
94	ND	ND	15.79
95	ND	ND	18.91
96	ND	ND	8.96
97	ND	ND	11.88
98	ND	ND	19.15
99	ND	ND	18.80
100	ND	ND	13.24
101	ND	ND	12.91
102	ND	ND	16.80

Hillslope data for water table monitoring wells which demonstrated a water table response during the study period. PoR refers to the entire period of record from 3/4/2014 to 9/12/2014. WTH refers to water table height.

Wells	Area (m2)	UAA (m2)	Soil depth (cm)	Ksat (cm/hr)	SWE (mm)
1	2200.12	2200.12	116.45	11.04	1608.62
2	538.94	2737.42	116.66	4.77	1612.08
5	1443.47	5736.86	110.92	9.39	1531.04
6	219.31	219.31	108.71	2.01	1555.45
7	153.83	153.83	108.79	3.35	1524.15
8	728.29	6834.28	107.96	1.30	1535.82

Wells	Local median Ksat (cm/hr)	Local mean Ksat (cm/hr)	Local median depth (cm)	Local mean depth (cm)	Mean soil depth (cm)
1	2.97	4.35	104.03	104.12	104.12
2	3.26	5.31	99.23	100.76	100.76
5	9.77	9.65	110.07	107.50	107.50
6	3.05	3.04	109.54	109.73	109.73
7	12.76	12.83	110.60	110.63	110.63
8	3.27	5.25	109.52	109.66	109.66

Wells	Std. deviation soil depth (cm)	Soil depth range (cm)	Local median SWE (mm)	Local mean SWE (mm)	UAA median Ksat (cm/hr)
1	5.82	26.71	1593.55	1597.80	2.97
2	8.03	27.65	1619.57	1607.34	3.16
5	6.61	27.49	1619.14	1616.88	5.44
6	1.77	9.00	1620.73	1611.72	3.05
7	2.05	7.58	1577.94	1589.47	12.76
8	1.53	8.71	1551.65	1562.68	4.88

Wells	UAA mean Ksat (cm/hr)	UAA median depth (cm)	UAA mean depth (cm)	UAA median SWE (mm)	UAA mean SWE (mm)
1	4.35	104.03	104.12	1593.55	1597.80
2	4.77	103.63	103.65	1593.55	1597.09
5	6.58	107.96	106.31	1601.49	1603.33
6	3.04	109.54	109.73	1620.73	1611.72

7	12.83	110.60	110.63	1577.94	1589.47
8	6.41	109.40	107.60	1595.88	1595.97

Wells	Duration saturation (hr)	Duration Saturation (%)	Mean WTH PoR (cm)	Median WTH PoR (cm)	Mean WTH Sat (cm)
1	1258.00	0.27	1.50	0.00	5.47
2	1465.50	0.32	3.43	0.00	10.75
5	1397.50	0.30	1.64	0.00	5.38
6	1167.50	0.41	4.88	0.00	11.98
7	263.50	0.09	2.84	0.00	30.86
8	1888.50	0.41	11.15	0.00	27.06

Wells	Median WTH Sat (cm)	Max WT Height (cm)	t connect downhill (hr)	t connect uphill (hr)	Δt saturation-melt (hr)
1	3.00	61.00	0.00	--------	367.50
2	11.00	44.00	0.00	646.50	557.50
5	5.00	52.00	850.50	0.00	341.50
6	8.00	42.00	193.00	366.00	563.50
7	21.00	137.00	123.50	139.00	340.50
8	24.00	122.00	--------	850.50	552.00

Wells	API March & April	API April	API June	API August	Average API
1	8.66	8.66	5.16	5.47	6.43
2	0.69	14.43	3.26	5.51	7.73
5	7.17	7.17	2.72	--------	4.95
6	0.92	14.43	--------	--------	14.43
7	7.17	7.17	--------	4.31	5.74
8	0.69	14.43	3.26	4.31	7.33