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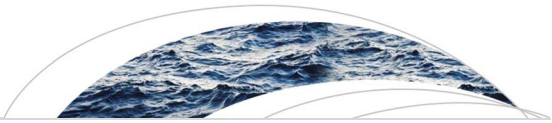

RESEARCH ARTICLE
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Key Points:
- On average, shallow groundwater wells required a storm of 31 mm or greater to respond
- The effect of topography and antecedent wetness on groundwater responses became more important as storms progressed
- Topography had a greater influence on the magnitude of water table response than on the response timing

Supporting Information:
- Supporting Information S1

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The Relative Influence of Storm and Landscape Characteristics on Shallow Groundwater Responses in Forested Headwater Catchments

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Abstract Shallow groundwater responses to rainfall in forested headwaters can be highly variable, but their relative strengths of influences remain poorly understood. We investigated the roles of storms and landscape characteristics on short-term, shallow groundwater responses to rainfall in forested headwater catchments. We used field observations of shallow groundwater combined with random forest modeling to identify the factors that affect shallow groundwater responses and the relative influences of key response drivers. We found that the rainfall thresholds required for groundwater responses were only met by the largest quartile of events, suggesting that most events contributed to unsaturated soil storage or were lost to evaporation. Significantly higher rainfall thresholds and longer response times for south facing catchments as opposed to north facing catchments highlighted the role of insolation in setting antecedent conditions that influenced the groundwater response. During storms, there were significantly larger increases in water table height in catchments dominated by coniferous forests compared to deciduous forests, indicating that local spatial characteristics of hillslopes could be more important factors for groundwater response than catchment wetness. The random-forest analysis revealed that total rainfall amount had the greatest influence on most groundwater responses, but the relative influence of topography and local antecedent wetness was more pronounced as events progressed, indicating a shift in hydrological processes during different stages of the groundwater response. These results have implications for our understanding of runoff generation processes, including processes that determine hydrologic connectivity between stream and hillslopes.

1. Introduction

Shallow groundwater in headwater catchments sustains aquatic and riparian ecosystems, supplies base flow to downstream environments, and provides valuable surface water for drinking, irrigation, and recreation (Alexander et al., 2007; Price, 2011; Singh et al., 2016). In headwater environments, shallow groundwater facilitates hydrological connectivity among various landscape elements (Bracken & Croke, 2007; Emanuel et al., 2014; Jencso et al., 2009; Pringle, 2003), influences soil biogeochemical cycling (McClain et al., 2003; Mulholland et al., 1990), and affects slope stability (Marchi et al., 2009; Montgomery et al., 2002; Onda et al., 2004). Given the importance of shallow groundwater to hydrological and biogeochemical processes in headwaters, research has long focused on shallow groundwater dynamics in these environments (Ali et al., 2011; Emanuel et al., 2014; Dunne & Black, 1970; Freeze, 1974; Gannon et al., 2014; Hursh & Brater, 1941; Jencso & McGlynn, 2011; Tani, 1997; Uchida et al., 2005; Whipkey, 1965; Woods & Rowe, 1996). Shallow groundwater dynamics can be influenced by the heterogeneity in the landscape (Wagener et al., 2007; cf. Bachmair & Weiler, 2011).

During rainfall events, shallow groundwater is often a key source of streamflow (Dunne, 1978; Haught & van Meerveld, 2011; Shanley et al., 2015), connecting various parts of the landscape during peak runoff (Hewlett & Hibbert, 1966; McGlynn et al., 2004) and facilitating solute transport to headwater streams (Anderson et al., 1997; Kendall et al., 1999; McGlynn & McDonnell, 2003; Scanlon et al., 2001; van Verseveld et al., 2009). A wide-ranging metrics have been used to quantify and assess groundwater responses to rainfall events, including threshold responses to rainfall (Peter et al., 1995; Tani, 1997; Tromp-van Meerveld & McDonnell,

2006a, 2006b; Whipkey, 1965), changes in water table elevation (Bachmair et al., 2012; Detty & McGuire, 2010; Dunne, 1978; Fannin et al., 2000; Sidle et al., 2000), and the timing of the groundwater responses relative to precipitation (Montgomery & Dietrich, 2002; Mosley, 1979; Penna et al., 2015; Rinderer et al., 2016). These various metrics describe different aspects of the groundwater hydrograph. However, a limited number of studies have examined the combination of metrics to offer a more nuanced understanding of shallow groundwater dynamics (e.g., Bachmair et al., 2012; Detty & McGuire, 2010). For instance, Detty and McGuire (2010) analyzed water table elevations and the area under the groundwater hydrograph in a forested headwater catchment of Oregon, USA. Bachmair et al. (2012) studied the response frequency of wells, rise in water table, slope of rise, and lag time from initial rise until peak along three hillslopes in Germany. Within this context, there remains a need to use multiple response metrics to highlight how rainfall affects various aspects of groundwater hydrograph differently, and how we can integrate these metrics to provide a more comprehensive understanding of groundwater responses in headwater environments.

Previously, groundwater responses to rainfall events have been attributed to bedrock topography (Noguchi et al., 2001; Tromp van-Meerveld and McDonnell 2006a,2006ab), surface topography (Anderson & Burt, 1978; Dunne & Black, 1970; Fujimoto et al., 2008; Lana-Renault et al., 2014; Penna et al., 2015; Rinderer et al., 2016; Sidle et al., 2000), and soil properties (Fannin et al., 2000; Mosley, 1979; Penna et al., 2015; Sidle et al., 2000). All of these factors exert important controls on groundwater responses to events, but our understanding of how the relative influences of these factors on groundwater responses vary in space and time has been limited to a few studies and catchments. For instance, using multivariate analysis, Bachmair and Weiler (2012) found that soil depth and topography had a greater influence on groundwater responses (e.g., water table and well activation) than vegetation properties on groundwater responses. However, the scope of their study was limited to five storms and topographically similar hillslopes. Other research (Rinderer et al., 2016) has attributed groundwater response timing and rainfall thresholds mainly to topography rather than storm properties.

Collectively, prior studies show how various factors interact to mediate shallow groundwater responses to rainfall, depending upon the response metric and the catchment characteristics. However, it remains to be seen whether landscape characteristics (e.g., topography, soils) are generally more important than storm characteristics in determining the nature of shallow groundwater responses to storms in headwater catchments. In particular, we know little about the relative effects of aspect (south, north) and vegetation type (deciduous and coniferous) on groundwater responses in humid environments. Further, how the relative influences of these drivers on groundwater response may vary with the seasons. Understanding the relative influences of these drivers in time is critical for predictive modeling. Such work has the potential to yield important insights for catchment hydrology.

To this end, we examined groundwater responses to 43 separate rainfall events at 22 landscape positions, representing various combinations of drainage area, aspect, and vegetation type and relatively deep and permeable soils commonly found in headwater catchments of the southern Appalachian Mountains. We used machine learning to conduct a multivariate analysis to quantify the relative influence of rainfall properties and landscape characteristics on groundwater responses. Our study addresses two primary questions: (a) how do shallow groundwater responses to rainfall vary within forested headwater catchments, including the threshold response, magnitude of the water table response, and response timing? (b) How do the relative influences of rainfall properties, topography, and antecedent conditions on shallow groundwater responses vary seasonally?

2. Study Site

This study was conducted at the USDA Forest Service Coweeta Hydrologic Laboratory (hereafter, Coweeta) located in the Nantahala National Forest of western North Carolina, USA (35°03′N, 83°25′W). The Coweeta Basin contains experimental and reference catchments covering a total area of 21.85 km^2 and ranging in elevation from 680 to 1,500 m above mean sea level. The Coweeta Creek, to which all experimental and reference catchments eventually drain, lies within the headwaters of the Tennessee River.

The climate is classified as maritime and humid temperate with cool summers and mild winters, including frequent short-duration rainfall events distributed year-round (e.g., Swift et al., 1988). The mean annual precipitation is 1,791 mm, and the mean annual temperature is 12.6 °C for the low-elevation (685 m above sea level) climate station with the longest record (1937 to 2011). At Coweeta, the growing season is considered to

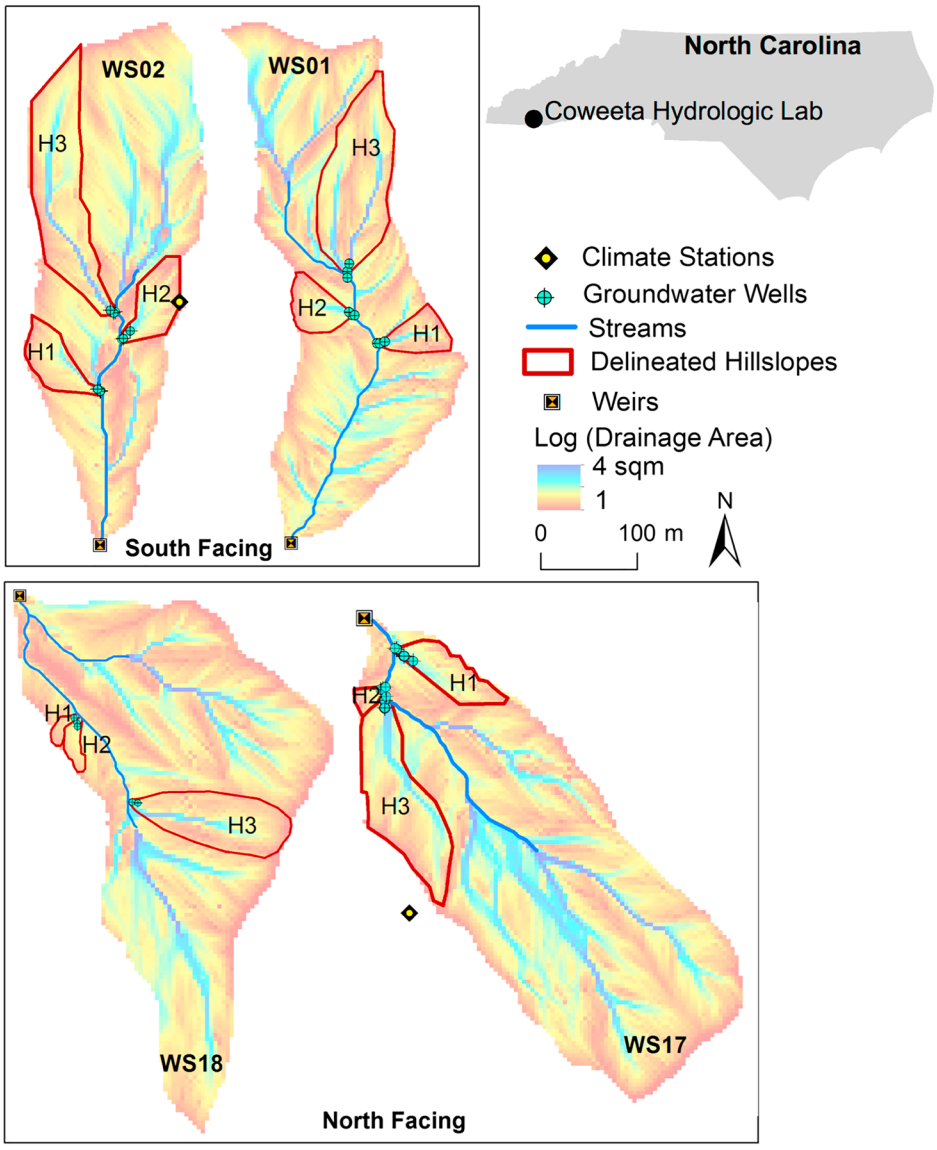

Figure 1. A map of study hillslopes in south facing (WS02 and WS01) and north facing (WS18 and WS17) catchments along with the location of groundwater wells, weirs, and climate stations. WS01 and WS17 are coniferous; WS02 and WS18 are mixed deciduous.

last from 15 April to 14 October, and the dormant season lasts from 15 October to 14 April (e.g., Swift et al., 1988).

Field observations focused on two pairs of catchments (Figure 1), with each pair consisting of one catchment dominated by naturally regenerated broadleaf deciduous forest (WS02, WS18) and an adjacent catchment containing a *Pinus strobus* L. (white pine) plantation (WS01, WS17). The catchments were originally part of a paired catchment experiment designed to examine the effects of forest management practices and vegetation types on the catchment water balance (Swank & Douglass, 1974). WS01 and WS02 are south facing catchments, whereas WS17 and WS18 are north facing catchments. All catchments were logged early in the 1900s, and the deciduous broadleaf catchments (WS02, WS18) were abandoned to secondary ecosystem succession in 1920 and are considered reference catchments. Treatment catchments were clear-cut in 1950 and later replanted with white pine at a 2 × 2-m spacing in 1956 (Ford et al., 2011). Soils within the catchments are deeply weathered, predominantly sandy loams inceptisols and relatively old ultisols (Swank & Crossley, 1988). Depths to bedrock can range from 0.9 to 3.5 m (Singh, 2016). The bedrock in these

Table 1
Summary of Landscape Variables for Study Catchments[a]

Landscape Variables	WS01	WS02	WS17	WS18
Minimum elevation (m)	705	707	739	719
Maximum elevation (m)	985	1005	1031	983
Channel head elevation (m)	869	817	815	796
Mean slope (deg)	28	27	29	28
Maximum slope (deg)	61	60	62	66
Catchment area (ha)	15	13	13	12
Dominant aspect	South	South	North	North
Perennial stream length (m)	700	411	300	375
Vegetation type (m)	Coniferous	Deciduous	Coniferous	Deciduous

[a]Estimated from 5-m DEM.

catchments is predominantly metamorphic and crystalline (Hatcher, 1988). Table 1 summarizes the essential characteristics of each study catchment. Singh et al. (2016) and Nippgen et al. (2016) provide additional site information about the study catchments.

3. Methods

3.1. Geospatial Analysis

The National Center for Airborne Laser Mapping collected aerial light detection and ranging data over the Coweeta Hydrologic Laboratory in 2010. Data sets produced by National Center for Airborne Laser Mapping included 1 × 1-m digital elevation models of the bare Earth surface and the top of the vegetation canopy. We resampled the 1 × 1-m bare Earth digital elevation model to 5-m resolution to avoid the confounding effects of microtopography on geospatial algorithms used to represent subsurface drainage patterns from surface topography (Seibert & McGlynn, 2007). We derived the topographic variables from the digital elevation model that are commonly used to describe the shape of hillslopes (Aryal et al., 2002; Bogaart & Troch, 2006) and to infer spatial patterns of water accumulation and flow (Seibert & McGlynn, 2007). Topographic variables used in the study include upslope accumulated area (UAA; Seibert & McGlynn, 2007), topographic wetness index (TWI; Beven & Kirkby, 1979), elevation (ELV), slope (SLP), plan curvature (PLC), profile curvature (PRC), distance from creek (DFC), gradient to creek (GTC), ratio of DFC to GTC (DFC/GTC), and elevation above creek (EAC). In the absence of detailed information about topography of the bedrock surface (e.g., Freer et al., 2002), we use surface topography to help interpret hydrological processes in the study catchments. Due to the relatively homogeneous underlying bedrock geology (Hatcher, 1988; Velbel, 1985), we assume that the general relationship between bedrock and surface topography is similar for the four watersheds.

3.2. Hydrometric Data

Runoff was measured continuously by the USDA Forest Service at 90° V notch weirs located at the outlet of WS01, WS02, and WS17, and at a 120° V notch weir located at the outlet of WS18. The Forest Service recorded rainfall depths at 30-min intervals at climate stations in south facing (RG20) and north facing (RG96) catchments at 740 and 894 m above mean sea level, respectively (Figure 1). The two rain gauges are located within 2 km from each other.

We installed wells to monitor the elevation of shallow groundwater on 12 hillslopes across the four catchments (Figure 1). Table 2 summarizes the spatial characteristics for all of the instrumented hillslopes. Each

Table 2
Spatial Characteristics of the Study Hillslopes

Hillslopes	UAA (m^2)	Elevation (m; Mean)	Slope (deg; Mean)	TWI (ln(m); Mean)	GTC (−; Mean)	DFC (m; Mean)	DFC/GTC (m; Mean)	Plan Curvature (−Mean)	Profile Curvature (−Mean)
WS1H1	4780	801	22	4.54	0.38	72	228	−0.09	−0.44
WS1H2	5584	819	28	4.58	0.48	80	184	−0.02	−0.71
WS1H3	13957	876	30	4.68	0.43	159	421	−0.10	−0.08
WS2H1	3276	807	27	4.76	0.48	100	229	−0.34	−0.38
WS2H2	2006	816	23	4.99	0.34	65	202	−0.57	0.32
WS2H3	19984	893	29	4.97	0.67	223	650	−0.21	−0.03
WS17H1	4800	792	30	5.04	0.46	94	233	−0.09	−0.12
WS17H2	825	775	20	4.31	0.41	27	66	−1.13	−1.52
WS17H3	11503	832	30	4.89	0.45	138	356	−0.22	−0.07
WS18H1	550	761	20	4.16	0.44	31	85	−0.18	−1.45
WS18H2	1075	766	23	4.63	0.39	42	125	−0.85	−0.76
WS18H3	10250	842	28	4.54	0.49	144	358	0.28	−0.31

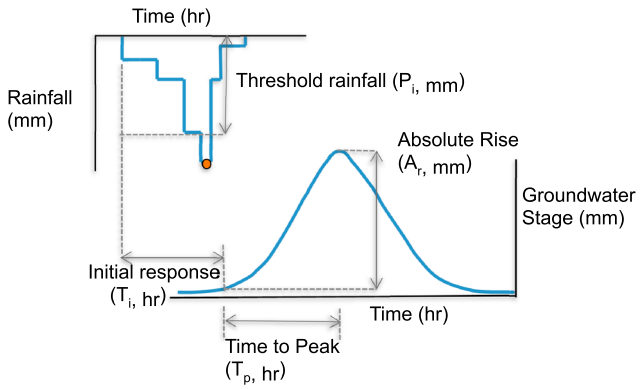

Figure 2. The response metrics estimated for each well during events.

hillslope was equipped with two wells, one located adjacent to the stream (NS) and another located at the break in slope between the hillslope and the axis of the stream valley (HS). The NS wells were located within approximately 5 m of the stream, and the HS wells were located within approximately 20 m of the stream. Wells were installed to the depth of refusal using a portable, gas-powered auger and a sledgehammer-driven steel rod, an installation method similar to Jencso et al. (2009). Well completion depths ranged from 0.9 to 3.5 m (Table S1). We interpreted these well depths (WD) as the practical depth to bedrock.

Wells were constructed from 3.8-cm-nominal-diameter Schedule 40 PVC pipe, which was slotted from approximately 10 cm below the ground surface to the completion depth. Wells were open at the bottom. Bentonite clay was packed around each well at the soil surface to prevent surface runoff or direct precipitation from entering the wells. Groundwater stage was measured at 30-min intervals using capacitance rods (Tru-Track, Inc., Christchurch, NZ) suspended above the bottom of each well. Data were collected between 1 October 2011 and 31 December 2013. Twenty two of the 24 wells recorded data through the entire study period.

3.3. Data Analyses

We identified 43 distinct rainfall events using the data from rain gauges that met the following criteria: (i) 30-min rainfall equaled or exceeded 0.5 mm, (ii) total event rainfall exceeded 20 mm, and (iii) at least 3 hr with no rainfall separated events. The 20-mm minimum storm depth criterion allowed us to focus on the large events (>75th percentile) that have become both more frequent and intense over the last 75 years in the region (Laseter et al., 2012). For each of these events, we estimated storm depth (SD, mm; i.e., total rainfall), storm period (SP, hr; i.e., event duration), peak intensity (PI, mm/hr; i.e., maximum rainfall intensity at 30-min interval), and mean intensity (MI, mm/hr; i.e., average rainfall intensity).

We calculated several common groundwater response metrics for each of the 22 monitoring locations for the 43 events (Figure 2). We tested several groundwater rise thresholds (6–12 mm/hr) and found that 12 mm/hr was the groundwater threshold required to detect an onset of the groundwater response. This value is similar to groundwater threshold values used by Bachmair et al. (2012). The response frequency (R_f, %) was defined for each location as the number of events that generated detectable groundwater responses in well. The threshold response rainfall (P_i, mm) was defined as the cumulative amount of rainfall that occurred prior to a groundwater response. The initial response time (T_i, hr) was defined as the time between the beginning of an event and a groundwater response. The absolute rise (A_r, mm) was defined as the cumulative change in water table since the beginning of an event. The time to peak (T_p, hr) was defined as the time between the initial groundwater response and the peak groundwater response. To quantify the variability in groundwater responses, the interquartile range was computed individually for each groundwater response, while concatenating all wells together. Figure 2 illustrates response metrics using an idealized hyetograph and well hydrograph. Antecedent groundwater level (AGL; mm) was defined as the groundwater stage 1 hr prior to the beginning of an event and used as a surrogate for local antecedent conditions. The AGL was only used to understand the influence of local antecedent conditions on the groundwater responses for each well. Antecedent catchment wetness (ACW; mm) was defined as the runoff at the catchment outlet an hour prior to the event and used as a surrogate for catchment wetness. The event characteristics and antecedent conditions were used as independent variables to understand the spatiotemporal patterns of groundwater responses (dependent variables).

3.4. Statistical Analyses

We used the two-sample Kolmogorov–Smirnov test and the Wilcoxon rank-sum test (Wilcoxon) to test for differences between the distributions and medians of groundwater response metrics, respectively. We used the Spearman's rank correlation coefficient (ρ; Spearman, 1904) to quantify the bivariate relationships between the absolute values of groundwater response metrics (P_i, A_r, T_i, T_p), and the independent explanatory variables. Correlations between individual groundwater response and an independent variable were estimated by concatenating all wells together. The independent variables include event characteristics (SD, MI, PI,

SP), antecedent condition variables (AGL, ACW), local topographic variables (e.g., SLP, PLC, PRC, UAA, TWI), and physical variables (well depth, WD; distance from stream, DFS) for each well.

We used a random forest (RF) model to evaluate the temporal changes in the relative influence of factors that may explain the groundwater responses. This type of model is a robust, multivariate, and nonparametric tool that uses a decision tree framework to predict responses to system inputs (Breiman, 2001; Breiman et al., 1984). Random forest models detect interactions among input variables and are insensitive to correlations among these variables (Loos & Elsenbeer, 2011; Strobl et al., 2009). Categorical variables can also serve as explanatory variables in random forest models. We used independent or explanatory variables to build a random forest model for individual groundwater response metric. The model was also conditioned upon categorical variables that included aspect (north and south facing) and the location of wells (NS or HS). We computed the percentage of variance explained to understand the explanatory power of independent variables, and the ranking of variable importance as a measure to understand the sensitivity of the independent variables to response metrics. The variable importance was evaluated as a percentage increase in mean square error while permuting each explanatory variable one at a time and keeping the other variables unchanged; so the greater the increase in mean square error is, the more important the variable is. The model was run 25 times, and the variable importance rankings were computed for the best performing RF model with the highest variance explained. The RF model parameters included the number of trees generated (n_{tree} = 1,000; default = 500) and m_{try} = 5 (default) as these parameters have minimal effect on RF model outcomes (Bachmair & Weiler, 2012; Díaz-Uriarte & DeAndres, 2006). We constructed and analyzed separate RF models for the 25-month period, dormant seasons, and growing seasons. The RF modeling was conducted with "randomForest 4.6–12" (Liaw & Wiener, 2002) in R statistical software (R Core Team, 2013).

4. Results

4.1. Event Characteristics and Catchment Water Balances

The rain gauges received a total of 4,775 mm (south facing) and 5,233 mm (north facing) of precipitation during the 25-month study period. When rainfall was detected, the median intensity was approximately 1.6 mm per 30-min period at both locations during the study period. Median storm depth and median storm period were not significantly different between both rain gauges (Wilcoxon, $p > 0.05$), and significant correlations were found among event properties between both rain gauges as well (Table S2). Twenty-six events occurred during the two dormant seasons, and the remaining 17 events occurred during the two growing seasons. The characteristics of these 43 events are summarized in Table 3, and a reference hyetograph and hydrograph in events are shown in Figure 3.

Although event characteristics for events >20 mm did not vary between north and south facing rain gauges, the annual water balances differed significantly for north facing and south facing catchments (Table S3). North facing catchments received an annualized average of 10% more (>200 mm) precipitation than south facing catchments. In particular, on an annualized basis, south and north facing catchments received 2,387 and 2,616 mm/year, respectively. Both years were relatively wet compared to the long-term mean annual rainfall of approximately 1791 mm/year. Runoff was greater for north facing than south facing catchments (Table S3). Within each north or south facing catchments, runoff differed by catchment vegetation types. Catchments dominated by deciduous vegetation yielded 37% more runoff (north facing) and 22% more runoff (south facing) than adjacent coniferous-dominated catchments. Similarly, water tables were generally lower in the coniferous catchments than in deciduous catchments. Water tables were typically higher in north facing catchments than in south facing catchments (Table S4).

4.2. Shallow Groundwater Responses

4.2.1. Response Frequency

The number of events that generated a detectable groundwater response in the wells (response frequency, R_f) varied with event properties and the spatial characteristics of the landscape corresponding to wells (Tables 4 and S1). There were no significant differences in response frequency between NS and HS wells for the study period (Wilcoxon, $p > 0.05$). In general, 13% of study wells responded infrequently or not at all (R_f: 0–9%), especially wells in which water tables were consistently close to the surface (e.g., WS17H3-HS) or consistently deep (e.g., WS2H1-HS; Tables 4 and S4). Overall, response frequency was not significantly

Table 3
Characteristics of Storms Selected for Analysis

		Rain Gauge 20				Rain Gauge 96			
Storm Number	Arrival Date	Storm Depth (mm)	Storm Period (hr)	Mean Intensity (mm/hr)	Peak Intensity (mm/30 min)	Storm Depth (mm)	Storm Period (hr)	Mean Intensity (mm/hr)	Peak Intensity (mm/30 min)
1	3/11/2011	22	4	6	6	27	4	7	6
2	15/11/2011	30	16	2	6	44	18	2	8
3	22/11/2011	29	3	11	14	34	3	11	19
4	27/11/2011	152	23	7	6	163	23	7	6
5	22/12/2011	69	9	8	14	82	10	9	18
6	27/12/2011	29	6	5	5	32	8	4	5
7	10/1/2012	43	15	3	7	44	15	3	6
8	17/1/2012	35	7	5	9	35	7	5	10
9	22/1/2012	36	13	3	4	29	14	2	4
10	26/1/2012	37	12	3	6	29	11	3	6
11	2/3/2012	32	6	6	6	31	5	7	6
12	5/4/2012	45	5	9	16	33	5	7	11
13	17/4/2012	65	17	4	8	68	16	4	10
14	6/5/2012	51	3	17	29	57	2	38	46
15	13/5/2012	53	27	2	7	71	26	3	6
16	31/5/2012	29	2	14	13	30	5	7	13
17	01/7/2012	36	6	6	14	32	5	6	14
18	14/7/2012	64	5	13	27	91	5	20	25
19	9/8/2012	31	2	15	15	36	3	14	22
20	17/9/2012	108	17	7	13	99	17	6	12
21	30/9/2012	156	30	5	15	169	30	6	22
22	10/12/2012	26	9	3	3	26	9	3	3
		Rain Gauge 20				Rain Gauge 96			
Event Number	Arrival Date	Storm Depth (mm)	Storm Period (hr)	Mean Intensity (mm/hr)	Peak Intensity (mm/30 min)	Storm Depth (mm)	Storm Period (hr)	Mean Intensity (mm/hr)	Peak Intensity (mm/30 min)
23	20/12/2012	36	7	5	5	62	8	8	8
24	24/12/2012	25	8	3	3	33	7	5	4
25	25/12/2012	52	12	5	6	42	13	3	3
26	17/1/2013	72	18	4	7	70	18	4	7
27	29/1/2013	180	27	7	21	146	19	8	15
28	21/2/2013	33	9	4	6	33	9	4	4
29	26/2/2013	57	13	5	6	61	12	5	5
30	5/3/2013	27	7	4	10	20	3	8	7
31	11/3/2013	42	10	4	8	40	10	4	7
32	11/4/2013	86	9	10	29	68	8	9	12
33	19/4/2013	38	7	5	8	37	8	5	6
34	28/4/2013	61	18	3	5	51	16	3	6
35	5/6/2013	45	4	11	28	36	5	8	14
36	27/6/2013	26	2	17	12	30	5	7	16
37	3/7/2013	83	16	5	14	78	16	5	20
38	5/7/2013	71	12	6	23	80	11	7	21
39	18/8/2013	26	9	3	4	25	8	3	3
40	25/9/2013	43	9	5	7	32	7	5	7
41	31/10/2013	25	13	2	3	32	12	3	4
42	26/11/2013	94	19	5	7	101	17	6	8
43	21/12/2013	132	38	3	7	142	38	4	7

different between wells in north facing (median R_f = 71%) and south facing (median R_f = 40%) catchments (Wilcoxon, $p > 0.05$).

4.2.2. Groundwater Rainfall Threshold, Response Magnitude, and Timing

The wells exhibited large spatiotemporal variability in the threshold amount of rainfall needed to activate a groundwater response (i.e., P_i; Figure 4a), and the median value was 31 mm. The median response threshold for north facing catchments was 6.2 mm less than the median response threshold for south facing

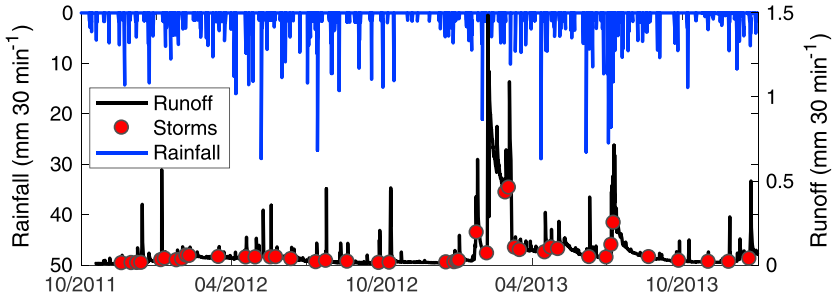

Figure 3. Rainfall and runoff measured at 30-min intervals for one of the south facing study catchments, WS02. Rainfall data were recorded at the rain gauge (RG20) in the south facing catchments. The red filled circle represents flow condition at the beginning of storms.

catchments (Wilcoxon, $p < 0.05$). Median values of rainfall needed to initiate a groundwater response differed significantly among HS wells, but not among NS wells (Figure 4a).

Groundwater initial response timing (T_i) ranged from 0 hr (i.e., simultaneous with the beginning of an event) to 42 hr after the beginning of an event (Figure 4b). The median values of T_i differed significantly among HS wells (Wilcoxon, $p < 0.05$). The HS wells are deeper than NS wells (Table S1), but the median initial response timings for HS wells were not necessarily longer than their corresponding NS wells (Wilcoxon, $p > 0.05$). Overall, we did not detect a significant difference in the median initial response timing between north facing and south facing catchments (Wilcoxon, $p > 0.05$), but the median initial response time for NS wells in north facing catchments was 1.5 hr shorter than for NS wells in south facing catchments (Wilcoxon, $p < 0.05$).

The median value of the absolute rise (i.e., A_r, the magnitude of groundwater rise during an event) did not differ significantly between north facing and south facing catchments (Wilcoxon, $p > 0.05$). In general, the median water level in NS wells rose 66 mm less than it did in HS wells (Wilcoxon, $p < 0.001$; Figure 4c). It took as long as 45 hr to reach the peak water level (time to peak, T_p), after the onset of response. The median time to peak was 3.5 hr shorter for NS wells than the HS wells (Wilcoxon $p < 0.05$; Figure 4d). Groundwater wells in relatively wet north facing catchments reached their peak almost an hour earlier than wells in south facing catchments (Wilcoxon, $p < 0.1$). These results highlight how antecedent conditions can influence groundwater response timing in these catchments.

Table 4
Summary of Groundwater Response Frequency for the Study Wells During a 25-Month Period

Catchments	Groundwater Wells	R_f (%)
WS01	H1NS	33
	H2NS	5
	H2HS	39
	H3NS	67
	H3HS	68
WS02	H1NS	33
	H1HS	25
	H2NS	57
	H2HS	89
	H3NS	75
	H3HS	100
WS17	H1NS	100
	H1HS	95
	H2NS	9
	H3NS	71
	H3HS	0
WS18	H1HS	70
	H2NS	71
	H2HS	41
	H2HS	26
	H3NS	14
	H3HS	100

The temporal variability in groundwater response metrics differed with event characteristics (Figures 5 and 6 and Table S5). We observed significant, positive correlations between rainfall characteristics and the temporal variability (i.e., interquartile range) of absolute rise ($\rho = 0.63$, $p < 0.001$) and threshold rainfall ($\rho = 0.64$, $p < 0.001$). We also observed significant, negative correlations between mean intensity and the variability in initial response timing ($\rho = -0.46$, $p < 0.01$) and variability in time to peak ($\rho = -0.32$, $p < 0.01$). One exception was the WS2H3-HS well, which had the steepest slope and largest drainage area of any study hillslope. This well had the smallest rainfall threshold and shortest initial response timing, regardless of event properties.

The median absolute rise in groundwater was significantly different between vegetation types (Wilcoxon, $p < 0.05$). The median value of absolute rise was at least a 40 mm (27%) greater for wells in coniferous catchments than the wells located in the mixed deciduous forest (Wilcoxon, $p < 0.01$).

Temporal patterns in groundwater responses were also affected by the seasons. Growing and dormant season responses were significantly different for all groundwater response metrics (Wilcoxon, $p < 0.05$), except for the rainfall threshold (Wilcoxon, $p > 0.05$). The seasonal effect on

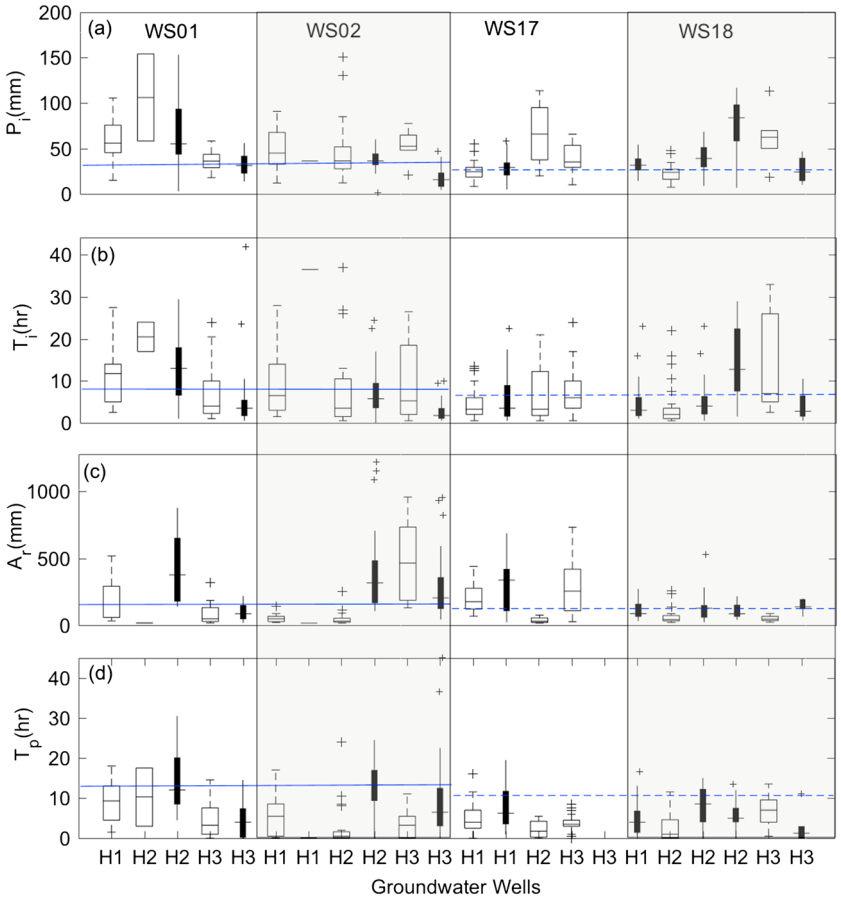

Figure 4. Box-and-whisker plot of groundwater response metrics: (a) P_i, (b) T_i, (c) A_r, and (d) T_p for the study catchments. Solid and dashed blue lines indicate median responses for south and north facing catchments. Filled boxes indicate HS wells, and open boxes indicated NS wells. The shaded gray rectangle indicates deciduous catchments, WS02 and WS18.

groundwater responses was more pronounced in south facing catchments than north facing catchments. For example, in south facing catchments, the median time to peak for groundwater wells during the dormant season was 5 hr longer than during the growing season (Wilcoxon, $p < 0.05$; Figures 5 and 6). In north facing catchments, the median time to peak for groundwater wells was 1.5 hr longer during the dormant season than during the growing season. Overall, these results revealed large variability in subsurface processes in the study catchments, where a range of spatial characteristics might interact with rainfall in multiple ways, during different times of the year, to generate groundwater response.

4.3. Statistical Analysis

4.3.1. Bivariate Relationships

Rainfall threshold and absolute rise were positively correlated with storm depth and negatively correlated with antecedent groundwater level (Figure 7). Similarly, groundwater response timing variables (e.g., T_p) were negatively correlated with peak and mean intensities and with antecedent groundwater levels, and they were positively correlated with storm depth (Figure 7). Further, correlations between response timing and event characteristics were stronger at the beginning of the event (i.e., T_i) than during the latter part of the event (i.e., T_p). Lastly, topographic variables and well depth were significantly correlated with the absolute rise and response timings (Figure 7). Overall, these findings highlight the intraevent and interevent heterogeneities that influence groundwater responses for these headwater catchments.

4.3.2. Random Forest Modeling

The performance (i.e., the percentage of variance explained) of random forest models varied with temporal scale (e.g., dormant, growing, two-year) and the groundwater responses (Figure 8). The model performances

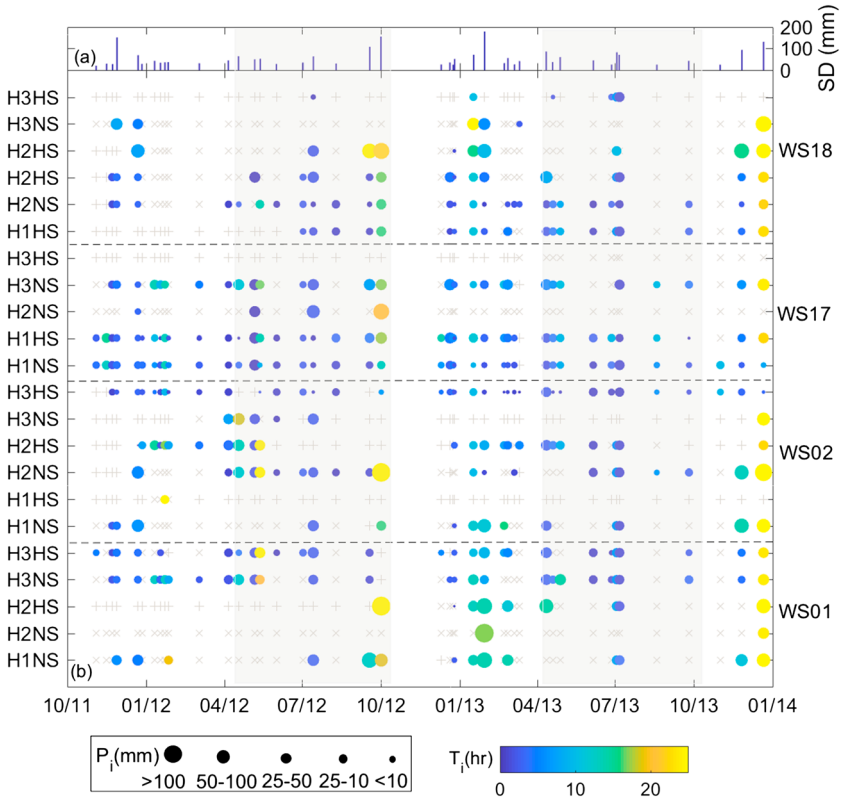

Figure 5. (a) Associated storm depth (SD) during each event and (b) spatiotemporal patterns for groundwater response metrics, rainfall threshold (P_i), and initial response timing (T_i) for all study catchments. The size of the circle represents the amount for P_i (mm) and color represents time (hr) for T_i. Shaded gray rectangles represent growing seasons, a gray cross represents no response during the storms, and a gray plus represents missing data.

varied from 32 to 75% and were consistently high (>60%) for initial response timing and relatively low (<40%) for time to peak. The model performance was also consistently higher during the relatively wet dormant season than during the growing season (Figure 8).

Overall, the relative importance of the explanatory variables for groundwater response varied with individual response metrics (Figure 9). However, out of 12 scenarios (i.e., all four response variables and three study periods), storm depth (10) was frequently among the top 3 highly ranked important factors followed by antecedent groundwater level (7), profile curvature (3), and mean intensity (3). In particular, storm depth was the most important variable for the patterns of rainfall threshold across all three study periods, followed by antecedent groundwater level. For the absolute rise, the three most highly ranked variables were a mix of event characteristics (storm depth), catchment topography (profile curvature), and antecedent conditions (antecedent groundwater level). For initial response time, the top-ranking explanatory variables were solely driven by event properties, including mean intensity, storm depth, and storm period (Figure 9). For time to peak, storm period was the most highly ranked variable over the entire two-year study period, as well as the growing seasons; storm depth was the most important variable during the dormant seasons. Topographic variables, that is, profile curvature, were frequently observed among the top 3 predictors in models that examined growing and dormant seasons separately.

5. Discussion

5.1. Groundwater Response Thresholds

Differences in the amount of rainfall required to generate subsurface flow can be attributed to the inherent heterogeneity in spatial characteristics of the hillslopes (cf. Weiler et al., 2006). Using a limited number of instrumented hillslopes, studies from various environments and catchments have reported rainfall

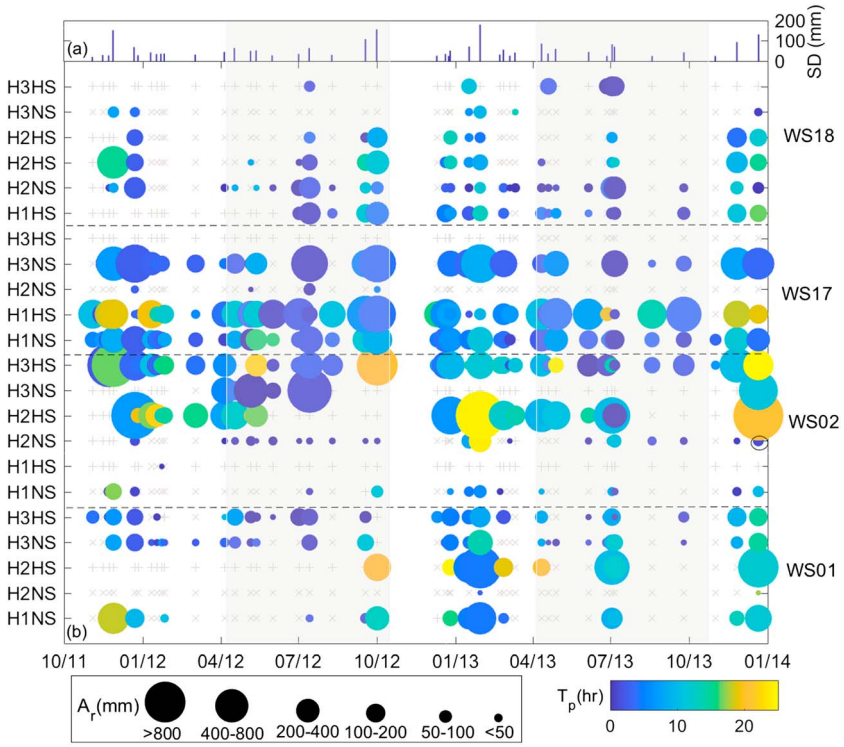

Figure 6. (a) Associated storm depth (SD) during each event and (b) spatiotemporal patterns for groundwater response metrics, absolute rise (A_r), and time to peak (T_p) for all study catchments. The size of the circle represents the amount for A_r (mm) and color represents the time (hr) for T_p. The shaded gray rectangles represent growing seasons, a gray cross represents no response during events, and a gray plus represents missing data.

thresholds from 6 to 55 mm (Mosley, 1979; Peter et al., 1995; Noguchi et al., 2001; Tani, 1997; Tromp-van Meerveld & McDonnell, 2006a; Whipkey, 1965). Given the differences in methods and instrumentation used to estimate rainfall thresholds, it is not only hard to generalize these results, but also a direct comparison of these response thresholds with our work is difficult. However, our analyses revealed a median P_i of 31 mm to generate groundwater response which falls within the previously reported range. Further, the large response threshold values (up to 152 mm) noted for our wells (Figure 4a) could likely be attributed to variability in the unsaturated storage capacity of the study catchments (Hewlett, 1961; Hewlett & Hibbert, 1966). Random forest analysis showed that well depth was one of the important variables for explaining threshold patterns during the study period (Figure 9). These findings complement Tromp-van Meerveld and McDonnell (2006a), who showed that threshold patterns for 147 events were sensitive to soil depth in a forested catchment of Georgia, USA. Overall, our analysis from 12 hillslopes further confirmed the prior response threshold values and highlights the wide range of values that may exist within catchments from the same environment.

Storm depth, antecedent groundwater level, and slope were some of the most important variables to explain patterns in rainfall thresholds, but the relative importance of antecedent groundwater level and slope varied between seasons (Figures 5, 6, and 9). For example, during the dormant seasons when ET was minimal, and the catchments were relatively wet, local slope had a higher explanatory power than antecedent conditions for rainfall thresholds (Figure 9). Previously, studies have collectively attributed the threshold response to both topography and storm depth, but our findings show that the relative influence of these driving factors varies with seasons. Recently, Rinderer et al. (2016) reported the dominant control of topographic variables such as slope on median threshold responses in a steeply forested catchment.

The local antecedent groundwater level was negatively correlated to rainfall threshold, and it had a greater importance for rainfall threshold than overall catchment wetness (Figure 9). Moreover, drier conditions required larger rainfall thresholds for responses (Figure 7). This relationship could explain the higher

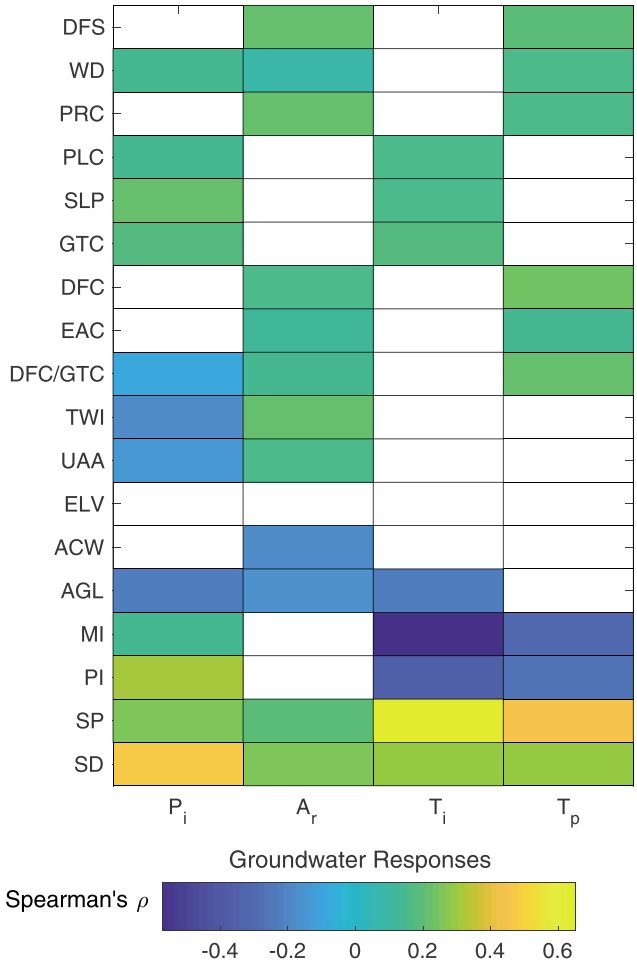

Figure 7. Spearman's correlation (rho; ρ) between explanatory variables and groundwater responses to events observed during the two-year study period. White boxes indicate nonsignificant relationships ($p > 0.05$). Abbreviations include rainfall threshold (P_i), absolute rise (A_r), initial response time (T_i), time to peak (T_p), well depth (WD), distance from stream (DFS), storm depth (SD), storm period (SP), peak intensity (PI), mean intensity (MI), antecedent groundwater level (AGL), antecedent catchment wetness (ACW), upslope accumulated area (UAA), elevation (ELV), slope (SLP), plan curvature (PLC), profile curvature (PRC), gradient to creek (GTC), ratio of DFC to GTC (DFC/GTC), elevation above creek (EAC), topography wetness index (TWI), and distance from creek (DFC).

rainfall threshold for HS than NS wells. Hillslope wells with greater storage deficits required more rainfall to elicit a response than their corresponding NS wells. Further, south facing catchments had larger rainfall thresholds to elicit a response than north facing catchments (Figures 4 and 5). South facing catchments have more insolation, greater potential evapotranspiration, and are drier overall than north facing catchments in the northern hemisphere (Emanuel et al., 2014; Hwang et al., 2012).

The catchment-wide median rainfall threshold of 31 mm suggests that a large number of storms at Coweeta mainly replenish shallow soil water, are taken up by vegetation, or are intercepted by the forest canopy. A long-term (approximately 75 years) statistical analysis of Coweeta rainfall shows that only 25% of storm magnitudes are greater than 17 mm (Laseter et al., 2012). Thus, the vast majority of storms at Coweeta are far too small to generate a groundwater response. Per these results, stormflows at Coweeta are rather small, with runoff coefficients estimated to be approximately 0.04 (Hewlett & Hibbert, 1966; Singh, 2016).

5.2. Absolute Groundwater Rise

Storm depth was identified as the most important variable for explaining patterns of the absolute rise in shallow groundwater, but its relative importance varied by season (Figure 9). The significant positive correlation between the absolute rise and storm depth (Figure 7) indicated that larger events generated a larger rise in water table at event scale. These results agree with recent studies from watersheds with different climate and physiographic characteristics. For instance, Bachmair et al. (2012) reported a strong positive correlation between absolute rise and storm depth in all seasons. Penna et al. (2015) observed strong positive correlations between storm depth and water table rise along two hillslopes in the Italian Alps. Overall, these studies highlight the strong influence of storm depth on the rise in water table at the event scale, regardless of differences in catchment properties (soil type, topography, vegetation) and hydroclimatic conditions.

Both antecedent conditions were negatively correlated with the absolute rise, but antecedent groundwater level frequently ranked among the top 3 predictors of the absolute rise (Figure 9). Drier antecedent conditions provide more storage, resulting in a greater rise in the water table. Our results are in line by Bachmair and Weiler (2012), who conducted multivariate analysis and showed that the catchment scale wetness was not among the most important predictors of water table rise during events. Penna et al. (2015) found a weak or no significant correlation between the rise in water table and local antecedent conditions for two hillslopes with shallow soils (approximately 1 m thick). The lack of unsaturated storage in shallow soils may have caused the weak effect of antecedent conditions on groundwater response observed by Penna et al. (2015). Together, these results demonstrate the importance of soil water storage and deficits in mediating the influence of antecedent conditions on water table during events.

We observed greater absolute groundwater rise in coniferous catchments than in mixed deciduous catchments and no significant difference in median absolute rise between north facing and south facing hillslopes, indicating that antecedent catchment wetness may not be an important driver of absolute rise at the event scale than storm properties and spatial characteristics of hillslopes. Similarly, Bachmair and Weiler (2012) did not detect any significant influence of vegetation properties on the rise in water table at the event scale, but they found very low importance (>5th rank) of throughfall and canopy cover on the rise in water table. We need more work at Coweeta to further quantify the influence of other vegetation properties such as throughfall and stemflow on water table rise during events. Overall, our findings complement prior studies at

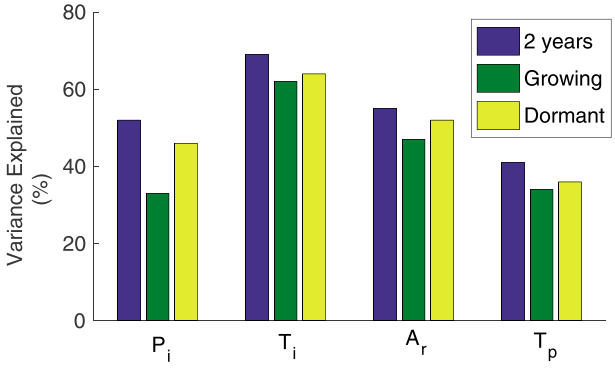

Figure 8. Percentage of variance explained for groundwater responses from all wells during the two-year period, dormant, and growing seasons. Abbreviations include rainfall threshold (P_i), absolute rise (A_r), initial response time (T_i), and time to peak (T_p).

Coweeta that attributed seasonal or annual scale streamflow patterns to differences in antecedent wetness set by differences in vegetation type and water use strategies (Nippgen et al., 2016; Swank & Douglass, 1974) or to differences in insolation based on the dominant aspect of a catchment (Hibbert, 1967).

The influence of topography on the rise in water table during events has been long recognized (cf. Dunne, 1978; Detty & McGuire, 2010; Rinderer et al., 2014). Our findings indicate profile curvature is one of the important topographic variables for driving the absolute rise in groundwater during storm events; however, the strength of this topographic influence varied seasonally (Figure 9). In general, profile curvature is proportional to the change in gradient along the maximum direction of slope (Moore et al., 1993) and can mediate the extent of saturation and influence water table response at the event scale along hillslopes (Aryal et al., 2005). These results agree with Bachmair and Weiler (2012), who found profile curvature to be the most important topographic variable for explaining water table responses along three hillslopes.

5.3. Groundwater Response Timing

Our findings suggest that event characteristics predominantly influence the initial groundwater response time but have a variable influence on time to peak (Figure 9). For instance, a negative correlation between

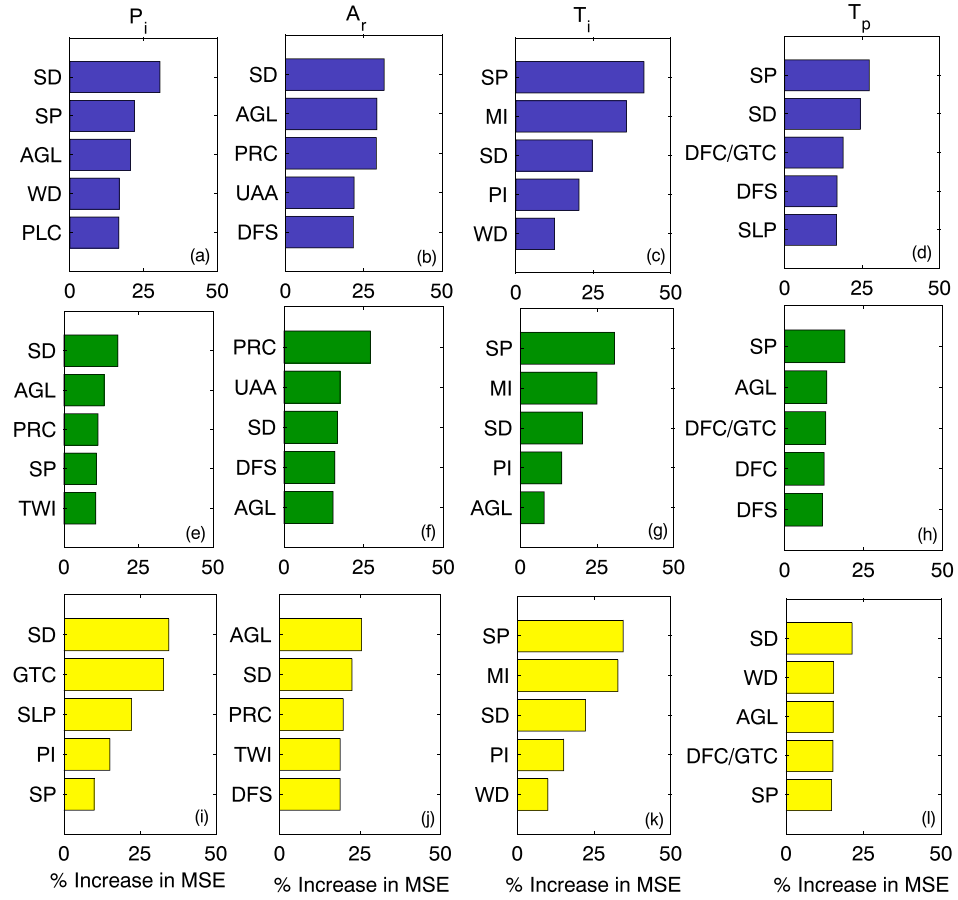

Figure 9. The relative importance of some of the highly ranked key drivers of groundwater responses, based on the increase in mean square errors (MSE) of random forest models, during the (a–d) two-year period, (e–h) growing seasons, and (i–l) dormant seasons. Out of 12 scenarios (i.e., all responses and temporal scales), SD (10) was frequently noted among the top 3 highly ranked important factors followed by AGW (7), SP (6), and PRC (3).

mean intensity and initial response timing indicate that more intense storms lead to more rapid groundwater response times. Further, the significant negative correlation between the variability in initial response time (Table S5) and mean intensity indicated that high-intensity storms lead to a more uniform response timing. We found similar relationships for the time to peak, but the ranking of the storm characteristics varied with the temporal scale (e.g., seasons and two years; Figure 9). These results complement those of Bachmair et al. (2012), who reported a negative correlation between response timings and event intensities, attributing some of the variabilities in response timing to the mean storm intensity. In contrast, Rinderer et al. (2016) found that storm characteristics had little influence on initial response times in a catchment dominated by less permeable soils. Soils at Coweeta are highly permeable with conductivities up to 100 mm/hr (Price et al., 2010). Wetting fronts in soils with low hydraulic conductivities and drainable porosities (e.g., Rinderer et al., 2016) may not travel as rapidly as they do in Coweeta soils, resulting in a minimal effect of event characteristics on the groundwater response. Differences in hydraulic properties of soils could influence the relationship between event characteristics and groundwater responses, and eventually subsurface runoff generation during storms among catchments. However, our interpretations are conditioned on the assumption that all of the wells used in this study have similar ranges of hydraulic conductivity. There are opportunities to study how heterogeneity in soil physical properties may contribute to the observed variability in groundwater responses at Coweeta.

The local antecedent groundwater level was one of the important variables to explain the patterns of time to peak but not for the initial response time (Figure 9). This assertion is further supported by the fact that NS wells always reached the peak response earlier than relatively dry HS wells, whereas the lack of a significant difference in initial response time between NS and HS wells could be attributed to the combined influence of antecedent conditions and the local topography. Similarly, responses were quicker during dormant seasons than during growing seasons. These results complement Bachmair et al. (2012), who reported similar seasonal differences in the time taken to reach the peak groundwater level.

The influence of topography was not observed for initial response time, but once the water table began to respond, the influence of topography on time to peak came into play. This suggests that the influence of topography on response timing was more pronounced later on during a storm (Figure 9). The ratio of DFC to GTC was one of the important topographic variables for explaining patterns in time to peak (Figure 9). The ratio of DFC to GTC is often related to the residence time of subsurface flow along a hillslope (Jencso & McGlynn, 2011). The positive correlation between the ratio DFC to GTC and time to peak suggests that shorter residence times lead to quicker peak groundwater responses. Previously, the explicit quantification of topographic influences on the time to reach peak grondwater levels has been rare. Recently, using multivariate analysis, Rinderer et al. (2016) attributed the patterns of initial response timing to mean curvature and upslope contributing area in a steep catchment. In contrast, we did not detect any topographic influence on the initial response timing. The lack of topographic influence on initial response time may highlight the importance of soil physical properties (e.g., soil depth, variation in hydraulic conductivity with depth) at Coweeta compared to topography at sites with shallower soils (e.g., Rinderer et al., 2016).

Our findings, together with other recent work (Bachmair et al., 2012; Bachmair & Weiler, 2012; Penna et al., 2015; Rinderer et al., 2016), suggest that the hydrological processes influencing groundwater response timing could be more sensitive to catchment characteristics (e.g., soil properties, topography) than the processes affecting the absolute rise of groundwater.

5.4. Implications

Our analyses advanced our understanding about how specific variables may interact to generate groundwater responses in humid-temperate catchments with deep, permeable soils (Figures 7 and 9). The large variability in water table rise and time to peak has implications for understanding subsurface contributions to nearby streams, and for understanding hydrologic connectivity in these landscapes. Above all, our observations highlight the need for spatially intensive measurements to understand better subsurface processes associated with groundwater responses to storms.

The random forest analysis has implications for refining process-based hydrological models that use topographic variables to parameterize subsurface flow (e.g., Beven & Kirkby, 1979; Emanuel et al., 2010; O'Loughlin, 1986; Scanlon et al., 2005). Our findings suggest that no single topographic variable is an effective predictor of groundwater responses at Coweeta (Figure 9). These results pose a challenge for models that

seek to simplify the representation of subsurface processes using topographic variables. Variation in the influence of topography and antecedent conditions on groundwater response timing during events (Figures 7 and 9) suggests that hydrological models should be explicit and careful in simulating various aspects of the shallow groundwater hydrograph. Studies such as ours, which seek to identify the relative importance of different storms and landscape characteristics on subsurface flow, offer a potential framework to refine hydrological models and to advance understanding of runoff generation processes.

In the southern Appalachians, storm intensities have been increasing and interstorm periods have lengthened during the past several decades (Burt et al., 2017; Laseter et al., 2012). These changes have the potential to alter the magnitude and timing of groundwater responses, affecting subsurface storage, streamflow, and the overall water balances of these catchments. On the other hand, headwater catchments with deep soils gradually release subsurface flow over time and sustain perennial, low-order streams (Price, 2011; Singh et al., 2016). Thus, the changes in subsurface flow can also have implications for perennial streams, associated riparian and aquatic habitats, and humans that rely on perennial streamflow for their freshwater needs in the southeastern United States (Caldwell et al., 2014).

6. Conclusions

This study highlighted the heterogeneity in shallow groundwater responses to rainfall events, and it revealed the relative influences of storm and landscape characteristics on groundwater responses. The high rainfall thresholds for groundwater responses at Coweeta suggest that most events replenish soil water, contribute to evapotranspiration, or are intercepted by the forest canopy, but they do not elicit a groundwater response. Storm depth was one of the most important predictors of groundwater response, whereas the relative influence of topography and local antecedent conditions tended to increase as events progressed. The profile curvature and the ratio of DFC to GTC had a significant influence on time to peak but not on the initial response timing, suggesting a shift in topographic influence associated with different stages of the groundwater hydrograph. A significantly higher absolute rise for wells in relatively dry coniferous catchments than deciduous catchments highlighted the greater influence of local spatial properties of hillslopes (e.g., topography, soil depth) and event characteristics on groundwater response.

This work advances our understanding of shallow groundwater dynamics in humid, mountainous landscapes, revealing the relative influence of rainfall properties and landscape characteristics on both the magnitude and timing of groundwater responses to events. This work has implications for understanding hydrologic connectivity, refining topography driven hydrological models and runoff generation processes that are important for human communities and for natural ecosystems that rely on water supplied by these types of catchments.

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