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Identifying long-term empirical relationships between storm characteristics and episodic groundwater recharge

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Key Points:
- Recharge to precipitation ratios evaluated for 35 years across North Carolina
- Greater storm size and intensity or shorter duration reduces episodic recharge
- Climate change may limit groundwater resources in the American Southeast

Supporting Information:
- Supporting Information S1

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Abstract Shallow aquifers are an important source of water resources and provide base flow to streams; yet actual rates of groundwater recharge are difficult to estimate. While climate change is predicted to increase the frequency and magnitude of extreme precipitation events, the resulting impact on groundwater recharge remains poorly understood. We quantify empirical relations between precipitation characteristics and episodic groundwater recharge for a wide variety of geographic and land use types across North Carolina. We extract storm duration, magnitude, average rate, and hourly weighted intensity from long-term precipitation records over periods of 12–35 years at 10 locations. Using time series of water table fluctuations from nearby monitoring wells, we estimate relative recharge to precipitation ratios (RPR) to identify statistical trends. Increased RPR correlates with increased storm duration, whereas RPR decreases with increasing magnitude, average rate, and intensity of precipitation. Agricultural and urban areas exhibit the greatest decrease in RPR due to increasing storm magnitude, average rate, and intensity, while naturally vegetated areas exhibit a larger increase in RPR with increased storm duration. Though RPR is generally higher during the winter than the summer, this seasonal effect is magnified in the Appalachian and Piedmont regions. These statistical trends provide valuable insights into the likely consequences of climate and land use change for water resources in subtropical climates. If, as predicted, growing seasons lengthen and the intensity of storms increases with a warming climate, decreased recharge in Appalachia, the Piedmont, and rapidly growing urban areas of the American Southeast could further limit groundwater availability.

1. Introduction

Groundwater is essential both as an economic resource and for maintaining ecological functions in natural systems. Humans have increasingly come to rely on groundwater as a primary water source and an important buffer to less reliable sources of freshwater from precipitation and surface water. Accordingly, in many regions, groundwater is being extracted at rates that far exceed sustainable levels [*Famiglietti*, 2014]. Recharge of groundwater reservoirs depends chiefly on infiltration of precipitation and subsequent percolation of infiltrated water below the root zone. Climate model simulations suggest that changing climatic conditions will substantially alter precipitation characteristics, especially by increasing the magnitude, intensity, and frequency of the largest storm events [*Allen and Ingram*, 2002; *Pall et al*., 2007; *Trenberth et al*., 2003]. However, the influence of these altered precipitation characteristics on groundwater recharge is complex and remains poorly understood [*Green et al*., 2011; *Taylor et al*., 2013].

Since human alteration of the landscape has major impacts on the groundwater system [*Calder*, 1993], the coupled influence of land use, vegetation, and soil type on net recharge has been well studied. Across various climates, the reduction of vegetative cover has often been shown to result in an increase in recharge. For example, many studies have found large increases in average annual recharge by the conversion of forests and shrubs to crops and grasses [*Allison et al*., 1990; *Hornbeck et al*., 1993; *Prych*, 1988; *Leterme and Mallants*, 2011] or the conversion of grass cover to bare ground [*Zhang and Schilling*, 2006]. In Texas, *Keese et al*. [2005] showed that recharge tends to increase with a decrease in the density of vegetation. Conversely, in the American Southwest, *Scanlon et al*. [2005] showed that the revegetation of agricultural land to natural brush and scrub led to decreased rates of recharge. These negative relationships between recharge and vegetative density are due largely to the interception of precipitation and transpiration of soil water [*Bosch and Hewlett*, 1982; *Brown et al*., 2005].

In many other locations, continued human alteration of the landscape and reduced vegetation density has decreased recharge. For example, spatially averaged infiltration rates can be reduced by urbanization [*Dams et al*., 2008], deforestation, and certain agricultural practices [*Dias and Nortcliff*, 1985a,b; *Hanson et al*., 2004]. Forest clearing for agriculture and urbanization has reduced recharge in east Java [*Bruijnzeel*, 1988] and urbanization has decreased recharge in China's Guishui River Basin [*Pan et al*., 2011] as well as across the majority of the Upper Illinois River Basin [*Arnold and Friedel*, 2000]. Apart from land cover, soil texture also influences recharge rates [*Anuraga et al*., 2006; *Zhang et al*., 1999], with clayey soils generally accommodating less recharge than sandy soils [*Cook et al*., 1992; *Keese et al*., 2005]. Thus, the impact of land use change and reductions in vegetation density on recharge rates vary with the geologic and climatic setting, and are controlled by localized hydrological processes.

Recharge is also governed by precipitation characteristics, such as duration, magnitude, and intensity of precipitation. Classical theory asserts that low-intensity rainfall over long time periods generates the greatest fractional recharge [*Freeze and Cherry*, 1979], and many modern studies have confirmed this [*Dourte et al*., 2012; *Huang et al*., 2012]. However, a variety of studies across geographically diverse landscapes have led to contrary conclusions. In east Africa, *Taylor and Howard* [1996] found that groundwater recharge was restricted to extreme rainfall events and that total recharge was better predicted by the number of heavy events than by net annual precipitation. *Crosbie et al*. [2012] similarly found that the majority of annual recharge in the Murray-Darling Basin, Australia, was generated by a small number of the largest precipitation events. A positive correlation between magnitude of precipitation and fractional recharge has also been shown in the agricultural region of the North China Plain [*Kendy et al*., 2003, 2004]. Further, seasonality of precipitation, antecedent soil moisture conditions, and climate variability have also been shown to significantly impact recharge rates across diverse geographic regions [*Lee et al*., 2006; *Vivoni et al*., 2009].

These seemingly contradictory explanations of the relationships between groundwater recharge and land cover, soil type, and storm characteristics reflect the complex, geographically dependent variations in infiltration and unsaturated zone storage dynamics. For infiltration to occur, precipitation must first exceed interception by the vegetation canopy. Subsequently, for infiltration to contribute to recharge, the soil must be wetted enough to allow vertical drainage below the root zone (i.e., matric potential is above field capacity). However, if the intensity of the precipitation reaching the ground surface exceeds the soil's infiltration capacity or precipitation magnitude exceeds unsaturated zone storage, runoff will occur and thereby limit the fraction of precipitation that can contribute to recharge. Thus, in some situations, increasing rainfall intensity might decrease recharge because thresholds for infiltration excess overland flow are reached. In other locations, increased rainfall duration may lead to decreased recharge because thresholds for saturation excess overland flow are reached. Thresholds for runoff generation by either infiltration or saturation excess depend not only on rainfall characteristics but also on the complex nonlinear influences of soil stratigraphy, hydraulic properties, topography, vegetation, and antecedent conditions [e.g., *Mirus and Loague*, 2013]. Similarly, the conditions favoring groundwater recharge over evapotranspiration or runoff generation depend largely on the nonlinear unsaturated zone response to precipitation. Given the predictions of altered storm characteristics due to climate change and ever-evolving land use patterns, it is important to understand the relationships between recharge and storm characteristics across land uses and soil types. What is lacking from the scientific record is a long-term empirical study of how storm characteristics have affected recharge across a climatically similar but physiographically diverse landscape.

One potential obstacle to empirical studies of this type is the dearth of methods available for estimating groundwater recharge which have fine spatial resolution and applicability over long periods of time and diverse landscapes [*Scanlon et al*., 2002]. For example, the base flow discharge method [e.g., *Meyboom*, 1961] and isotopic or chemical tracers [e.g., *Taylor et al*., 1989] are both capable of calculating recharge over tens of years (or centuries). However, these methods tend to integrate over months or years making it impossible to isolate individual recharge events. Conversely, seepage meters [*Scanlon et al*., 2002], heat tracers [e.g., *Rorabough*, 1964], and lysimeters [e.g., *Allen et al*., 1991] may be used to measure recharge over very small time scales. Regrettably, their expense and relative complexity have inhibited development of long-term data sets, making rigorous statistical analysis difficult. Finally, diffuse flow methods for calculating recharge from unsaturated hydraulic conductivity and soil moisture measurements, such as the zero plane flux method [*Richards et al*., 1956]) and various Darcian methods [e.g., *Nimmo et al*., 1994], ignore preferential flow, which is often a major contributor to recharge [*Cuthbert et al*., 2013; *Mirus and Nimmo*, 2013].

The water table fluctuation (WTF) method [*Meinzer*, 1923; *Healy and Cook*, 2002] estimates groundwater recharge by integrating the rise and fall of the water table over time. In shallow aquifers, where the water table responds quickly to water inputs, recharge events may be isolated and associated with individual precipitation events. The Episodic Master Recession (EMR) method [*Nimmo et al*., 2015] is an adaptation of the WTF method that facilitates analysis of groundwater recharge and concomitant precipitation at high temporal resolution in a consistent and rigorous manner. Further, the EMR method relies primarily on two of the most widely available and readily accessible types of long-term hydrologic data (groundwater levels and precipitation), which facilitate large-scale studies across geographically diverse regions. Given water table and precipitation records of sufficient duration and temporal resolution, it is thus possible to use the EMR method to evaluate the influence of storm characteristics on episodic groundwater recharge.

Here we present a novel application of the EMR method with the objective of improving empirical understanding of (1) how storm characteristics relate to groundwater recharge and (2) whether those relationships are affected by the physiographic characteristics of the landscape. Because climate models tend to predict an increase in the frequency and magnitude of the largest storms and a lengthening growing season, we are particularly interested in understanding how fractional recharge responds to storm magnitude, intensity, and seasonality. To do so, we assess long-term trends in the relationships between fractional recharge and storm characteristics across a broad geographic gradient in the American Southeast at locations with different land use and land cover. We analyze the relative strengths of these relations across a variety of locations, and our quantitative assessment of how recharge relates to changes in precipitation regimes accounts for possible variations in land development and geography. Finally, in light of this analysis, we assess the possible impacts of climate change and land use patterns on groundwater recharge in humid subtropical and subtropical highland climates.

2. Study Area and Long-Term Data Sets

We selected the state of North Carolina, USA, as the study area due to its geographic diversity across consistent latitude, as well as the availability of high-resolution water table data within a variety of land use and land-cover types. North Carolina is divided into three physiographic provinces from east to west: the Coastal Plain, the Piedmont, and Appalachia. The Coastal Plain is flat, experiences heavy annual precipitation (120–160 cm) [*State Climate Office of North Carolina*, 2015], has sandy soils, and is underlain by shallow localized sedimentary aquifers [*U.S. Geological Survey*, 2015]. The Piedmont consists of rolling hills and experiences somewhat less annual precipitation (100–120 cm), while Appalachian precipitation is location dependent (100–180 cm), in part because the region is characterized by some of the greatest relief in the eastern U.S. The Piedmont and Appalachia are both underlain by complex fractured Triassic rocks covered by thick regolith. Though most accessible groundwater is stored in shallow regolith, the secondary fractures of the crystalline bedrock are also tapped for groundwater extraction [*U.S. Geological Survey*, 2015].

We inspected all the available high-resolution (h^{-1}) U.S. Geological Survey (USGS) water level records [*U.S. Geological Survey*, 2015] from North Carolina (56 total wells) using the SeriesSEE software package [*Halford et al*., 2012] and established a set of selection criteria to identify data that would be suitable for our analysis. Out of the 56 wells we analyzed, only 10 wells included water-level records that met the selection criteria of: (1) clear water table responsiveness to individual recharge events, (2) water-level fluctuations that were not dominated by diurnal evapotranspiration signals, (3) greater than 10 years of continuous water-level observations, with limited data gaps, and (4) close proximity to a rain gage with available data for the duration of observation. For the fourth criterion, we relied on the nearest high-resolution (h^{-1}) National Oceanic and Atmospheric Administration (NOAA) precipitation measurements. Figure 1 shows the locations of the 10 sites considered, and Table 1 summarizes the physical characteristics of each location.

All of the 10 wells that met the selection criteria (Figure 1 and Table 1) are in relatively shallow surficial aquifers, with an average depth to water table of 2–3 m and a typical seasonal range of water table depths of 1–2 m. Two of the data sets (A1 and A2) represent relatively undeveloped locations in the Pisgah National Forest in the Appalachian Mountains, though A2 abuts a trail network and has seen moderate landscape alteration. Both Appalachian wells are in sandy loam soils [*Soil Survey Staff*, 2015]. The next two locations (P2 and P3) are in the central Piedmont and have thick clayey or loamy clayey soils, as does the fifth location (P1) located in the border region between the western Piedmont and the eastern Appalachian Mountains.

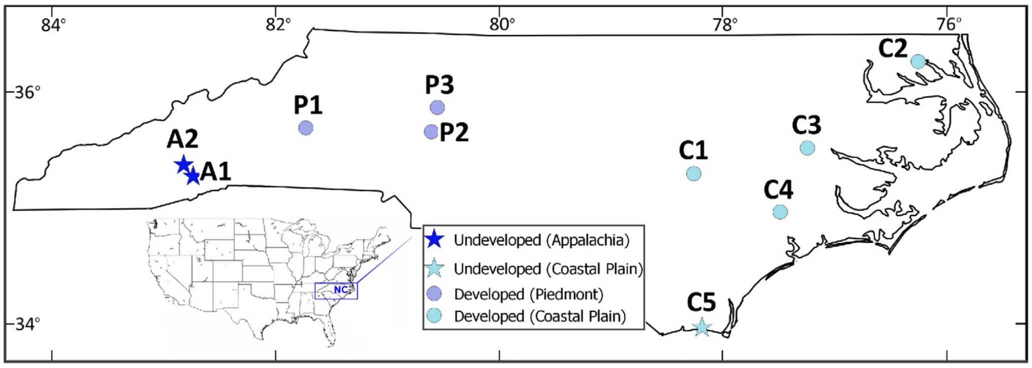

Figure 1. Map of North Carolina (NC), with locations of the 10 water-level records used in this study.

These five Piedmont and Appalachian wells fall within the range of the Piedmont and Blue Ridge crystalline-rock aquifer system, with four wells in regolith (A1, A1, P2, and P3) and one (P1) in undifferentiated bedrock. The remaining five sites are in the Coastal Plain and fall within the range of the surficial aquifer system of eastern North Carolina. All five Coastal Plain wells are in shallow post-Miocene rocks with overlying soils ranging from loamy (C2), to loamy-sandy (C1, C3, and C4), to sandy (C5).

To account for the potential impact of land use, we assessed fractional land cover in the proximate area (radius of 500 m) of each well site using the National Land Cover Database 2011 [*Homer et al.*, 2015]. First, we simplified the class structure into two categories: "developed" (NLCD classes: Developed and Planted/Cultivated) and "undeveloped" (NLCD classes: Barren, Forest, Shrubland, and Herbaceous), with areas of open water being removed. To correct for dynamic land-cover attributes or possible misattributions by the NLCD, we visually compared the data set with current and historical geospatial data from Google Earth dating back to 1993. In the four sites (C1, C3, C4, and C5) in which they appeared, the NLCD classes Woody Wetlands (90) and Emergent Herbaceous Wetlands (95) coincided with incipient regrowth in areas subject to clear cutting during the period of record. Therefore, we calculated fractional land cover using two different methods: (1) excluding these classes and (2) categorizing them as "developed." In both scenarios, the same three locations (A1, A2, and C5) were less developed (20–31% and 18–31%) while the seven other locations were more heavily developed (48–88% and 56–89%).

3. Methods

3.1. The EMR Method

The WTF method relates rises in groundwater levels to recharge arriving at the water table:

$$R=S_y\ \Delta H_e \qquad (1)$$

where R is recharge [L]; S_y is specific yield; ΔH_e [L] is the effective rise in the water table, which is actual groundwater rise due to recharge corrected for ongoing groundwater recession (discussed below). The WTF

Table 1. Summary of Physical Characteristics at Each Location

Location	Latitude	Longitude	Level of Development	Dominant Soil Type	Region	Proximate City	Distance to Rain Gauge (km)	Number of Events Captured	Aquifer
A1	35.285833	−82.728056	Undeveloped	Loam	Appalachia	Asheville	23	460	Regolith
A2	35.387778	−82.812222	Undeveloped	Sandy-loam	Appalachia	Asheville	25	653	Regolith
C5	33.941389	−78.198611	Undeveloped	Sand	Coastal Plain	Wilmington	45	186	Post-Miocene rocks
P1	35.717222	−81.725556	Developed	Sandy-loam	Piedmont	Ashford	27	175	Undifferentiated bedrock
P3	35.899819	−80.554781	Developed	Clayey-loam	Piedmont	Yadkinville	23	325	regolith
P2	35.682783	−80.607047	Developed	Loam	Piedmont	Mooresville	23	444	Regolith
C1	35.309722	−78.272778	Developed	Sandy-loam	Coastal Plain	Clinton	30	284	Post-Miocene rocks
C3	35.538333	−77.261389	Developed	Sandy-loam	Coastal Plain	Greenville	14	467	Post-Miocene rocks
C4	34.970000	−77.503333	Developed	Loamy-sand	Coastal Plain	Morehead City	74	254	Post-Miocene rocks
C2	36.308333	−76.275278	Developed	Loam	Coastal Plain	Elizabeth City	7	296	Post-Miocene rocks

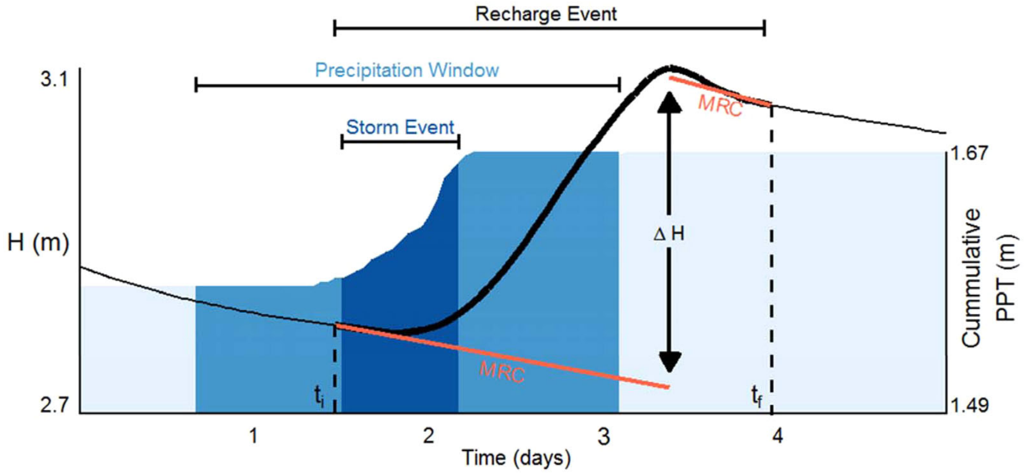

Figure 2. Graph illustrating an example implementation of the EMR method using observed data at C2 in late January 1993. The black line shows water table height above datum, made bold during periods of recharge and thin between periods of recharge. Red lines are MRC extrapolations forward and backward in time from the start and end of a period of recharge. Rise in water table is calculated as the difference between these extrapolations at each event. Cumulative precipitation is shown in blue, with medium blue indicating the time window during which precipitation may have generated recharge (i.e., the Precipitation Window) and dark blue indicating the time period when 90% of this precipitation fell (i.e., the Storm Event).

method can be applied to shallow, unconfined aquifers that show steep water level rises and declines [*Healy and Cook*, 2002]. Possible sources of error include changes in the water table elevation due to anything other than recharge or steady water table recession, including: (1) strong evapotranspiration-driven diurnal fluctuations [*White*, 1932], (2) heavy groundwater pumping [*Healy and Cook*, 2002], (3) changes in atmospheric pressure [*Weeks*, 1979], (4) pressure changes due to entrapped air [*Krul and Liefrinck*, 1946], and (5) rapid conversion of capillary water to phreatic water where the water table is near the ground surface [*Heliotis and DeWitt*, 1987]. We eliminate the first two of these errors by careful site selection (see criteria described above) while the remaining types of error described above are inherently minimized by application of the EMR method [see *Nimmo et al*., 2015].

The EMR method uses a computer program (written in the software package R) to identify episodic recharge by searching for periods of significant water level rises, which are estimated using a master recession curve (MRC) [$L\,T^{-1}$] and a fluctuation tolerance parameter (d_T) [$L\,T^{-1}$]. An MRC is a mathematical representation of expected water table decline in the absence of episodic recharge as a function of hydraulic head [*Heppner and Nimmo*, 2005; *Crosbie et al*., 2005] and d_T is an estimate of the maximum magnitude of water table fluctuations caused by factors other than recharge. Thus, a recharge event is identified if:

$$\Delta H_a > d_T - \Delta H_{MRC} \tag{2}$$

where ΔH_a is the *actual* change in water table level; ΔH_{MRC} is the MRC extrapolated water table decline in the absence of recharge. Since recharge has already begun when ΔH_{MRC} exceeds this threshold, the beginning of the event (t_i) is set to the time when ΔH_a first exceeds ΔH_{MRC}. A recovery time parameter (t_p) is then used to determine the precipitation event window to attribute to each recharge event.

The end of a recharge event is often characterized by nonrecharge related water table declines (e.g., escape of entrapped air). To account for the effects of these fluctuations, the end of a recharge event (t_f) is defined as the earliest time when ΔH_a equals ΔH_{MRC} after having first decreased to some value below ΔH_{MRC}, then water levels are extrapolated forward and backward in time from t_i and t_f using the MRC. ΔH_e is defined as the difference between these two extrapolations at time t_{i+p}. S_y is measured or estimated for each location, and R is solved for using equation (1). An example of how the EMR method is applied for a single storm event is illustrated in Figure 2.

3.2. Parameterization and Data Analysis

The EMR method uses four parameters that are unique to each site: MRC, d_T, t_p, and S_y [see *Nimmo et al*., 2015]. We calculated a unique MRC for each site in Table 1 using recessional data during long (>10 days) interrecharge periods. To maximize sensitivity to recharge events while minimizing the impact of nonrecharge related water table fluctuations, we set d_T to the maximum value of the difference between the MRC calculated recession and observed water table fluctuation during long (>10 day) periods without precipitation. t_p is an estimate of the time of delay between the onset of a storm event and the initiation of episodic recharge at each location. We assigned t_p an initial value of 2.5 days then decreased this value in 1 h increments until recharge events were maximally disaggregated while precipitation windows still contained all precipitation likely to have impacted the associated recharge event.

Although S_y has a substantial impact on R (see equation (1)) and is a major source of uncertainty in the WTF method [*Healy and Cook*, 2002], accurate estimates of S_y are not available for all sites. However, in the absence of spatial or temporal variability of soil-moisture retention characteristics, specific yield may be treated as a scaling factor. Since our objective is to understand long-term RPR trends as a function of storm characteristics rather than to calculate accurate estimates of actual recharge, we normalize RPR values at each location by first assuming a temporally constant S_y value as calculated using a pedotransfer function and average values reported by *Johnson* [1967], then dividing by the mean RPR value at each site (see S.1). By extracting mean RPR values in this manner, we are able to compare the change in relative magnitude of RPR against other parameters among all locations.

After all recharge and storm events were identified, we removed any events containing substantial gaps in water level or precipitation data from our analysis. We also removed any recharge "events" that lasted longer than 10 days, which are instead representative of diffuse seasonal recharge (not episodic) and cannot reasonably be associated with individual storm events. Due to the distance between several of the precipitation and water table gauges and the error introduced by the spatial variability of precipitation, we eliminated any event below a minimum precipitation threshold (set to 1 cm) for which minor errors in measurement would introduce disproportionate error in the RPR estimate. We also eliminated several anomalous events for which RPR was calculated to be negative or orders of magnitude greater than the median for the location, which we attributed either to measurement errors in precipitation, to water table fluctuations that overwhelmed the recharge signal, or to wet antecedent conditions that were not accounted for in our time-lag selection criteria. These isolated anomalies represented less than 0.4% of the 3556 events examined, leaving 3544 individual events suitable for analysis.

For these events, the duration of a storm event (*DUR*) was defined as the time period within the precipitation window beginning after 5% of total precipitation had fallen and ending when 95% had fallen. Therefore, the magnitude of a storm (*MAG*) was set to 90% of the precipitation that fell during the precipitation window. We defined the depth to water table (*DEP*) of an event as the depth in meters to the water table at t_i. While *DUR*, *MAG*, and *DEP* are useful variables for assessing the impact of saturation excess runoff on recharge, to assess the impact of infiltration excess runoff and antecedent soil moisture conditions on recharge, we derived three additional variables: average rate of precipitation (*AVG*), weighted hourly intensity (*INT*), and precipitation recurrence interval (*RCR*). We defined *AVG* as the mean rate of precipitation during a storm (i.e., *MAG*/*DUR*) and *INT* with the following equation:

$$INT = \frac{\sum (HI)^2}{MAG} \tag{3}$$

where *HI* is hourly rainfall intensity. *RCR* is the length of time prior to the initiation of a storm event during which there was negligible precipitation (defined as <1 cm during any 24 h period). We further separated events by seasonality, with all events occurring between 15 April and 15 October deemed "summer" events and all others deemed "winter" events. Additionally, we evaluated the correlations between RPR and *DUR*, *MAG*, *AVG*, *INT*, *RCR*, and seasonality of storm event.

For each location, we tested values of RPR, *DUR*, *MAG*, *DEP*, *AVG*, *INT*, *RCR*, and actual recharge (RECH) for normality using the Shapiro-Wilk test [*Birnbaum and Tingey*, 1951]. At 99% confidence, none of the data sets were normally distributed (see supporting information, section S2 and Figure S3). Therefore, we tested the significance of the relationships between RPR and each storm characteristic with both the Kendall [*Kendall*, 1938] and Spearman [*Spearman*, 1904] rank correlation tests at each location. We analyzed the change in typical RPR values along incremental increases of storm characteristic values. This was accomplished by ordering the storm events at each location by storm characteristic value, binning the events by quintile,

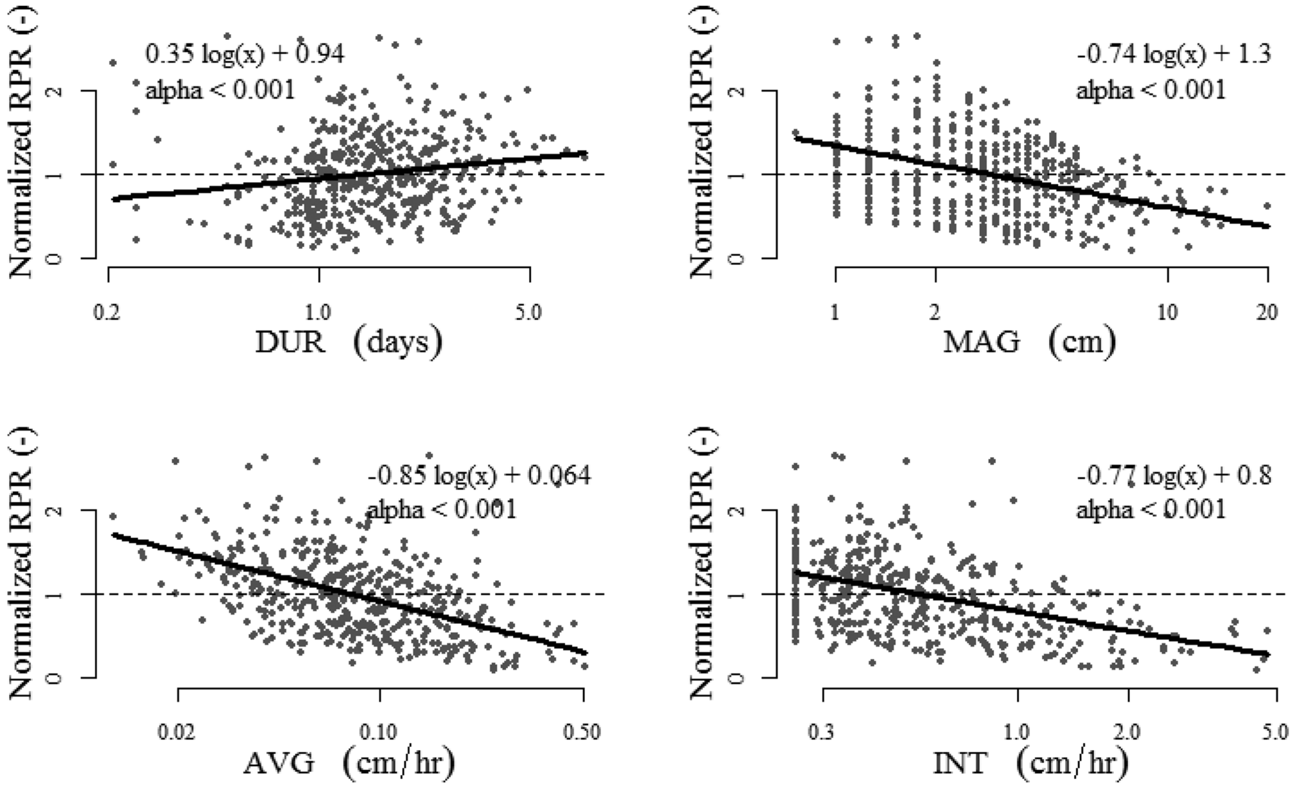

Figure 3. Normalized RPR values plotted against precipitation characteristics for all events at P2 from 11 January 1989 to 10 January 2013. Reported alpha values represent results of both Kendall and Spearman correlation rank tests. Dark black lines are models of logarithmic regression, the equation of which is reported at the top of each plot.

and then assessing the change in median RPR value between the upper and lower quintiles (see supporting information section S3). We then generated a logarithmic model to describe all statistically significant relationships (e.g., Figure 3).

At no location was *RCR* significantly correlated with RPR, leading to the conclusion that the length of time between precipitation events is a poor predictor of RPR in North Carolina, so it was excluded from further analysis. While *DEP* was not significantly correlated with RPR at 6 of the 10 locations, it showed a weak positive correlation with RPR at one location (P2) and a weak negative correlation with RPR at three locations (C1, C2, and C4). We assessed the internal correlation of the storm characteristic variables used in this study by evaluating the r^2 values of linear models describing the relations among *DUR*, *MAG, AVG*, and *INT*. *DUR* was independent ($r^2 \leq 0.25$) from all other storm characteristics at all locations. While *MAG* and *AVG* were independent at four locations and relatively convolved ($0.25 \leq r^2 \leq 0.51$) at six locations, *MAG* and *INT* were relatively convolved at only one location. Despite the reliance on hourly average rates of precipitation for the calculation of both *AVG* and *INT*, *AVG* was independent of *INT* at six locations and only relatively convolved at four locations. This evaluation of relations between storm characteristics and RPR, as well as their internal correlations, helped us identify which variables were relevant for quantifying potential controls on episodic recharge with the EMR method.

4. Results

4.1. Storm Characteristics

Figure 4 illustrates the relative strength of the relationships between RPR and storm characteristics at each location. At all locations, *MAG*, *AVG*, and *INT* were negatively correlated with RPR, while *DUR* and RPR were positively correlated. However, while the correlations between RPR and *AVG* and *INT* were universally significant at 99% confidence, the significance of relationships involving *DUR* and *MAG* was location dependent.

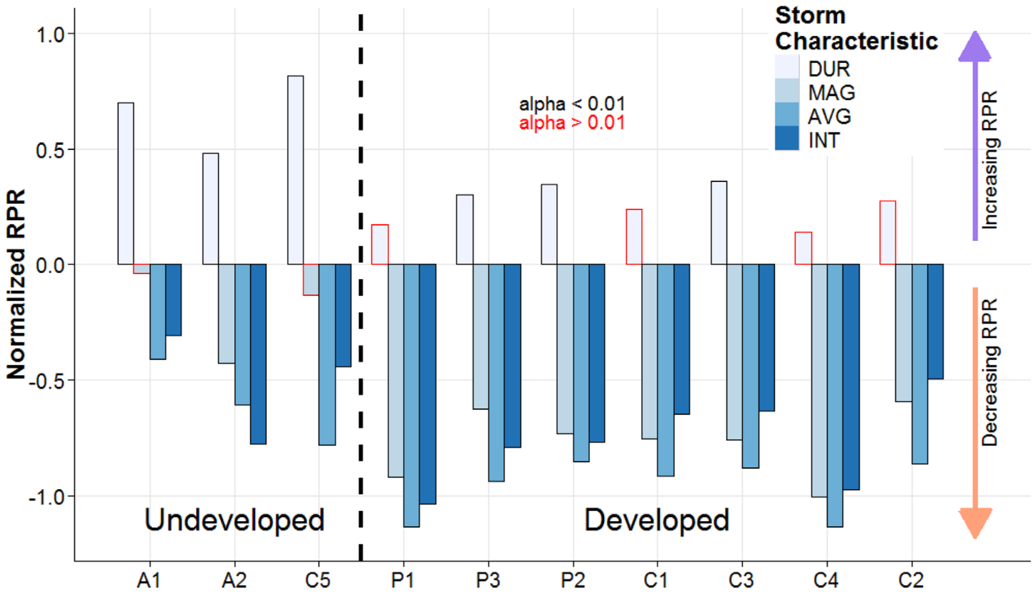

Figure 4. Relative value of scaling component of logarithmic model for relation between RPR and storm characteristic at each location. Maximum alpha values (lowest correlation) of both the Kendall and Spearman correlation rank tests are used to distinguish statistically significant (black outlines) from not significant relations (red outlines).

AVG exhibited the strongest negative constraint on RPR in 9 of the 10 locations studied. The relative strength of this relationship was greatest in the developed locations, with median RPR values for the first and fifth quintiles decreasing by as much as 69% (see supporting information Figure S5). The three locations where RPR values showed the weakest relationship with *AVG* were in areas classified as undeveloped, with sandy or sandy loamy soils. A similar, though muted, response to land use type was evident in the relationship between RPR and *INT*.

In heavily developed locations, the response of RPR to *MAG* was similar to that of RPR to *AVG*, with median RPR values of the first and fifth quintiles decreasing by as much as 53% (see supporting information Figure S5). *MAG* was not significantly correlated with RPR at two of the three undeveloped locations and only modestly impactful at the third (A2), where median RPR values of the first and fifth quintile decreased by only 11%. Conversely, at all heavily developed locations, *DUR* was the weakest control on RPR of any of the storm characteristics and was statistically insignificant in this regard at four of the seven locations. In two of the three undeveloped locations, however, *DUR* was the strongest control on RPR of any of the storm characteristics, with median RPR values of the first and fifth quintiles increasing by as much as 196%. The third undeveloped location, A2, also showed a strong positive response to *DUR*, although *DUR* was not the single greatest control on RPR.

The S_y values we used in calculating both actual RPR and RECH are poorly constrained and a source of major uncertainty. However, since S_y is included as a scaling factor in the calculation of each term, the value of S_y does not affect the relation between actual RPR and RECH. To examine how the relations in Figure 4 influence actual recharge amounts, we compare RPR and RECH using a linear model (Figure 5). At all locations, the actual recharge (RECH) was positively correlated with RPR with 99% confidence, though the relationship was relatively weak ($r^2 \leq 0.3$). At the seven undeveloped locations (P1, P2, P3, C1, C2, C3, and C4) the slope of the model was relatively moderate ($0.8 \leq m \leq 1.6$) while at the three developed locations (A1, A2, and C5) the slope was relatively steep ($2.3 \leq m \leq 4.2$). This implies that for the developed sites the actual amount of recharge to shallow aquifers is even more sensitive to precipitation.

4.2. Seasonality

At 99% confidence, none of the data (except for winter RPR values at P1) were normally distributed, so we investigated the significance of the relative difference between summer and winter RPR values with the Mann-Whitney U test [*Mann and Whitney*, 1947]. As Figure 6 shows, median RPR values tended to be higher during the winter than during the summer at all locations, though at only six locations was the difference

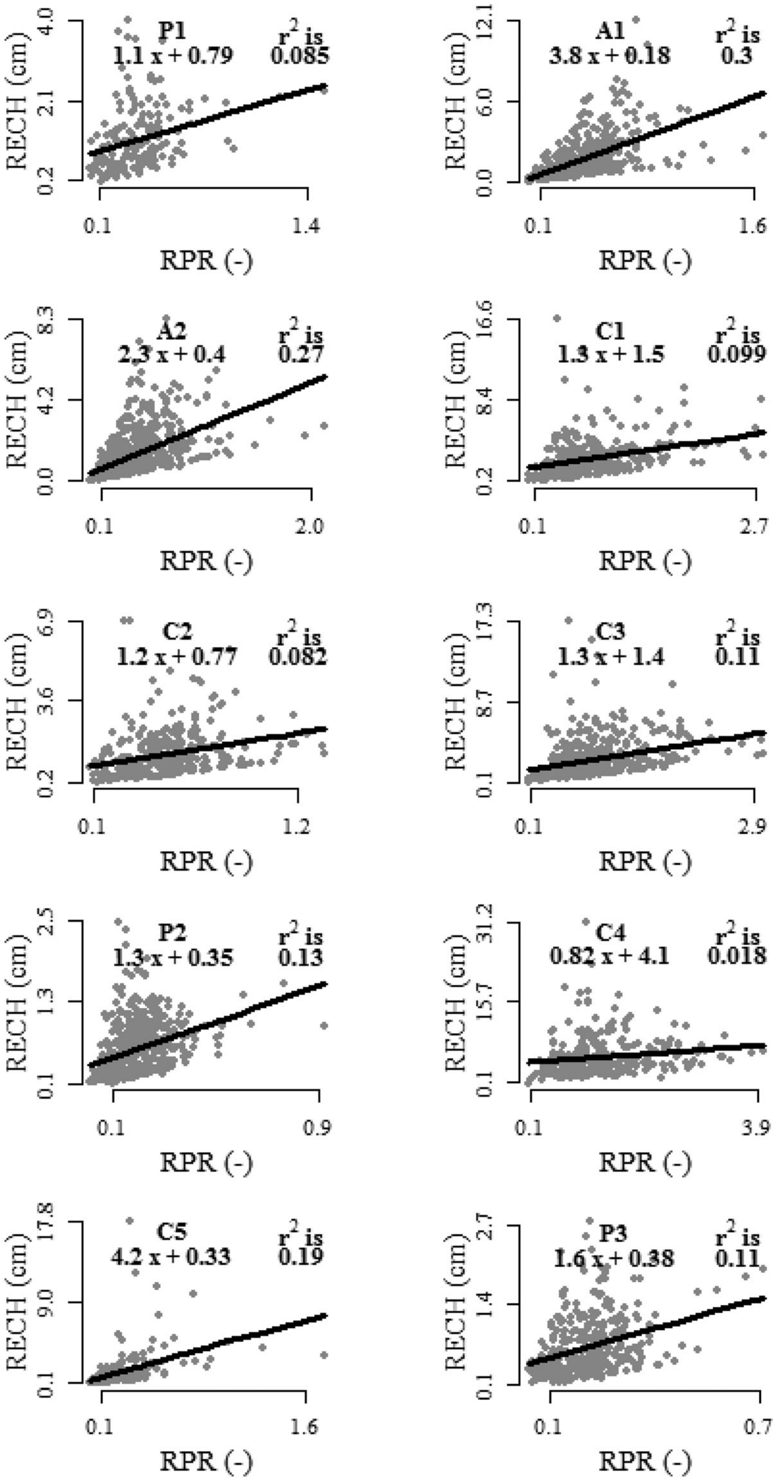

Figure 5. Plots showing relation between RECH and RPR for each monitoring location, calculating with S_y values from pedotransfer functions in unconsolidated regolith aquifers and *Johnson* [1967] in bedrock aquifers (see Table 1).

significant at 99% confidence. The locations exhibiting significant seasonal differences showed no observable similarities in land use type. Instead, seasonal influence in RPR followed a geographic pattern. In the inland part of the state (Appalachia and the Piedmont), median winter RPR values were as much as 84% higher than in the summer, and four of five locations exhibited statistically significant seasonal impact.

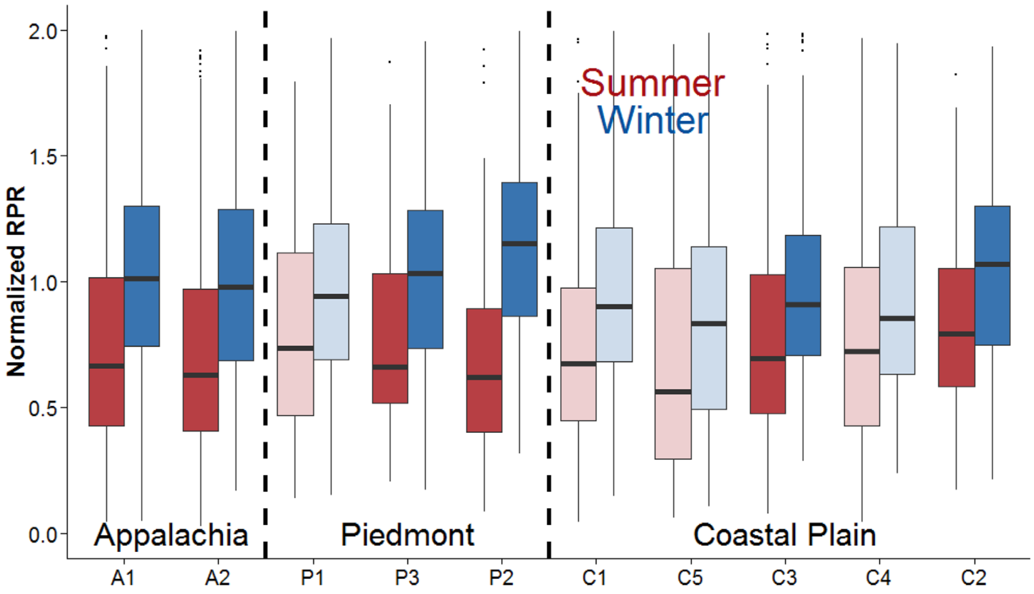

Figure 6. Normalized RPR values of summer and winter events during the period of record for each location. Red and blue boxes represent 25th to 75th percentile RPR values during the summer and winter, respectively. Dark boxes represent statistically significant differences between summer and winter RPR values, and faded boxes represent seasonal RPRs that are not significantly different. Sites are organized by geographic region.

Along the Coastal Plain in the eastern part of the state, seasonal impact was insignificant at all locations except two (C2 and C3).

To address the possible impacts of interseasonal storm characteristic variability, we also inspected the relative values of all storm characteristics during summer and winter months. During the summer, storms that generated recharge tended to be slightly longer (greater *DUR*) at all locations and slightly larger (greater *MAG*) at all locations except in Appalachia, where seasonality had no impact. In contrast, *AVG* was constant throughout the year at all locations except two in the Piedmont (P2 and P3, where *AVG* was higher in the summer). However, *INT* was significantly greater during the summer at all locations.

We assessed the impact of seasonality on the strength of the relationship between RPR and each storm characteristic by: (1) normalizing RPR values at each location, (2) isolating summer and winter events, (3) generating a logarithmic model describing RPR-to-storm characteristic relationships during each season at each location, and then (4) comparing the relative strength of the scaling components of the logarithmic models for summer events to those for winter events. Figure 7 shows the results of this analysis. At all locations except two (C2 and C3), the effects of storm characteristics on RPR were generally enhanced during the summer and diminished during the winter. Longer storms (greater *DUR*) generated higher typical RPR values during the summer than during the winter at all undeveloped locations, while the effects of *DUR* on RPR were relatively constant at developed locations. The effects of *MAG* on RPR, however, were greatly enhanced during the summer at all Piedmont locations, while seasonality had minimal impact on *MAG* relationships elsewhere. *AVG* and *INT* both exhibited stronger relations with RPR values during the summer than during the winter at all locations except two (C2 and C3).

5. Discussion

5.1. Hydrologic and Seasonal Controls on RPR

Overall, our results suggest that RPR is strongly influenced by storm characteristics, and that the nature and magnitude of that influence is somewhat related to the physiographic characteristics of the landscape, including the degree of development or disturbance. These complex interrelationships are indicative of the subtle interplay of the various hydrologic components governing interception, infiltration, evapotranspiration, redistribution, and macropore flow. Our data sets allowed us to account for the potential influence of

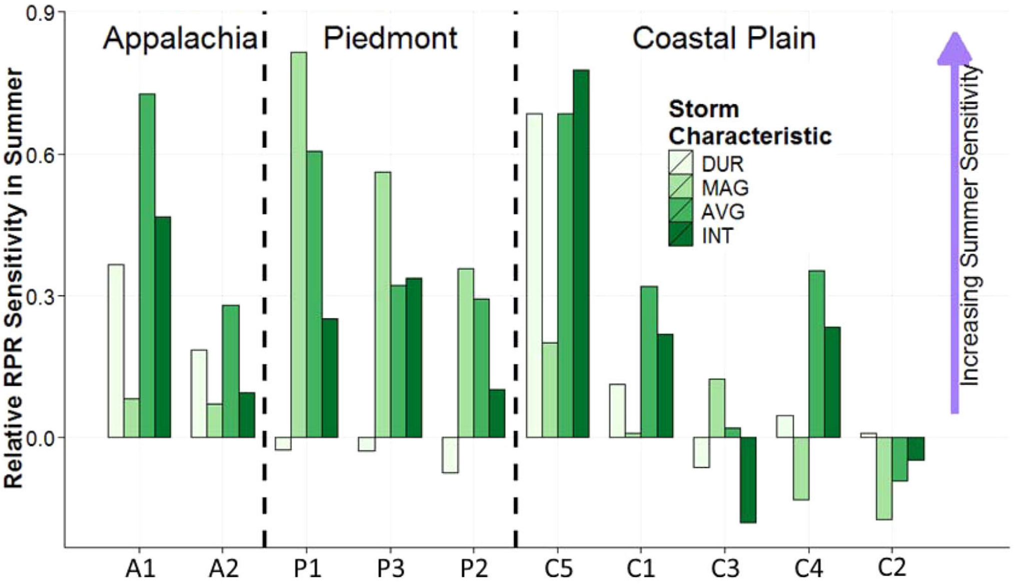

Figure 7. Relative sensitivity of RPR-to-storm characteristic relationships during the summer as compared to during the winter. A value of 0.3 represents a 30% increase in sensitivity during the summer, a value of −0.3 represents a 30% decrease in sensitivity during the summer. Sensitivity is defined as the difference between the relative value of the scaling component of the logarithmic model relating RPR to storm characteristic at each location during the summer and during the winter.

land use and geographic setting on recharge to precipitation ratios. However, additional factors such as slope, lithology, and vegetation type, which we did not consider, would also contribute to the intersite variability we observed. Regardless, careful analysis of the EMR results reveals some insights about the dominant processes and seasonal controls that influence episodic recharge across the southeastern U.S. and as well as specific insights at each site.

Possibly the most striking result is the strong decrease in RPR with increasing *AVG* and *INT* at all locations (Figure 4). This indicates that the generation of overland flow is likely an important constraint on groundwater recharge to shallow aquifers in humid climates across the southeastern U.S. This could be due either to higher rainfall intensities leading to infiltration excess overland flow or to slow drainage of already wet soils leading to saturation excess overland flow. Further, the strength of these relationships is greater at developed locations than undeveloped locations, implying that naturally vegetated locations are less sensitive to increasing rainfall rates. *Dunne et al*. [1991] have attributed decreasing infiltration rates during storms to the development of surface seals on certain types of bare soils. Another possible explanation of this result is that lower infiltration capacities of compacted urban and agricultural soils lead to a greater magnitude and earlier onset of runoff, thus reducing recharge.

The relationship between *MAG* and RPR also illustrates the potential impact of landscape alteration on infiltration processes in humid climates. A negative relationship between *MAG* and RPR indicates that saturation excess overland flow is an important constraint on episodic recharge. Furthermore, our finding that *MAG* is a powerful constraint on RPR at the developed locations, but generally irrelevant at the undeveloped locations suggests that anthropogenic alteration of the landscape has decreased the natural storage capacity of soils. This may be due to a variety of factors associated with landscape disturbance and vegetation removal, including the compaction of shallow subsurface clays, reduction of macropore and soil structures, and the loss of relatively porous topsoil.

The positive relationship between *DUR* and RPR is evident across North Carolina. The higher fractional recharge resulting from longer duration storms may be attributed to: (1) hydraulic conductivities of soils increasing with increasing soil moisture content, allowing enhanced drainage when rainfall intensities are sufficiently low; (2) enhancement of macropore flow under near-saturated conditions; (3) the filling of interception and antecedent soil moisture stores before significant recharge can occur. However, the influence of storm duration is notably weaker or negligible at the more developed locations, which can be attributed to both the decrease in macropores in compacted urban and disturbed agricultural soils, and the decrease in vegetative cover (and therefore interception capacity) at developed locations.

The lack of strong relationships between RPR and *DEP* is a somewhat curious result of this study. *Crosbie* [2003] showed that RPR is influenced by depth to water table in shallow aquifers in Minnesota, where RPR is minimized at very shallow depths (<1 m) likely due to a reduction in available storage and decreases with increasing depth thereafter partly due to the attenuation of the recharge signal by the unsaturated zone. The long-term average impact of *DEP* on RPR may be somewhat obscured at the locations used in this study due to the strong influence of seasonality on RPR, with RPR being much higher in the winter (when the water table is relatively high) and much lower in the summer (when the water table is relatively low).

While the actual values of RPR and RECH used in this analysis are poorly constrained due to the absence of accurate estimations of S_y, it is interesting to note the character of the relationship between them (Figure 5). Though RPR is not the primary constraint on RECH, the relationship is universally positive and generally greater than one-to-one, with an incremental increase in RPR tending to lead to a disproportionate increase in RECH. Therefore, the long-term average decrease in RPR predicted by this analysis may substantially underestimate long-term average decrease in actual recharge in North Carolina.

Our analysis clearly shows the somewhat expected result that RPR in North Carolina is greater in the winter than in the summer (Figure 6), but we also show that recharge is more sensitive to storm characteristics during the summer than during the winter (Figure 7). In the summer, fractional recharge likely decreases due to increased canopy interception and higher rates of evapotranspiration. The diminishing influence of seasonality on RPR along the Coastal Plain can most likely be attributed to (1) the less drastic variations in seasonal temperature and vegetation in coastal environments, and (2) the fact that the greatest fraction of forest cover in the vicinity of each location selected for this study on the Coastal Plain is pine, as opposed to mixed deciduous forests [*Homer et al.*, 2015]. The increased sensitivity of RPR to storm characteristics during the summer across all sites is partly a result of the increased variability in antecedent conditions, such as interception storage and rates of evapotranspiration. Also, since summer storms that generate recharge (e.g., hurricanes) tend to be slightly larger and substantially more intense than winter storms, the relative impact of the various storm characteristics may be heightened during the summer.

5.2. Contradictions, Limitations, and Future Considerations

Our results demonstrate that large, short, high-intensity storms tend to generate the lowest relative RPR (Figure 3), which is contrary to some previous findings that have shown a positive relationship between RPR and large, powerful storms [e.g., *Crosbie et al.*, 2012]. This apparent contradiction is related to three important factors influencing episodic recharge. First, North Carolina is considerably more humid than the location of many previous studies [e.g., *Crosbie et al.*, 2012; *Kendy et al.*, 2003, 2004]. In arid climates, significant recharge may only occur after large storms have filled relatively high antecedent soil moisture deficits, while in humid climates with relatively shallow water tables low soil moisture is rarely a limiting factor. Second, because the intensity and magnitude of more extreme storm events are expected to increase most in a warming climate [*Min et al.*, 2011], we have limited the scope of our study to storms large enough and intense enough to actually generate significant, observable episodic recharge. Therefore, by excluding storms below this threshold we have potentially eliminated from our analysis the storm sizes and intensities for which fractional recharge might be expected to increase. Finally, whereas many previous studies [e.g., *Taylor and Howard*, 1996] have assessed the impact of daily (or monthly) precipitation totals on net recharge, this study analyzes the characteristics of individual storms using hourly precipitation and water table response data (Figure 2). Thus, what we may consider to be several small storms over a period of weeks may have been defined as a single large event by other studies.

Of course, our study is not without assumptions and uncertainty. In particular, diffuse recharge, which is not captured by the EMR method, is also important for water resources and groundwater levels. It is likely that climate and land use change will also subtly influence the complex factors governing this constant rate component of recharge, particularly through increased potential evapotranspiration. However, since there is strong evidence that climate change will influence the size, severity, and frequency of extreme storm events [*Kirtman et al.*, 2013], and little is known about how this will impact recharge, we have focused on quantifying those potential impacts first. The distance between the wells and precipitation gauges used in this study is another potential source of uncertainty. We mitigated this uncertainty by limiting our study to locations with exceptionally long periods of record, thereby allowing us to identify statistically significant relationships from a large number of unique events. We suspect that future studies using more precisely collocated wells and precipitation gauges may see stronger (but qualitatively similar) relationships between RPR and storm characteristics.

Further, though this is the largest high-resolution study of its kind to date, 10 locations remain a relatively small sample size, and hourly precipitation data may be of too coarse a resolution to adequately represent *INT*. We have confined this initial study to North Carolina to evaluate only subtropical climates in the southeastern U.S. where appropriate data were available. We encourage researchers with access to long-term, high-resolution water-level and precipitation records at other locations to explore the potential utility of the EMR method for understanding how storm characteristics and other factors may influence RPR across different climates and geographic regions. Finally, future studies using finer resolution precipitation data and robust estimates of specific yield may provide more quantitatively accurate estimates of how *INT* impacts recharge rates, which can be used to directly inform land and water-resources management decisions.

5.3. Implications for Water Resources

Our results suggest that lengthening summer growing seasons and an increase in the frequency and intensity of large storms in the coming century may lead to a decline in RPR and thus in groundwater availability across the American Southeast absent increases in precipitation. Recent studies show little evidence for large precipitation increases in North Carolina [*Sobololwski and Pavelsky*, 2012]. This result calls into question the foundation of the sustainable yield concept underpinning many municipal development policies, since such methods use static average annual recharge rates to estimate sustainable withdrawals from shallow aquifers [e.g., *Sophocleous*, 2000]. Furthermore, since stream base flow is dependent on groundwater, lower groundwater levels may also damage or destroy fragile riparian ecosystems [*Brunke and Gonser*, 1997]. Whether the problem of declining groundwater recharge is ameliorated or exacerbated may hinge on future land use policy. One potentially positive outlook of our findings is that declining recharge in Appalachia may actually decrease the potential for natural hazards such as large, deep landslides.

The relations developed in this paper demonstrate that storm characteristics constrain long-term average RPR values to a degree that is both statistically significant and quantifiable. In the absence of more complicated analytical methods, these relations may serve as an empirical control on groundwater response to precipitation in future modeling efforts. The relative simplicity of our approach highlights the substantial value of continuous, long-term, high-resolution groundwater monitoring conducted by the USGS and other agencies worldwide. Analysis of similar data sets in different locations could also show whether these relationships are particular to humid, subtropical environments in the American Southeast, or are more generally applicable outside of climates like that of North Carolina. The impact of magnitude and intensity of precipitation on recharge deserves particular attention since (1) these characteristics play an outsized role in governing RPR in developed environments, and (2) they are likely to increase substantially as the global climate continues to change.

6. Summary and Conclusions

We investigated empirical relations between storm characteristics and the ratio of precipitation that contributes to recharge (RPR). We examined water-level records from 56 individual USGS monitoring wells across North Carolina, USA, and were able to use long-term precipitation and water table fluctuations at 10 of these locations, which included 3544 storm events that generated episodic recharge. At all sites, average RPR values increased with storm duration and decreased with storm magnitude, average rate, and weighted hourly intensity. The negative constraints on RPR were magnified both at developed locations and during the summer. At all locations, RPR also tended to be lower in the summer than in the winter, though this effect was smaller on the Coastal Plain region. Climate models predict an increase in the size and intensity of the largest storms and a lengthening of the growing season over the coming century. In the absence of other influences, our results suggest that groundwater recharge is likely to decrease across North Carolina, especially in urban environments, agricultural areas, Appalachia, and the Piedmont.

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