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RESEARCH ARTICLE

Bidirectional stream–groundwater flow in response to ephemeral and intermittent streamflow and groundwater seasonality

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Abstract

It is often assumed that the net groundwater flow direction is towards the channel in headwater streams in humid climates, with magnitudes dependent on flow state. However, studies that characterize stream–groundwater interactions in ephemeral and intermittent streams in humid landscapes remain sparse. Here, we examined seasonally driven stream–groundwater interactions in response to temporary streamflow on the basis of field observations of streamflow and groundwater on an adjacent hillslope. The direction of hydraulic head gradients between the stream and groundwater shifted seasonally. The stream gained water (head gradients were towards the stream) when storage state was high. During this period, streamflow was persistent. The stream lost water to the groundwater system (head gradients were away from the stream) when storage state was low. During this period, streamflow only occurred in response to precipitation events, and head gradients remained predominantly away from the stream during events. This suggested that mechanisms other than deep groundwater contributions produced run-off when storage was low, such as surface and perched subsurface flowpaths above the water table. Analysis of the annual water balance for the study period showed that the residual between precipitation inputs and streamflow and evapotranspiration outputs, which were attributed to the loss of water to the deeper, regional groundwater system, was similar in magnitude to streamflow. This, coupled with results that showed bidirectionality in stream–groundwater head gradients, indicated that headwaters composed of temporary (e.g., ephemeral and intermittent) streams can be important focal areas for regional groundwater recharge, and both contribute to and receive water, solutes, and materials from the groundwater system.

KEYWORDS

ephemeral streamflow, groundwater recharge, headwaters, intermittent streamflow, stream–groundwater interactions, temporary stream

1 | INTRODUCTION

Historically, headwater streams in humid regions have been generally viewed as gaining systems. Several benchmark studies (e.g., Hewlett, 1974; Pinder & Jones, 1969; Sklash, Farvolden, & Fritz, 1976) introduced and built on the variable source area framework for streamflow generation, which influenced how researchers studied subsurface flow contributions to streams for decades. At the receiving end of groundwater flowpaths, streams were largely viewed as pipes, accumulating and transporting water to the oceans. Increasingly by the 1990s, however, researchers argued that the complex pathways water take do not stop once in the stream channel (Bencala, 1993; Winter, Harvey, Franke, & Alley, 1998). This shifted the longstanding conceptual framework towards the idea that surface water and groundwater were interconnected components of the landscape (Bencala, 1993; Brunke & Gonser, 1997; Winter et al., 1998). Since then, stream–groundwater interaction studies greatly increased in number as researchers focused on understanding the controls and variability of water movement across the stream–groundwater interface (Fleckenstein, Krause, Hannah, & Boano, 2010).

Although substantial research on stream–groundwater interactions has been conducted at the local or reach scale (Harvey &

Gooseff, 2015), there is still a large gap in knowledge regarding the role of streams in the hydrogeology of basins (Dahl, Nilsson, Langhoff, & Refsgaard, 2007; Hayashi & Rosenberry, 2002; Ivkovic, 2009). For instance, some regional climate models route water at the base of the soil column directly into rivers, which bypass deeper storage and flowpaths, en route to the ocean. Recently, however, research has suggested that flowpaths that originate in headwaters can be important for deeper storage and regional scale subsurface flowpaths. For example, Schaller and Fan (2009) used hydrologic data to show that headwaters can be important for deep groundwater recharge and regional scale subsurface flowpaths, which may not resurface as stream water at the headwater catchment scale. However, there are still mechanistic gaps in our understanding of where regional groundwater recharge occurs in headwater landscapes.

There has historically been a divide in the conceptualization of stream–groundwater interactions between catchment hydrology and hydrogeology frameworks within the headwaters of humid landscapes. Catchment hydrology has traditionally described streamflow generation processes within the variable source area concept (Hewlett & Hibbert, 1967; Hursh, 1936). Researchers have demonstrated that the degree and extent of surface and subsurface contributions to streamflow in headwaters can fluctuate but predominantly in a unidirectional framework with gradients towards the stream (Dunne & Black, 1970; Hewlett & Hibbert, 1967). Research documenting reversal in flow direction (e.g., stream discharge to groundwater) in humid landscapes has been limited. One exception is the reversal of flow direction due to temporary bank storage (Cooper & Rorabaugh, 1963; Todd, 1955). This reversal in gradients has been shown to occur during high stormflow (e.g., floods), which temporarily raises the stream height above the floodplain groundwater level. This gradient reversal has been suggested to modify the stream hydrograph by diminishing the magnitude of peak flow (Pinder & Sauer, 1971). As the stream hydrograph recedes faster than floodplain groundwater levels, the direction of flow reverses back towards the stream, which can extend baseflow duration (Whiting & Pomeranets, 1997). Although bank storage can produce bidirectional gradients between streams and shallow groundwater on an event basis, it has been typically observed in higher order streams (Bates et al., 2000; Squillace, 1996). Although this mechanism can lead to temporary shallow water storage in the riparian zone, it is unclear how it can influence deeper groundwater recharge and whether it is an important mechanism within ephemeral and intermittent headwater streams of humid landscapes. In this study, an ephemeral stream is defined as a channelized or unchannelized portion of the landscape that only flows temporarily in direct response to precipitation inputs. An intermittent stream is defined as a channel that flows seasonally (i.e., flow for 3 months or longer) in response to the seasonal rise in the water table. That said, any streamflow that activates in direct response to precipitation during dry periods in an intermittent stream channel is classified as ephemeral flow. A temporary stream is used to encompass both ephemeral and intermittent streams in this study.

From a traditional hydrogeological point of view, streams represent the surficial expression of groundwater. The dynamic expansion and contraction of the stream network within headwaters has been suggested to be in response to the seasonal rise and fall of the water table (de Vries, 1995; Winter et al., 1998). Within this conceptualization of stream–groundwater interactions, Winter et al. (1998) suggested that the location where the water table and the geomorphic stream channel first meet must be downstream of dry reaches. The seasonal rise in the water table thus shifts this interface upstream, which can activate streamflow in previously dry channels. That said, more mechanistic research in the headwaters of humid landscapes is needed to confirm this conceptual explanation of stream–groundwater interactions surrounding temporary stream activation.

Key points

- Temporary (e.g., ephemeral and intermittent) streams can act as both groundwater recharge and discharge zones.
- Annual contributions to regional groundwater recharge were similar in magnitude to annual streamflow.
- Changes in the direction of stream–groundwater head gradients may lead to temporal variability in streamflow generation processes.

Most mechanistic research on stream–groundwater interactions in ephemeral and intermittent streams has taken place in arid and semi-arid regions (Bull & Kirkby, 2002), where these temporarily flowing channels are the predominant fluvial system. In these water-limited environments, ephemeral and intermittent streams are often perched above the water table and can undergo substantial transmission losses through the unsaturated zone to the saturated zone (Lane, 1983). The quantification of transmission losses can provide valuable information about aquifer recharge, and much effort has been put towards developing methodologies to better quantify recharge estimates for assessments of water resources and potential contamination in these arid landscapes (Niswonger, Prudic, Fogg, Stonestrom, & Buckland, 2008; Scanlon, Healy, & Cook, 2002; Shanafield & Cook, 2014). Although transmission losses along ephemeral and intermittent streams in arid regions are commonly observed, studies documenting groundwater recharge characteristics in temporary streams in humid landscapes are uncommon.

For this study, we used field-collected hydrologic data from 1 October 2014 to 20 June 2016 from a headwater catchment in the humid Piedmont region of North Carolina, United States, to present new understanding as well as a call for new research related to the bidirectionality of stream–groundwater flow surrounding temporary streamflow activation. We relate streamflow dynamics at the outlet of an ephemeral-to-intermittent drainage network to the seasonal water table dynamics along a characteristic groundwater well transect observed internally to the catchment. We hope these initial findings from a singular well transect may provide motivation for additional spatially distributed hydrological studies in these complex landscapes. This study also presents a water balance approach to quantify the magnitude of regional groundwater recharge occurring in this characteristic headwater catchment.

2 | METHODS

2.1 | Study site

This study took place in a 3.3 ha headwater catchment with an ephemeral-to-intermittent drainage network located in the Duke Forest Research Watershed (North Carolina, USA; Figure 1), which is a satellite site of the Calhoun Critical Zone Observatory in the Piedmont of South Carolina. The spatial extent of intermittent and ephemeral channels (Figure 1) was determined from 77 repeated mapping campaigns of the surface drainage network across a range of flow conditions (see Zimmer & McGlynn, 2017). The intermittent channel extent was coincident with the geomorphic channel extent, whereas the ephemeral channel extent represented surface flow beyond the geomorphic channel. Duke Forest has a humid subtropical climate with measured annual precipitation of 1,136 mm, mean annual temperature of 15.5 °C, and mean annual evapotranspiration of 720 mm (Novick, Oishi, & Stoy, 2016). There is negligible seasonality in monthly precipitation, and it is almost entirely rain-dominated with a long growing season from April to October (Figure 2a).

The catchment is located within the Carolina Slate Terrane, which is composed of fine-grained felsic, metamorphic rock, overlain by Ultisol soils of the silt loam Georgeville series (Bradley & Gay, 2005). These soils are characterized by an argillic Bt horizon, which is classified by an increase in clay content and a rapid decrease in saturated hydraulic conductivity with depth (Soil Survey Staff, 2016). Below the argillic Bt horizon is the C horizon and saprolite layer (defined as parent material weathered in place that can be hand-augered), which was shown to be of variable depth across the catchment. On the basis of installation of 12 groundwater wells, the depth to hand-auger refusal, which was indicative of the transitional zone between saprolite and more competent weathered bedrock (in sensu Anderson, von Blanckenburg, & White, 2007), was observed to generally deepen away from the stream, with shallow depths in the lower hillslopes (~1 m) and greater depths in the upper hillslopes (>9 m). This increasing regolith depth away from the stream is indicative of a near horizontal upper bedrock weathering zone, which has also been observed in geophysical assessments of the highly weathered subsurface landscape at the nearby Calhoun Critical Zone Observatory in the South Carolina Piedmont (St Clair et al., 2015).

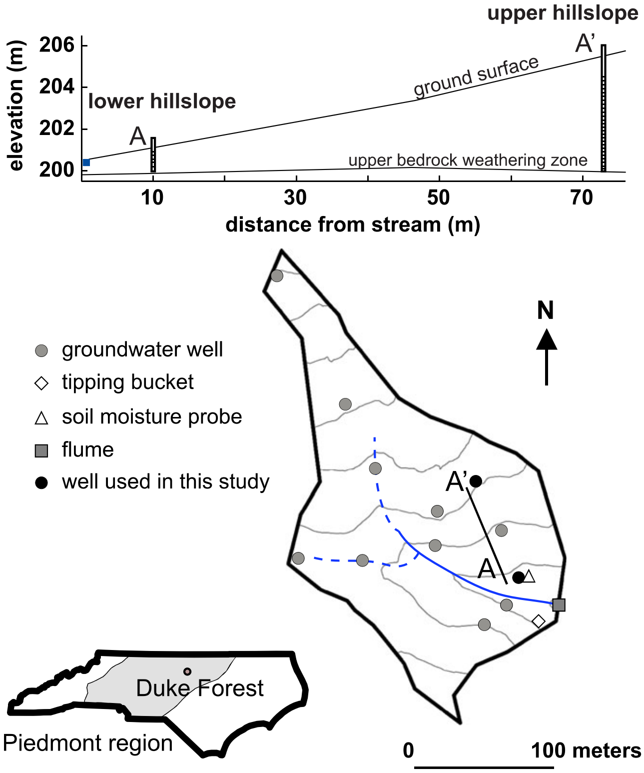

FIGURE 1 Map of 3.3 ha research catchment, with bottom inset map indicating location of Duke Forest in North Carolina, United States, with shaded area indicating Piedmont physiographic region. Blue dashed lines indicate observed maximum extent of ephemeral streamflow, and blue solid line indicates observed maximum extent of intermittent streamflow. Top inset figure is cross section of hillslope (A to A') with locations of wells used for this study and ground and upper bedrock weathering zones labelled (3× vertical exaggeration)

Forest age is approximately 80–100 years (Oishi, Oren, & Stoy, 2008) represented with a mix of mature natural and planted pine (predominately loblolly pine, *Pinus taeda*) as well as numerous species of deciduous hardwoods, including oaks (*Quercus* spp.), hickories (*Carya* spp.), elms (*Ulmus* spp.), sweetgum (*Liquidambar styraciflua*), and tulip poplar (*Liriodendron tulipifera*). Historical land use activity includes widespread agricultural practices, such as farming and tobacco production, common across the south-eastern United States of America, occurring predominantly in the 18th through early 20th centuries (Richter, Markewitz, Trumbore, & Wells, 1999).

2.2 | Hydrometric installations and measurements

This study utilized field-collected data, including streamflow magnitudes, precipitation inputs, and groundwater levels from 1 October 2014 to 20 June 2016. Five-min stage data from a stilling well within an engineered 3-ft H-flume at the catchment outlet (Figure 1) were recorded using a capacitance water level recorder (±1-mm resolution; TruTrack Inc., New Zealand) and converted to run-off using the field-verified geometric relationship between water height and run-off in the flume (U.S. Department of Agriculture, 1972). Throughfall and rainfall were recorded at 5-min intervals using a 0.1-mm increment tipping bucket (Campbell Scientific, USA). A tipping bucket measuring throughfall was located near the catchment outlet (Figure 1), whereas a rainfall tipping bucket was located in a forest clearing 200 m outside the catchment (not pictured in Figure 1). The rainfall time series was used in this study due to the potentially high spatial variability in throughfall amounts across the catchment, which could not be captured from just one throughfall tipping bucket.

Groundwater levels were monitored at 5-min intervals in 12 groundwater wells using a combination of capacitance water level recorders (±1-mm resolution; TruTrack Inc., New Zealand) and pressure transducers (±0.1-mm resolution; Solinst, California, USA). The wells were installed to hand-augered refusal depths, which represented the transitional zone between saprolite and more competent weathered bedrock, and were screened to within 10 cm of the ground surface. The wells were distributed across a range of landscape positions, including lower hillslope, mid hillslope, and upper hillslope locations in valley hollows and convergent and planar hillslopes (Figure 1). This

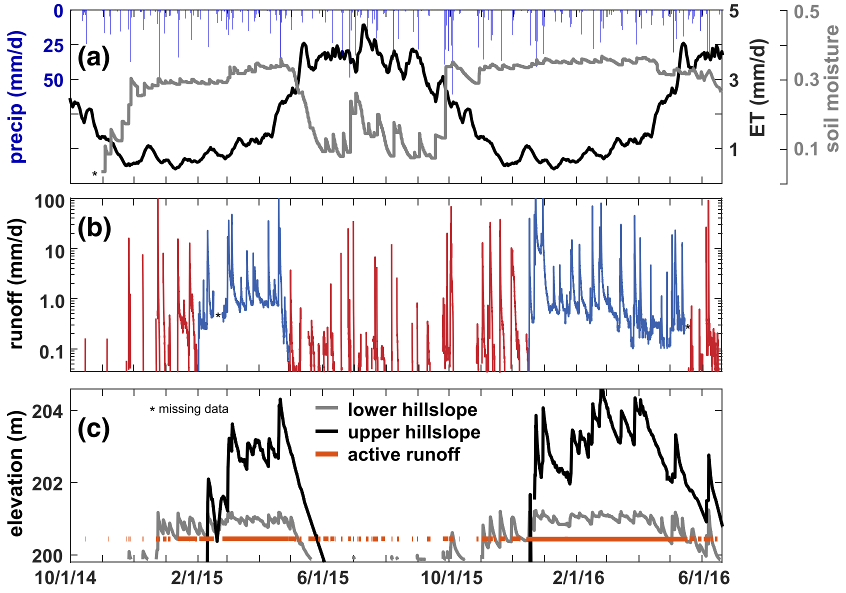

FIGURE 2 Time series of (a) precipitation (blue bars), soil water content (grey line), and evapotranspiration (black line) and (b) run-off at catchment outlet in semilog space to highlight variability in flow magnitudes. Blue periods indicate persistent flow that occurs when catchment storage is high, and red periods indicate when streamflow is active only in response to precipitation events, when catchment storage is low. (c) Elevation of groundwater at lower hillslope (grey line) and upper hillslope wells (black line). Orange line represents periods when run-off is present and is set at the elevation of streambed at the base of the hillslope well transect

study utilized characteristic groundwater data from one transect along a convergent hillslope, located 25 m upstream of the catchment outlet (Figure 1). Although other groundwater well transects were present, the design of this particular transect allowed for exploration of stream–groundwater gradients due to uniform depths of the screened wells across the transect. The other groundwater well transects were not all screened to uniform depths and thus were not used in this study. That said, the results obtained from data from this transect provide initial results that hopefully motivate additional spatially distributed studies in these hydrological systems. As clarified by 77 surface drainage network mapping campaigns across a range of flow conditions (Zimmer & McGlynn, 2017), streamflow at the base of the hillslope groundwater well transect always occurred when there was measureable streamflow at the catchment outlet. Therefore, this study could use flow dynamics at the catchment outlet to investigate relationships between streamflow at the base of the hillslope transect and groundwater flow in the hillslope. Stream level at the base of the hillslope transect was observed to vary minimally (0–0.18 m) relative to the hillslope length (76 m); therefore, the streambed elevation was used as the stream level elevation, regardless of the discharge amount. A 12-cm soil water content reflectometer (Campbell Scientific, USA) was vertically installed from 5 to 17 cm depth below ground at the lower hillslope location of this transect to capture shallow soil water content dynamics at 5-min intervals. This study utilized the 3-day soil moisture minimum to represent a generalized catchment storage state while ignoring flashy responses to individual precipitation events (Figure 2a).

Lateral hydraulic head gradients across the hillslope were calculated by dividing the difference in water level in two wells by the distance between the two wells (A and A' in Figure 1). Stream–groundwater head gradients were calculated by dividing the difference in elevation between the streambed (when streamflow was present) and the groundwater in the lower hillslope well by the distance between the centre of the streambed and well. All instrument locations were surveyed using a Nikon Nivo 5.M total station (<1 cm resolution, Nikon-Trimble Co., Toyko, Japan).

An annual water balance for the 2015 water year (1 October 2014 – 30 September 2015) was calculated using data collected on-site as well as from local datasets (Table 1), such that

$$\text{precipitation} = \text{streamflow} + \text{evapotranspiration} + \text{residual}. \quad (1)$$

Measured precipitation at the study site totalled 1,136 mm for the 2015 water year. This annual precipitation amount was compared to a 10-year precipitation time series from a National Oceanic and Atmospheric Association (2016) station <14 km from the study site, which showed average annual precipitation of 1,141 ± 137 mm. The year 2010 was the most recent water year in which precipitation fell below the standard deviation of the average (995 mm), which suggests that there was no significant change in catchment storage between the 2014 and 2015 water year. Average annual evapotranspiration was calculated to be 720 ± 78 mm from 8 years of 30-min data collected from an eddy covariance flux tower within the Duke Forest (Novick et al., 2016). A daily time series of evapotranspiration was derived from averaging daily values from four consecutive non-drought years within

TABLE 1 Flux components of the 2015 water year water balance

Inputs			
	Year	Average flux amount (mm)	Potential deviation (mm)
Precipitation			
This study	2015	1,136	–
Outputs			
Evapotranspiration			
Novick et al. (2016)	2001–2008	720	78
Streamflow			
This study	2015	220	–
Residual			
This study	2015	196	78

Note. Residual was calculated as difference between precipitation inputs and evapotranspiration and streamflow outputs.

that dataset (Figure 2; Figure 3a). Annual streamflow of 220 mm was measured at the catchment outlet, and error in this value was assumed minimal as discharge calculations were confirmed through manual instantaneous discharge measurements across a variety of flow states. A mass balance approach (Equation 1; Table 1) was used to estimate the residual water in the 2015 water year not accounted for by measured precipitation (1,136 mm), average local evapotranspiration (720 mm), and measured streamflow (220 mm) to be 196 mm (Figure 3a). This residual was classified as annual groundwater recharge. Although groundwater recharge can be calculated from an annual budget due to assumptions of no change in soil zone storage year-to-year, bi-weekly residuals calculated and presented in Figure 3 b represent both short-term changes in soil zone and groundwater storage as well as groundwater losses/gains.

3 | RESULTS

3.1 | Annual and seasonal soil moisture, stream, and groundwater dynamics

The catchment was classified as in either a high or low storage state, which was determined by shallow soil water content in a lower hillslope position (Figure 1; Figure 2a). In general, when evapotranspiration was low, catchment storage was high, the water table was elevated, and streamflow was persistent (Figure 2). When evapotranspiration was high, catchment storage was low, water table elevations were low, and streamflow occurred only in response to precipitation inputs.

Streamflow was present during 44% of the 2015 water year. Sixty-three per cent of that time occurred when catchment storage state was high (mid-January through April), comprising 83% of annual streamflow (183 mm). This was a period of persistent streamflow with baseflow present during inter-storm periods, classified as intermittent streamflow (Figure 2b). Approximately 32% of annual precipitation (346 mm) fell in this time and 19% of annual evapotranspiration occurred (117 mm; Figure 2d).

The remaining 37% of the time when streamflow was present occurred when catchment storage state was low (May through January) and represented 17% of annual run-off (37 mm), 81% of annual evapotranspiration (500 mm), and 68% of annual precipitation (790 mm; Figure 2d). During this period, no baseflow was present, and the run-off only occurred in direct response to individual precipitation events (e.g., ephemeral streamflow).

Water table observations in wells were limited to at and above hand-augered refusal depths (Figure 2c), which were suggestive of proximity to the transition between the saprolite base and the weathered upper portions of the competent bedrock. Groundwater in the lower and upper hillslope wells was present 47% and 31% of the 2015 water year, respectively; the majority occurred when catchment storage state was high.

At the onset of increasing evapotranspiration in April 2015, the water table across the hillslope lowered rapidly (Figure 2c). By late May, the water table fell below the bottom of all the groundwater wells and was no longer observable. The water table did not rise high enough to be measured again in the upper hillslope until early winter. In the lower hillslope, episodic saturation occurred in response to precipitation events throughout the growing season, but a sustained water table did not form again until early winter (Figure 2c). Although the transitional period between absence and sustained presence of a water table for the lower hillslope was prolonged, there was a much shorter transitional period captured in the upper hillslope well. The streambed elevation at the transect base was plotted in Figure 2c to provide reference for when the water table elevation was above or

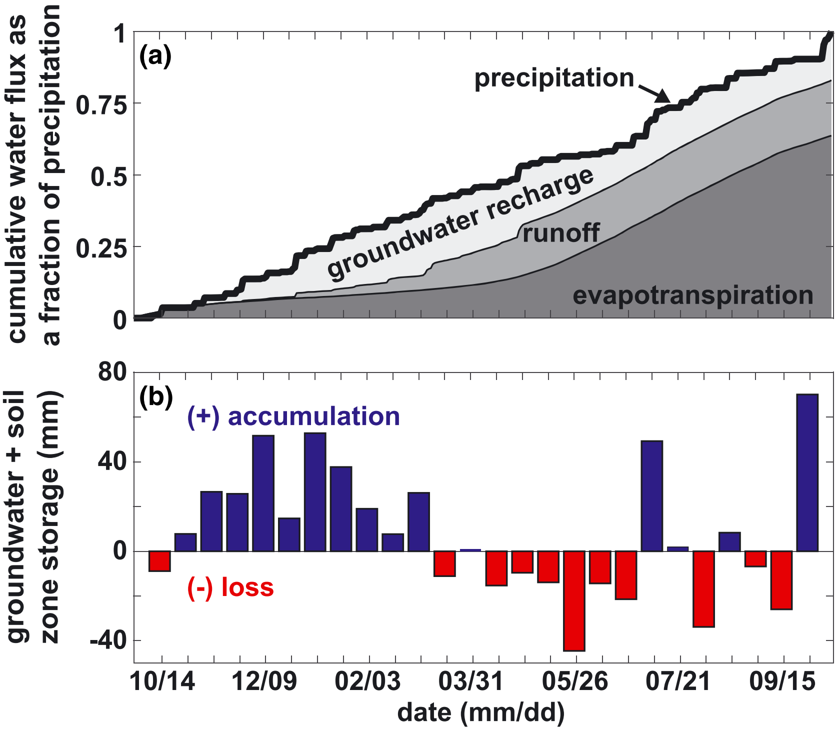

FIGURE 3 (a). Cumulative water fluxes (precipitation, groundwater recharge, run-off, and evapotranspiration) as a fraction of precipitation for 2015 water year, with totals for each flux on the right. Precipitation and run-off are from 5-min field-measured data and average daily evapotranspiration was calculated from the dataset by Novick et al. (2016). The annual residual is the input fluxes (precipitation) minus output fluxes (run-off and evapotranspiration) and represents groundwater recharge across the year. (b) Residuals from water mass balance calculations over 14-day periods. Positive values (blue bars) indicate increases in soil water storage and groundwater (precipitation inputs greater than evapotranspiration and streamflow outputs), whereas negative values (red bars) indicate decreases in soil water storage and groundwater

below the streambed, which indicated gaining or losing stream gradients, respectively.

Calculations of an annual water budget presented a 196 mm residual for the 2015 water year (see Section 2.2 for calculation details), which was classified as groundwater recharge (Figure 3a). A bi-weekly (14 days) water budget was also conducted (Figure 3b), where residuals were classified as a combination of groundwater and soil zone storage as well as groundwater gains and losses. In Figure 3b, sustained periods of soil zone and groundwater accumulation occurred from early November to early March. Sustained periods of soil zone and groundwater loss occurred from April through June. Periods of fluctuation occurred in July through September, driven by variability in precipitation timing and magnitudes (Figure 3a).

3.2 | Stream–groundwater head gradients

The seasonality of catchment storage state induced by evapotranspiration and reflected in catchment run-off dynamics (Figure 2) played an important role in the timing, characteristics, and direction of stream–groundwater head gradients in these headwater hillslopes (Figure 4). This study examined stream–groundwater head gradients between the groundwater in the lower hillslope and the adjacent stream (Figure 4a) as well as the lateral head gradients in the groundwater system across the hillslope (Figure 4b).

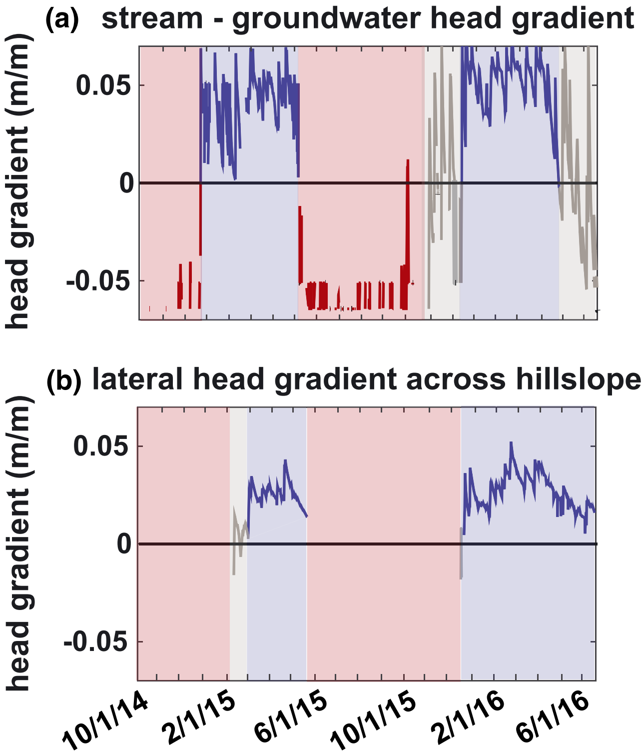

FIGURE 4 Time series of (a) stream–groundwater head gradient and (b) lateral head gradient across lower and upper hillslope wells. Periods with positive gradients (highlighted with blue) indicate head gradient towards the stream. Periods with negative gradients (highlighted with red) indicate head gradient away from the stream. Periods highlighted with grey indicate a transitional period with rapidly fluctuating gradient directionality. Lack of a head gradient calculation within periods is due to lack of stream or water table measurements at one or more locations

During periods when evapotranspiration was low and catchment storage state was high, the predominant hydraulic head gradient was towards the stream (blue sections in Figure 4). During the 2015 water year, head gradients were towards the stream 68% of the time when streamflow was present. When evapotranspiration was high and catchment storage state was low, the predominant hydraulic head gradient was away from the stream (red sections in Figure 4). No head gradients could be calculated between the upper and lower hillslopes during the red sections of the time series shown in Figure 4b, due to lack of groundwater present in the upper hillslope well. That said, the periodic presence of groundwater in the lower hillslope throughout this period suggested lateral head gradients were away from the stream during this time. During the 2015 water year, head gradients were away from the stream 32% of the time when streamflow was present. During the transitional wet-up period (October to January), the catchment began to accumulate water due to decreased evapotranspiration (Figure 2a). During this period, the hydraulic head gradient fluctuated between towards the stream and away from the stream (grey sections in Figure 4). There was also a transitional dry-down period as the seasonal water table declined due to increased evapotranspiration (Figure 2). During this period, the hydraulic head gradient reversed direction rapidly (blue to red transition in Figure 4). Although the stream–groundwater head gradients (Figure 4a) and the lateral head gradients across the hillslope (Figure 4b) showed similar directionality and behaviour, stream–groundwater head gradients were much more variable and transitional.

4 | DISCUSSION

In traditional hydrogeology, streams have been suggested to represent the dynamic surficial expression of the water table (de Vries, 1995; Winter et al., 1998). Stream channels upstream of this surficial water table expression have been thought to be zones where transmission losses to the unsaturated subsurface (e.g., losing streams) occurred when streamflow was activated by localized precipitation inputs (Winter et al., 1998), though few studies have confirmed this in humid regions. The importance of these transmission losses to regional groundwater recharge in humid regions is largely unknown. In addition, catchment hydrology has conceptualized streamflow generation processes within the variable source area concept (e.g., gaining stream framework), which focused on the characterization of the degree and extent of subsurface contributing areas to the stream (Hursh, 1936; Hewlett & Hibbert, 1967; Dunne & Black, 1970). Historically, there has been less focus on the interactions between stream water and groundwater once the contributing waters reach the channel. As a result, little is known about stream–groundwater interactions and regional groundwater recharge during temporary (i.e., ephemeral and intermittent) stream activation in the headwaters of humid landscapes. To address this knowledge gap, we used field-collected data on stream and water table dynamics within an ephemeral-to-intermittent drainage network to conceptually understand stream–groundwater interactions during periods of non-perennial streamflow. Through this, we provide hypotheses for dominant flowpaths leading to streamflow activation dependent on the directionality of the stream–groundwater head gradient.

4.1 | Conceptual framework for groundwater recharge and run-off generation sources under losing and gaining stream conditions

Our results show that seasonality in evapotranspiration caused a rise and fall in the water table across the study period (Figure 2), which produced bidirectionality in both stream–groundwater head gradients as well as in lateral head gradients internally within the catchment (Figure 4). When evapotranspiration was low and catchment storage state was high (Figure 2), there was seasonally persistent streamflow and hydraulic head gradients were towards the stream (Figure 4). We highlighted this portion of the water year in blue in Figure 5a. We hypothesize that these dynamics represent a seasonal period when water table contributions dominate run-off and provide sustained baseflow during inter-storm periods (Figure 5). Much catchment hydrology has been focused on quantifying streamflow generation processes in this gaining stream framework (Blume & Van Meerveld, 2015; Jencso et al., 2009; Weyman, 1970). As the seasonal water table rose in direct response to precipitation events during this period, we hypothesize that activation of surface and shallow subsurface flowpaths played an important role in contributions to streamflow, although these processes were not characterized in this study (see Zimmer & McGlynn, 2017 for detailed analysis).

When evapotranspiration was high and storage state was low, streamflow occurred in direct response to precipitation events, and stream–groundwater head gradients were away from the stream (Figure 4; Figure 5). We highlighted this portion of the water year in red in Figure 5a. Because there was no direct evidence of water table contributions to streamflow during this period due to either calculated head gradients away from the stream or lack of any calculated gradients due to absence of the water table, another water source must have activated streamflow. Although Winter et al. (1998) suggested that streams in humid regions can lose water to the subsurface when the water table is below the streambed, they did not provide details about the mechanisms for streamflow activation during these periods.

We hypothesize shallow surface or subsurface flowpath contributions perched above the water table drove streamflow when stream–groundwater head gradients were away from the stream (Figure 5). The argillic Bt horizon seen in many soil types, including highly weathered soils characteristic of the Piedmont region where this study was conducted, has been shown to provide conditions for activation of transient, perched, shallow water tables (Chittleborough, 1992; Elsenbeer, 2001; Johnson, Lehmann, Couto, Novaes Filho, & Riha, 2006). Previous studies conducted in proximate regions (e.g., margin of Blue Ridge physiographic province) with similar saprolite development to the neighbouring Piedmont physiographic province have shown these flowpaths to be important to streamflow generation (Scanlon, Raffensperger, & Hornberger, 2001; Scanlon, Raffensperger, Hornberger, & Clapp, 2000). Although our study highlighted that stream–groundwater interactions can be bidirectional in response to temporary streamflow activation, more process-based research is needed to better understand the temporal and spatial dynamics of both deep and shallow perched water table contributions to streamflow across fluctuating stream–groundwater head gradient directions in order to better manage these connected resources and understand source water contributions to downstream flow.

The magnitude of regional and deep groundwater recharge happening across ephemeral and intermittent drainages of headwater catchments that dominate Piedmont landscapes is not yet known. To begin to address this and to quantify the ramifications of reversing stream–groundwater head gradients, we employed a simple catchment

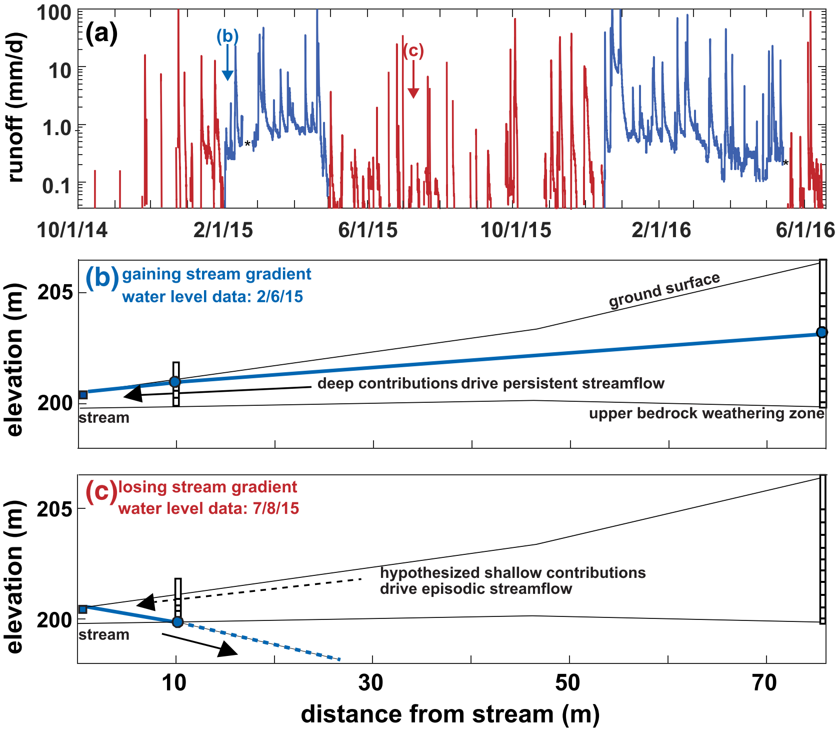

FIGURE 5 (a) Time series of run-off in semi-log space, with red and blue periods indicating when streamflow was ephemeral (flow activation in direct response to precipitation inputs) or intermittent (persistent flow for 3 or more months), respectively. (b) Representative water level data (2/6/15) when gradients were towards the stream (gaining, persistent flow) with solid arrows indicating direction of groundwater flow. (c) Representative water level data (7/8/15) when gradients were away from the stream (losing, ephemeral flow) with solid arrows indicating direction of groundwater flow. Black dashed arrow indicates hypothesized shallow flowpaths driving streamflow during ephemeral flow activation. Hillslope cross section shown with 3× vertical exaggeration

water balance analysis (Equation 1; Table 1) taking advantage of a 5-year period of relatively stable precipitation and evapotranspiration in the area. Water mass balance approaches are commonly employed to quantify gains and losses in small stream reaches (Covino & McGlynn, 2007; Payn, Gooseff, McGlynn, Bencala, & Wondzell, 2009; Bergstrom, Jencso, & McGlynn, 2016), quantify transmission losses in ephemeral stream reaches to regional groundwater in semi-arid and arid landscapes (Abdulrazzak, Sorman, & Alhames, 1989; Covino & McGlynn, 2007; Walter, Necsoiu, & McGinnis, 2012), indirectly calculate evapotranspiration at the catchment scale (Sivapalan, Ruprecht, & Viney, 1996; Zhang, Potter, Hickel, Zhang, & Shao, 2008), and to assess short- and long-term changes in catchment storage state (Nippgen, McGlynn, Emanuel, & Vose, 2016). In humid regions, it is less common to use water balances to estimate regional groundwater recharge in headwaters because losses to deeper groundwater are often assumed to be minor fluxes relative to streamflow and evapotranspiration (Bormann & Likens, 1967; Likens, Bormann, Johnson, & Pierce, 1967). However, we used a water mass balance approach for the 2015 water year to estimate water fluxes not accounted for by measured precipitation (1,136 mm), average local evapotranspiration (720 mm), and measured streamflow (220 mm). The positive residual in the water balance amounted to 196 mm (Figure 3a), only 11% less than measured streamflow.

Positive or negative residuals in catchment water balances can be due to changes in catchment storage from 1 year to the next (e.g., Nippgen et al., 2016), water budget error in calculating or measuring precipitation, evapotranspiration, or stream discharge, or unaccounted components that most often include gains from or losses to the groundwater system (e.g., Genereux, Jordan, & Carbonell, 2005). In this study, regional annual precipitation amounts have not been below the 10-year average of 1,141 ± 137 mm (see Section 2.2) since 2010, suggesting that catchment storage recovery from recent drought does not explain this large residual. Periodic instantaneous discharge measurements across a multitude of flow states corroborated the stream stage–discharge rating curve for the engineered 3-ft H-flume, and therefore, streamflow measurement error was minimal. Oishi, Oren, Novick, Palmroth, and Katul (2010) showed relatively invariant dynamics of annual evapotranspiration based on 4 years of continuous eddy covariance measurements in a similar setting in a deciduous tree stand in the Duke Forest (<8 km from our study site). They calculated a standard deviation of 26 mm (<5% of reported mean), suggesting that there is minimal year-to-year variability in evapotranspiration at this site. Similar studies conducted in the Duke Forest in both hardwood and deciduous forests over 4- and 8-year periods found standard deviations of annual evapotranspiration to be 11.3% ($\sigma = 74$ mm) and 10.8% ($\sigma = 78$ mm) of the mean, respectively (Novick et al., 2016; Stoy et al., 2006). These studies include drought years as well as high rainfall years, which could cause larger standard deviations than expected during our study period, which had a typical annual rainfall amount. Thus year-to-year variability in evapotranspiration does not appear to explain this large residual.

Along with the annual water budget, we also conducted a bi-weekly (14 day) water budget to calculate temporal changes in soil zone storage and losses/gains to groundwater (Figure 3b). Here, we see increases in soil zone storage and groundwater recharge during fall through winter months. We also see decreases in soil zone storage and groundwater in spring. Fluctuations throughout summer months suggest that precipitation timing and magnitude play an important role in soil zone storage and groundwater dynamics within months where hydraulic head gradients are generally away from the stream.

Our results suggest that the magnitude of groundwater recharge that does not resurface as streamflow at the headwater catchment scale is an important and substantial vertical flux from non-perennial headwater systems, effectively recharging the local deep groundwater system with significant implications for regional groundwater recharge. In fact, at this headwater catchment scale, we calculated that annual groundwater recharge is similar in magnitude to annual streamflow (within 11%; Table 1). We suggest that this mechanism is often overlooked in humid headwater regions and warrants more attention, especially within a larger watershed and regional context.

5 | IMPLICATIONS AND CONCLUSIONS

For this study, we characterized streamflow and water table dynamics in a non-perennial headwater catchment in a humid landscape in order to improve our conceptual understanding of stream–groundwater interactions during temporary streamflow activation. This research provided three important findings for stream–groundwater interactions in this low relief landscape: (a) non-perennial (e.g., ephemeral and intermittent) streams can act as both groundwater recharge and discharge focal areas in these humid regions, (b) the bidirectionality of stream–groundwater head gradients shown in this study may suggest that flowpath contributions to streamflow may temporally shift in dominance, and (c) on an annual basis, groundwater recharge can be similar to measured streamflow across non-perennial headwater catchments, which are prevalent across this region.

Our results showed bidirectionality in stream–groundwater head gradients dependent on catchment storage as well as a substantial positive residual in the 2015 annual water balance. These results strongly suggest temporary streams can act as both sources and sinks for groundwater across humid headwater landscapes such as the Piedmont. At this study site, which is characteristic of the headwaters of the Piedmont, we have recorded drainage densities of up to 8.6 km km^{-2} (Zimmer & McGlynn, 2017), driven largely by channels supporting non-perennial streamflow. These drainage densities fall at the upper end of the range observed worldwide in catchments varying in geomorphology, climate, and size (Godsey & Kirchner, 2014), suggesting this and potentially other highly weathered systems have stream networks comprised disproportionally of ephemeral and intermittent stream sections. Therefore, the stream and groundwater dynamics observed in this headwater catchment are integral and prominent aspects of not only this Piedmont landscape but likely the hydrology of other highly weathered regions extensive worldwide. It is clear more research on this topic is needed to understand the extent of stream–groundwater interactions in these landscapes.

Both the bidirectionality of stream–groundwater head gradients and capacity for deep groundwater recharge that can occur in ephemeral and intermittent streams in highly weathered headwater landscapes can have substantial impacts on the redistribution of water across larger watersheds and regions. The local recharge dynamics characterized in this study indicate non-local influences on downstream systems through regional groundwater recharge with subsurface flowpaths that do not appear to resurface at headwater catchment scales. Although these widespread, common landscape features have the potential to have a substantial effect on regional hydrology, the mechanisms represented in this study for groundwater recharge and shifting stream source waters are often overlooked. We suggest that more process-based research is needed to understand groundwater recharge focal areas and run-off generation processes during periods when groundwater gradients are away from the stream. This is critical for understanding recharge dynamics and shifting stream source water contributions across larger watersheds that are composed of many ephemeral and intermittent headwater catchments.

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