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Time-lapse animation of hillslope groundwater dynamics details event-based and seasonal bidirectional stream–groundwater gradients

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1 | DESCRIPTION

Stream water–groundwater (SW-GW) interactions and hydrological connectivity are two important processes that drive much of the variability seen in streamflow characteristics. Measurement "snapshots" of hillslope flowpath connections (Bracken et al., 2013; Nippgen, McGlynn, & Emanuel, 2015) and SW-GW gradients and associated biogeochemical patterns (Lautz & Fanelli, 2008; Vidon & Hill, 2004) are commonly used to categorize different characteristics or states of catchment and stream response. Studies that have fine resolution or long-term datasets still often distill this information by displaying representative periods or events (e.g., Nippgen, McGlynn, & Emanual, 2015). Although these snapshot approaches provide useful information, they can oversimplify complex interactions or conceal the varying time scales (e.g., event responses nested within seasonal dynamics) of hillslope connectivity and SW-GW interactions, shifts, and flow reversals. Because of these issues, catchment hydrologists have been encouraged to move beyond the snapshot approach (e.g., Bracken et al., 2013).

Perennial streams in headwaters of humid climates are common foci for catchment hydrology. In these perennial reaches, the degree of hillslope connectivity and SW-GW gradient magnitudes and directions can temporally shift on seasonal or event bases dependent on hydrological characteristics such as catchment storage and hydromorphology (Jencso et al., 2009; Nippgen et al., 2015; Rodhe & Seibert, 2011; Todd, 1955). Although these perennial streams are often viewed within a gaining stream system framework (Winter, Harvey, Franke, & Alley, 1999), little work has characterized temporal SW-GW interactions and hillslope connectivity within the ephemeral and intermittent sections of these headwater catchments.

This study sought to address a lack of understanding regarding the temporal dynamics of SW-GW interactions and process-based stream–hillslope connectivity within ephemeral and intermittent drainages. Our study site is located in the Piedmont region of North Carolina, USA, which is characterized as low relief with highly weathered, deep soils. Although this landscape type is underrepresented in hillslope connectivity studies (Bracken et al., 2013), it is a globally ubiquitous landscape type that is undergoing increasing development and land use pressure (Terando et al., 2014). This study uses the power of animated data visualization to highlight a novel application of groundwater levels in uncovering event- and seasonally-driven (dis)connections between temporary streamflow and the complex groundwater system common in highly weathered landscapes.

We monitored fine temporal resolution (5 min) streamflow and groundwater levels across an adjacent hillslope for 1 year within a 3.3-ha ephemeral-to-intermittent drainage network in the Duke Forest, North Carolina, USA (36°2′3.4728″N, 79°4′52.752″W; see Zimmer & McGlynn, in review for more site details). Groundwater wells were hand augered to refusal depths at lower, mid-, and upper hillslope positions along a representative convergent hillslope. At these sites, we also installed shallow wells to the depth of the most prominent confining soil horizon (A/Bt horizon or Bt/C horizon interfaces), confirmed by field-saturated hydraulic conductivity measurements using a constant head permeameter (Amoozegar, 1989). Water levels were monitored using pressure transducers (+/−0.1 mm resolution, Solinst) and capacitance recorders (+/−1 mm resolution, TruTrack, New Zealand). Because of the minimal range in observed stream level (0–0.18 m) relative to hillslope length (76 m), the streambed elevation was used as the stream elevation, regardless of discharge magnitude.

(The video is viewable only on the PDF. It can only be played when the PDF is Downloaded, and Adobe Acrobat and Flash Player were installed in the PC. You may download the Flash player at: https://get.adobe.com/flashplayer/.)

The MPEG-4 file (with narration; Movie 1) shows a data-driven animation of streamflow and hillslope groundwater dynamics from October 1, 2015, through September 30, 2016, to highlight the various time scales of the dynamic SW-GW interactions and hillslope connectivity associated with temporary streamflow. The temporal dynamics of two groundwater tables are shown in the lower plot; the shallow, transient, perched water table (light blue), and the deeper water table (dark blue). Through this animation, one can track the (dis)connections vertically in the soil profile between water tables (shallow and deep) as well as laterally across the hillslope.

When there was streamflow present, about two-thirds of it was characterized as intermittent or seasonal streamflow (blue portions of the streamflow hydrograph; top plot). This occurred when catchment storage was high. About one-third of streamflow occurred when catchment storage was low and was characterized as ephemeral (i.e., only flows in response to precipitation inputs; red portions of the streamflow hydrograph).

During intermittent streamflow, the deeper groundwater gradient was toward the stream. This evidence of a gaining stream system is in line with the common framework of streamflow generation in humid regions (Winter, Harvey, Franke, & Alley, 1999). In the upper hillslopes, the deeper and perched water tables stayed vertically disconnected, that is, there was no saturated continuum between groundwater zones. In the lower hillslope, the deeper water table was elevated into shallow soil horizons, and no perching of a shallow water table occurred. During ephemeral streamflow, the gradient between the stream and the deeper water table was away from the stream (i.e., losing stream system), which is a novel observation surrounding SW-GW interactions in temporary streams in humid regions. This suggests streamflow-enhanced groundwater recharge can be a prominent process in headwaters systems. During this period, perched, shallow water tables dominated contributions to streamflow.

This data-rich time series reveals many complex hydrological processes at both long- (i.e., seasonal) and short- (i.e., individual events) time scales, including the connectivity of both shallow and deep groundwater and the bidirectionality in SW-GW gradients through time. This novel visualization has the power to highlight the complexities of groundwater connectivity across a hillslope and provide a more complete process-based understanding of streamflow generation processes in this landscape. These system complexities are often simplified through traditional forms of data visualization (e.g., time and space snapshots), but are important to consider when addressing questions related to seasonal and event-driven catchment hydrology.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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