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RESEARCH AND OBSERVATORY CATCHMENTS: THE LEGACY AND THE FUTURE

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The evolving perceptual model of streamflow generation at the Panola Mountain Research Watershed

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Abstract

The Panola Mountain Research Watershed (PMRW) is a 41-hectare forested catchment within the Piedmont Province of the Southeastern United States. Observations, experimentation, and numerical modelling have been conducted at Panola over the past 35 years. But to date, these studies have not been fully incorporated into a more comprehensive synthesis. Here we describe the evolving perceptual understanding of streamflow generation mechanisms at the PMRW. We show how the long-term study has enabled insights that were initially unforeseen but are also unachievable in short-term studies. In particular, we discuss how the accumulation of field evidence, detailed site characterization, and modelling enabled a priori hypotheses to be formed, later rejected, and then further refined through repeated field campaigns. The extensive characterization of the soil and bedrock provided robust process insights not otherwise achievable from hydrometric measurements and numerical modelling alone. We focus on two major aspects of streamflow generation: the role of hillslopes (and their connection to the riparian zone) and the role of catchment storage in controlling fluxes and transit times of water in the catchment. Finally, we present location-independent hypotheses based on our findings at PMRW and suggest ways to assess the representativeness of PMRW in the broader context of headwater watersheds.

KEYWORDS

catchment storage, flow paths, hillslope connectivity, perceptual models, Streamflow generation, tracers

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1 | INTRODUCTION

Development of perceptual models of streamflow generation processes are central to the field of catchment hydrology and are recognized among the 23 major Unsolved scientific Problems in Hydrology (UPH; Blöschl et al., 2019). Specifically, UPH 8: "Why do streams respond so quickly to precipitation inputs when storm flow is so old, and what is the transit time distribution of water in the terrestrial water cycle?" and UPH 12: "What are the processes that control hillslope–riparian–stream–groundwater interactions and when do the compartments connect?" But despite widespread interest in such questions, place-based research where these questions can be answered is limited. And many, if not most of our field sites and studies are short-term in duration, often on the timescale at which a student earns a PhD.

Here, we synthesize catchment research at the Panola Mountain Research Watershed (PMRW) where continuous observations over the past 35 years have addressed these key unanswered questions in hydrology and also related questions, such as UPH 9: "How do flood-rich and drought-rich periods arise, are they changing, and if so why?" And UPH 13: "What are the processes controlling the fluxes of groundwater across boundaries (e.g., groundwater recharge […])?"

Here we describe how our perceptual understanding of streamflow generation at PMRW has evolved, through rejection and refinement of hypotheses, by focusing on two lines of research. Firstly, the hydrologic storm response on hillslopes, as measured at a trench face (Freer et al., 2002; Tromp-van Meerveld & McDonnell, 2006a, 2006b) and at the hillslope-riparian transition (van Meerveld et al., 2015). Secondly, the extensive subsurface characterization of the catchment combined with age-dating techniques (Burns et al., 2003) and baseflow recession analysis (Peters & Aulenbach, 2011). Many unpublished observations also shaped our ideas and hypotheses about runoff generation processes. We discuss how these observations led to follow up studies that ultimately yielded new challenges to our evolving understanding. In doing so, we also highlight how measurements designed for one purpose provided critical insights to other processes and the development of new hypotheses. We further note how subsurface characterization through geophysical and geochemical measurements enabled more precise process identification. Here, we highlight the importance of long-term place-based studies, generalize our findings, and provide research recommendations to others.

2 | STUDY SITE DESCRIPTION

PMRW is a 41-ha headwater catchment within the Piedmont Physiographic Province of the United States (U.S.), located 25 km southeast of Atlanta, Georgia. PMRW was initiated by the U.S. Geological Survey (USGS) in 1985. Since then, PMRW has been an experimental catchment for long-term monitoring and water quality sampling of precipitation, streamflow, groundwater, and soil water. Initial research was part of the USGS Acid Precipitation Thrust Program (1985–1995), focusing on the effects of atmospheric acidic deposition. PMRW was selected because high sensitivity to acidic deposition effects was expected due to thin soils and weakly reactive granodiorite bedrock. From 1991–2016, PMRW was among five diverse study catchments of the USGS Water, Energy and Biogeochemical Budgets (WEBB) Program. Research in WEBB focused on the water cycle, streamflow generation, geochemical mass balances, and element cycling (Baedecker & Friedman, 2000; Huntington et al., 1993). Current research focuses on evapotranspiration, recharge, and drought as part of the USGS Climate Research and Development Program. Research at PMRW has been greatly enhanced by academic collaboration.

Elevations at PMRW range from 224 to 279 m above sea level. The climate is humid continental to subtropical. Annual precipitation averaged 1250 mm (<1% as snow) (water years 1986–2018) and is relatively uniformly distributed throughout the year (Figure 1). Frontal systems bring long duration, typically low intensity rainstorms in winter. In contrast, short intense convective thunderstorms are common in spring and summer (April–September). Annual average air temperature is 15.1°C (water years 1986–2018) and monthly average temperatures range from 5.2°C (January) to 24.5°C (July). Annual runoff averaged 358 mm, resulting in an average runoff ratio of 0.29 (water years 1986–2015; annual range 0.13–0.50; Aulenbach & Peters, 2018). Runoff is highest between January and March and lowest between July and October (Figure 1). Seasonality of the water budget results from high rates of potential evapotranspiration (PET) in summer that frequently exceed precipitation, reflecting water-limited conditions. Actual evapotranspiration (AET), as determined from a long-term water budget with storage, averages 71% of P, about 75% of PET—indicating water deficits (Aulenbach & Peters, 2018). Groundwater recharge occurs predominantly between September and March when precipitation exceeds PET.

Second-growth forest occurs over 90% of PMRW, regenerated naturally on abandoned agricultural land. In the Georgia Piedmont, forests were cleared and settled by about 1800, with subsistence farming later replaced by cotton growing (Brender, 1974). Tree species include about equal amounts of deciduous, coniferous, and mixed forest, and bedrock outcrops occupy the remaining 10% of the area. Present-day deciduous and mixed forest stands were thought to be abandoned in the early 1900's while areas with coniferous stands were in pasture as recently as the 1960's (Huntington et al., 1993). The oldest deciduous trees date from about 1905 (one white oak from ~1870), and the oldest coniferous trees date from about 1935 (based on unpublished dendrochronology analyses from 1992 and 1994; Thomas, C. E., U.S. Forest Service, written communication, June 1994). Hillslope soils are predominantly sandy loams (Inceptisols and Ultisols). Soils in the riparian zone are loams of varying textural composition (Natural Resources Conservation Service, 2017). Bedrock consists of 320-million-year-old Panola Granite, a biotite–oligoclase–quartz microcline granodiorite intrusion, and the Clairmont member of the Stonewall, an amphibolite-biotite gneiss country rock (Crawford et al., 1999; Higgins et al., 1988, 2003; Williams, L., U.S. Geological Survey, written communication, 2006). Porous, weathered saprolites

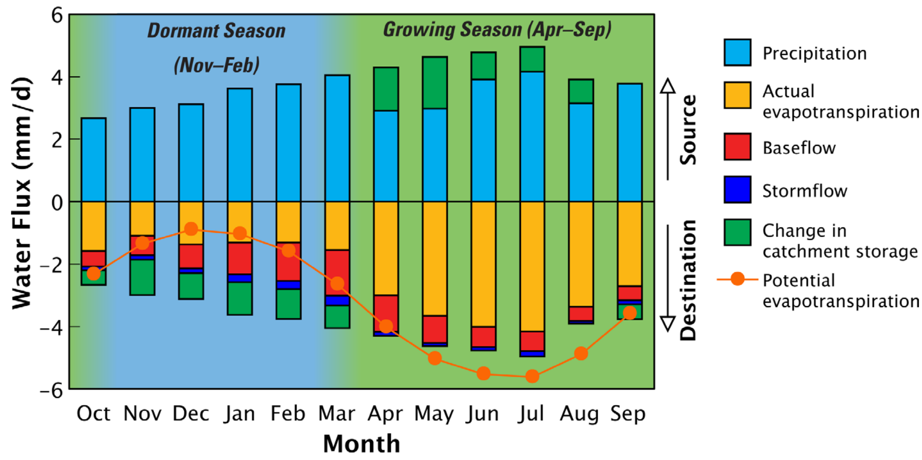

FIGURE 1 Average monthly water budget for the Panola Mountain Research Watershed, water years 1986–2015. Based on data from Aulenbach and Peters (2018)

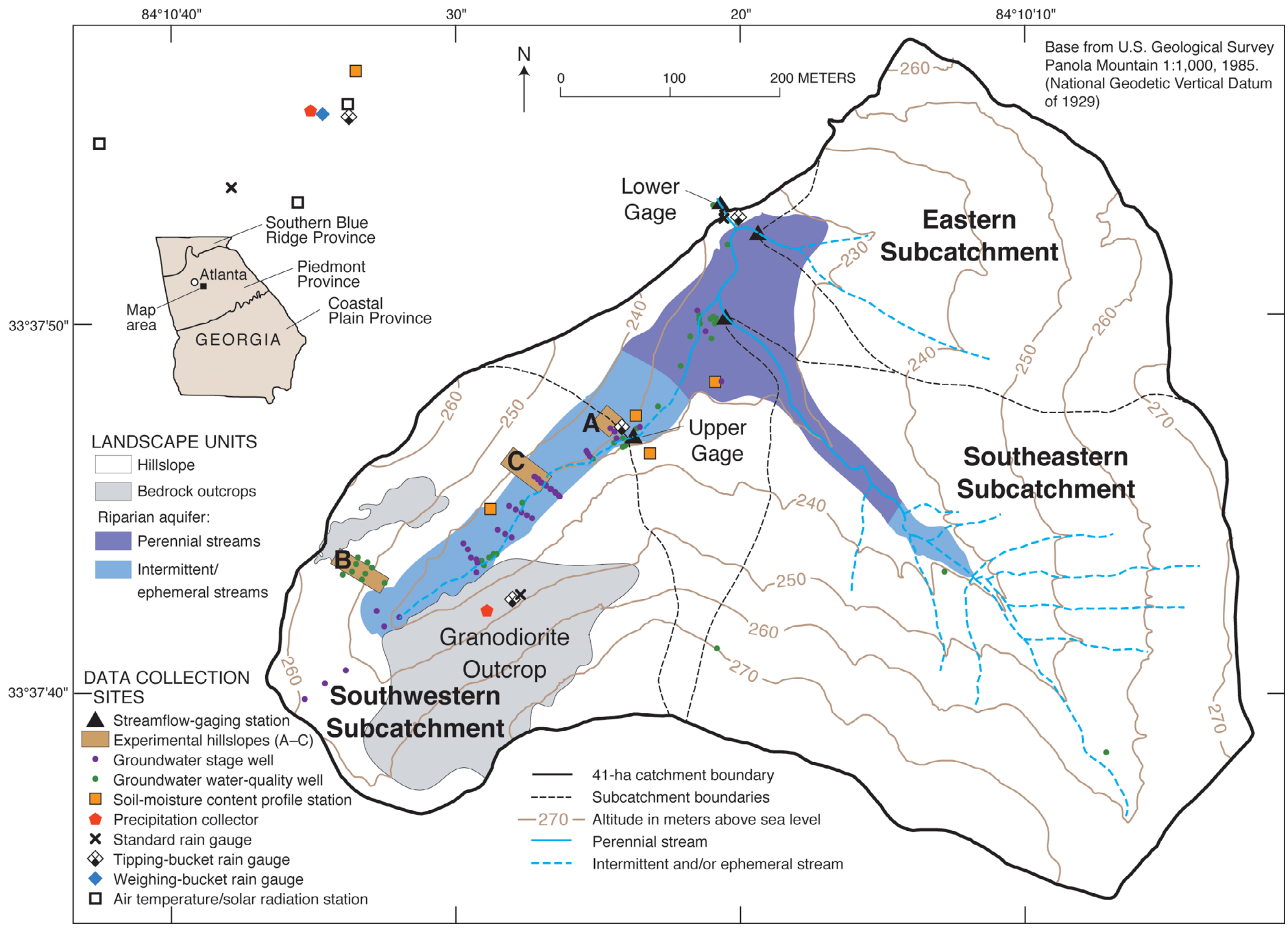

FIGURE 2 Map of Panola Mountain Research Watershed showing locations of major subcatchments, streams, topography, landscape units, and selected data collection sites

have developed above the bedrock and are up to 3–4 m thick on the Panola Granite (White et al., 2001) and typically 5 to 20 m thick on the amphibolite-biotite gneiss (Huntington et al., 1993).

The watershed includes three tributaries draining the southwestern (SW), southeastern (SE) and eastern (E) subcatchments (Figure 2). The SW subcatchment follows the main tributary and contains the 3-ha Granodiorite Outcrop that generates substantial storm runoff at PMRW. Upstream portions of the SE subcatchment contain deep erosion gullies up to 4 m in depth resulting from the steep slopes and erosion-prone farming practices typical of the Southern Piedmont (Brender, 1974; Trimble & Goudie, 2008). The perennial stream in the lower part of the catchment is underlain by a 5 m deep aquifer, including both soils and regolith. A piezometer placed in the stream in this area indicate head substantially above the stream surface (screened 145–84 cm below streambed), suggesting low aquifer permeability. Hillslopes in the SW subcatchment have an average soil depth <1 m. Hillslopes in the SE and E subcatchments have not been extensively characterized.

Streamflow is monitored at two permanent gages: the Lower Gage at the outlet of the 41-ha watershed and the Upper Gage at the outlet of the 10-ha SW subcatchment. Two temporary gages were operated for a few years on the E and SE tributaries (Figure 2). Most research has focused on the riparian area around the perennial stream and the SW subcatchment. Initial research focused on stormflow generation from the Granodiorite Outcrop and the chemical response of the stream to dry acidic deposition on the outcrop. Research and monitoring were initiated before the advent of cellular technology and sensors with built-in data loggers. Power and a coaxial communication network were therefore established in the SW subcatchment. To take advantage of this infrastructure (and datasets already collected for this subcatchment), subsequent studies also focused on the SW subcatchment. Specific research study areas within this SW subcatchment and referred to herein include (locations identified by letters in Figure 2 and study periods indicated in parentheses): (a) the 20 by 20 m hillslope plot adjacent to the Upper Gage instrumented for throughfall, soil water, and groundwater monitoring (1994–1995; Peters & Ratcliffe, 1998; Ratcliffe, 1996; Ratcliffe et al., 1996); (b) the heavily instrumented 48-m long planar hillslope (Figure 3a; including wells, piezometers, tension lysimeters, tensiometers, and sap flow sensors) opposing the Granodiorite Outcrop above a 20-m long trench excavated to bedrock (Figure 3b) to monitor subsurface flow (1995–1998 and 2002; Freer et al., 1997, 2002; Tromp-van Meerveld et al., 2007), and; (c) a 36-m long planar hillslope (36% slope) connected to a 10-m wide riparian area (10% slope) adjacent to the intermittent stream channel instrumented with a network of groundwater wells (2009; Figure 3c; van Meerveld et al., 2015).

FIGURE 3 Photos of (a) the trenched hillslope (site "B" in Figure 2), (b) the associated trench, (c) the wells and break in slope at the hillslope riparian site (site "C" in Figure 2). Photographs by H. J. van Meerveld, University of Zurich

3 | THE ROLE OF THE HILLSLOPES IN STREAMFLOW GENERATION

3.1 | Initial perceptual model

The initial perceptual model of the hillslope role in streamflow generation at PMRW was based mainly on three lines of inquiry: (1) observed hillslope groundwater responses, (2) an end-member mixing analysis (EMMA) at the catchment outlet, and (3) hydrometric measurements and tracer studies at the hillslope plot (Figure 2 "A"). This initial conceptualization provided motivation for the trenched hillslope study (Figure 2 "B" and Figure 3a,b), initiated to better understand hydrologic hillslope flowpaths and connectivity to the riparian aquifer.

Piezometers that were distributed across the hillslope near experimental hillslope "A" (Figure 2) and equipped with maximum rise indicators (i.e., cork dust that clings to a wooden stick inserted in the well) rarely showed water table presence. A water table at the base of hollows was expected, which would extend some distance upslope during rainfall events (the "saturated wedge") based on the analysis of Freeze (1972) and experimental evidence at Bicknoller Combe in England by Weyman (1973).

End-member mixing analysis was used by Hooper et al. (1990) and Hooper and Christophersen (1992) for a geographic source hydrograph separation at the Lower Gage using ambient tracers. They found that streamwater sources varied seasonally, with groundwater from the SW subcatchment (measured at a well across the channel from the outcrop) dominating streamwater during wet winter months when vegetation is dormant and groundwater contributions from the lower riparian area dominating streamflow during dry summer months. Antecedent wetness conditions and rainfall intensity also determined how much shallow soil water (measured by a zero-tension lysimeter directly beneath the soil A-horizon adjacent to the Upper Gage) contributed to streamflow during rainfall events. The two groundwater sources were chemically distinct because of contrasting mineralogy between the lower watershed (magnesium and calcium-rich gneiss) and the SW subcatchment (sodium-rich granodiorite). At this time, the E and SE subcatchments had little sampling, and available end-member source signatures were assumed representative of large areas of the catchment. The upper catchment end member (the "hillslope end member", represented from a well in the riparian zone) was assumed to occur throughout the granodiorite areas of the catchment, above the contact with the country rock and the lower catchment end member (the "groundwater end member") was assumed present throughout the catchment below the contact with the country rock.

A hydrometric study of three large precipitation events (59–85 mm) at the hillslope adjacent to the Upper Gage (Figure 2 "A") combined time-domain reflectometry in the unsaturated zone with groundwater level data (Figure 2 "A"), and indicated that the groundwater rise preceded the arrival of the soil-water wetting front (Ratcliffe, 1996; Ratcliffe et al., 1996). The interpretation of these observations was that macropores allowed water to bypass the unsaturated zone and a perched water table forms in the middle of the soil profile. Weathered soil at PMRW was expected to form a clay-rich horizon (B_t horizon; Buol & Weed, 1991; West et al., 2008) that would serve as an aquitard, but a clear B_t-horizon was only observed for soils in relatively flat landscape positions. Soil horizonation is only weakly developed on the hillslopes. Concerns were also expressed regarding the difficulty in observing a saturated wedge. Other interpretations of these data were possible (groundwater response at the hillslope base could have been explained by bank storage from streamflow initiation in the adjacent channel) but the first interpretation guided subsequent studies.

Before installation of the trench, tracer studies using chloride conducted on this same hillslope (Figure 2 "A"; Peters & Ratcliffe, 1998) and using lithium bromide to characterize subsurface flowpaths on ridgetop soils in the SW catchment (Huntington et al., 1994) supported the view that rainwater bypassed the unsaturated zone via macropore flow. Also, preferential flow was observed in laboratory infiltration experiments on undisturbed soil cores from hillslope and ridgetop sites near the trenched hillslope (Figure 2 "B", McIntosh et al., 1999). Thus, the perceptual model before trench installation was that macropore transport was important to shallow water table development, that in-turn induces downslope water flow and ultimately contributes to streamflow. However, transport via groundwater or through the unsaturated zone at hillslope "A" was too slow to contribute to peak streamflow. Because the study area was 20 m from the stream, soil water closer to the stream was assumed to be the main contributor to stormflow. Furthermore, stormflow at the Upper Gage was predominantly rainfall (i.e., "new water") which was assumed to fall in (channel interception) or near (overland flow and soil water from near-channel areas) the stream, or to originate as runoff from the Granodiorite Outcrop in the SW subcatchment.

The chloride (Peters & Ratcliffe, 1998) and EMMA (Hooper et al., 1990; Hooper & Christophersen, 1992) tracer studies were not directly comparable. First, the chloride tracer study focused on the SW subcatchment, while the EMMA study encompassed the entire catchment. Second, the chloride study was a time-separation into old and new water while the EMMA study was a geographical separation where end members were assumed constant over time (Christophersen & Hooper, 1992).

Heading into the trenched hillslope study, the perceptual model of streamflow generation recognized the dominance of groundwater contributions to annual streamflow volumetrically (with seasonally varying contributions from the lower and upper watersheds) and the quick response to rainfall events attributed to shallow soil water presumably originating from the outcrop or from rain that rapidly transited the near riparian zone (Figure 4, original perceptual model). Macropores were thought to be an important transport mechanism to the water table that would induce downslope water flow that contributes to streamflow.

3.2 | Main results and changes in the perceptual model of the role of hillslopes in streamflow generation

The trenched hillslope study (Figure 2 "B") was initiated to test hypotheses regarding hydrologic flowpaths on the hillslopes. The

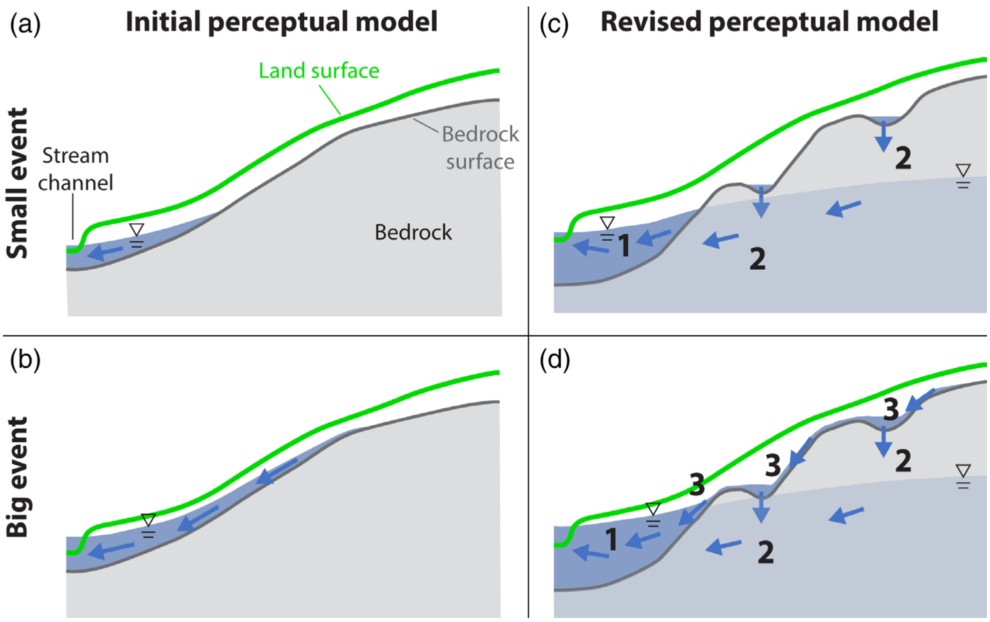

FIGURE 4 Initial (left) and revised (right) perceptual model of the dominant flow pathways on the hillslopes and riparian zone at PMRW during a small (top) and a large rainfall event (bottom). The dark blue represents the saturated area in the soil and the light blue represents the saturated area in the bedrock. The arrows indicate some of the flow pathways. The numbers indicate some of the important changes: 1, deeper soils in the riparian zone; 2, importance of flow through the bedrock and recharge of the riparian aquifer by this water; and 3, fill-and-spill mechanism on the hillslope

initial perceptual model allowed an initial set of hypotheses: (1) Saturation should develop in hillslope hollows above the trench, and (2) Stormflow exiting the trench should be chemically similar to the EMMA analysis hillslope end member. Subsurface runoff from the trench-face was measured in 2-m hillslope segments and from five individual macropores (Figure 3b). Tensiometers were installed across the lower hillslope to capture saturated zone development. Bedrock-soil interface topography was determined using a soil corer and small hand auger over a 2-m grid. Depth to bedrock was highly variable (0–1.83 m, mean 0.63 m).

Initial observations from the trenched hillslope study led to rejection of the first hypothesis that hillslope groundwater development was controlled by surface topography. Saturation during events did not develop initially beneath the shallow surface hollow and flow volumes draining through individual trench sections were not well correlated to downslope flow accumulation based on topographic gradients. Rather, the more tortuous topography of the soil-bedrock interface, which differed from the topography of the land surface, controlled subsurface flow volumes (Freer et al., 2002). Trench face flow was more strongly related to subcatchment area as defined by the bedrock topography and associated downslope flow accumulation. Flow from instrumented macropores was substantial during larger events, representing up to 46% of the runoff volume. Burns et al. (1998) observed that variation in water quality among different trench segments and between the macropores and the trench segments could be explained by the flushing frequency, which was consistent with the bedrock-controlled spatial saturation patterns.

Fortunately, data collection at the trench continued for several years. Analysis of the stormflow response from February 1996 through May 1998 indicated that significant (>1 mm) subsurface flow occurred only during large (>55 mm) rainfall events when antecedent moisture conditions were high (Tromp-van Meerveld & McDonnell, 2006a). Comparison with long-term rainfall records suggested that an average of only 3.2 events per year were larger than this threshold during the fall-spring period and 1.4 events per year during winter, when antecedent moisture conditions are highest and significant subsurface stormflow is most likely.

Hydrus-2D model simulations using the measured surface and bedrock topography suggested that a saturated wedge would not develop and expand upward from the bottom of the trench but would instead develop at the ridgetop where soils are shallower and then expand and cascade downslope. To test these simulations, the piezometers installed at each hillslope depth-to-bedrock measurement location were converted to maximum water-level rise indicators, and several new wells were installed. The findings confirmed the model simulation dynamics and provided a basis for the rarity of trench flow. Hillslope soils remain largely unsaturated, except for discontinuous pockets of saturation in bedrock depressions that fill, and when the rainfall events are sufficiently large, spill and fill other depressions, referred to as the fill-and-spill mechanism. These saturated zones connect down to the trench face only when the rainfall threshold is exceeded ("3" in Figure 4) (Tromp-van Meerveld & McDonnell, 2006b). Similar, but less clear patterns were observed on the lower hillslope by Freer et al. (2002) during a single rainstorm, which similarly showed the importance of hillslope connectivity for initiation of trench flow.

The relevance of these observations at the trenched hillslope to streamflow generation was assessed by examining hillslope connectivity to the riparian area downvalley from the trench (Figure 2 "C"), where flow was unaffected by the trench. This hillslope has thicker soils and a smaller bedrock outcrop near the ridgetop than the trenched hillslope. This hillslope was instrumented with 26 wells to observe the occurrence and flow direction of perched groundwater. As expected, the hillslope was disconnected from the stream most of the time, but when hillslope saturation occurred almost the entire hillslope was connected to the stream. Connectivity was manifest as more sustained streamflow during and after these events (van Meerveld et al., 2015). Furthermore, the water levels in riparian zone wells peaked simultaneously with establishment of hillslope connectivity. Flow directions on the hillslope indicated competing influences of bedrock and surface topography, the former dominating when water tables were low at the start and the end of an event (down-valley) and surface topography determining flow directions under wet conditions at the event peak (more down-slope) (van Meerveld et al., 2015).

3.3 | Emergent evidence of the importance of infiltration to bedrock

Five sprinkler experiments were performed on the trenched hillslope and a lithium bromide solution was applied on the hillslope as a line tracer to track flow paths. Sprinkler volumes equal to total annual rainfall were applied over 4 to 10 days. Tracer recovery was low, but the experiment provided an important insight that most of the applied water was lost to bedrock. Infiltration was confirmed from bedrock moisture responses at three locations downslope of the trench face measured by capacitance sensors installed in tight-fitting holes drilled into competent bedrock (Tromp-van Meerveld et al., 2007). Bedrock recharge was also inferred to occur on hillslope "C" (Figure 2) from water collecting in bedrock depressions at the base of soils during events (Figure 4 "2"; van Meerveld et al., 2015) and model simulations (Tromp-van Meerveld & Weiler, 2008). The bedrock had previously been considered fairly impermeable and this flowpath was not included in the earlier perceptual model of flowpaths. Instead, water transport through the bedrock is the dominant transport mechanism from the hillslopes to the riparian zone (near "2" in Figure 4). Furthermore, distributed hydrological modelling of the trenched hillslope indicated that groundwater recharge to bedrock accounted for 74% of throughfall while runoff only accounted for 2.6% of throughfall in 1997 (Appels et al., 2015). Long flowpaths through bedrock are consistent with a groundwater age of 26–27 years in a deep bedrock well near the Lower Gage (Burns et al., 2003). Bedrock cores as deep as 25 m from PMRW indicate the presence of weathered fractures (Huntington et al., 1993). Contemporaneous geophysical studies of the Granodiorite Outcrop and bedrock below the hillslope did not reveal extensive vertical fractures (Hebert, 2005; Toteva, 2006) but ground-penetrating radar indicated horizontal fractures to a depth of at least 3 m (Hebert, 2005). A later recession modelling analysis for streamflow at the outlet suggested that recharge of the perennial-stream riparian aquifer through bedrock fractures from the hillslope (near "2" in Figure 4) may explain the slow drainage and nonlinear recession behaviour at PMRW (Clark et al., 2009).

3.4 | Chemistry of subsurface hillslope flow

Broader relevance of the trenched hillslope studies is also apparent within the context of the entire body of research at PMRW. Samples collected at the trench-face are of a calcium sulfate composition, which had not been previously observed at PMRW (Hooper, 2001). The chemical dissimilarity between subsurface trench-face water and the initial outlet EMMA hillslope end member is the basis for rejection of the second proposed hypothesis regarding chemical similarity between trench stormflow and the hillslope end member, and suggested minimal connectivity between hillslopes and the stream. Further analysis indicated that water with trench-face composition accounted for only 2% of streamwater chemistry variation at the Lower Gage over an extended period (Hooper, 2003). However, Burns et al. (2001) indicated that a trench-face composition hillslope endmember represented 19% and 16% of total runoff at the Upper Gage during two large (62 and 96 mm, respectively) winter storms. However, this discrepancy can be explained by mixing of water passing the Upper Gage with water of a different chemistry residing in the lower part of the catchment. Other research on calcium cycling at PMRW (Huntington, 2000) discovered that the upper 6 m of a bedrock core was largely depleted of calcium (White et al., 1999). Mineralogical analysis indicated no lithogenic sulfur source. Thus, the chemistry of trench samples is likely controlled by anion and cation exchange processes in the soil, whereas stream chemistry is dominated by weathering processes. Trench hillslope soils are predominantly Inceptisols originating from more recent colluvial processes and have a coarser (i.e., sandy-loam) texture than the older more highly weathered Ultisols found in the riparian area (and most of hillslope C; Figure 2). Hillslope Inceptisols do not have the same strong sulfate adsorption capacity as the highly weathered riparian Ultisols (Shanley, 1992), explaining the higher sulfate concentrations in trench samples.

Observed differences between trench chemistry and the stream led to formation of a place-independent hypothesis: stream chemistry would be more similar to the trench chemistry if the residence time in the riparian aquifer was shorter. This led to a three-catchment intercomparison study among Panola (long residence time), Sleepers River, VT (wetter, intermediate residence time), and Maimai, New Zealand (very wet, thin soils, short residence time). Results of these studies partially supported that hypothesis, but required a refinement that soil water on planar to concave slopes is chemically distinct from stream water, even in the wettest catchment. (Hjerdt et al., 2001).

4 | THE ROLES OF RIPARIAN GROUNDWATER AND CATCHMENT STORAGE IN STREAMFLOW GENERATION

4.1 | Initial perceptual model and hypotheses

At the beginning of the PMRW study, the role of groundwater in streamflow generation was assumed to be minor. PMRW was considered to be a small, headwater catchment underlain by impermeable granodiorite rock, present in all outcrops. Surely, whatever alluvial aquifer exists was assumed to be small and residence times of the water were believed quite short, on the order of months.

4.2 | An evolving perceptual model of the role of riparian groundwater in streamflow generation

Geophysical and geochemical measurements at PMRW were first made in 1985 and 1986. These were motivated by an earlier study in the Adirondack Mountains, NY showing that groundwater contributions determined the difference in the chemical response of two lakes to acidic deposition (Peters & Murdoch, 1985). These measurements showed surprising results. Bedrock cores from the riparian zone indicated that the gneiss country rock was close to the surface near the Upper Gage and dominated surface mineralogy in the lower riparian area. Seismic refraction transects indicated that soils plus regolith was up to 5 m deep in the lower riparian area. The hillslopes generally had much thinner soils plus regolith, typically <1 m deep. Later research in the SW subcatchment, including well transects installed to bedrock or refusal across the intermittent stream (Peters, Freer, & Aulenbach, 2003) and a knocking-pole survey at a 10-m grid-size (Zumbuhl, 1998) confirmed the presence of a deep riparian aquifer in this area. Deep erosional gullies in the E and SE subcatchments indicated deep soils in these areas as well. Riparian zones with deep soils and regolith are estimated to represent about 15% of the watershed area.

While these observations indicated a potentially large role for groundwater in streamflow generation, water budget analysis at PMRW initially assumed that change in storage was insignificant at annual time scales. This lack of focus on water storage also emanated from difficulty in quantifying storage spatially and temporally (e.g., McNamara et al., 2011).

However, the significance of storage became apparent later from analyses of baseflow dynamics. Baseflow varied by almost two orders of magnitude, from 0.07 mm·d^{-1} during extreme drought to upwards of 2 mm d^{-1} in late winter, when the intermittent stream in the SW subcatchment was flowing. Baseflow varies seasonally and averaged from 0.45 mm·d^{-1} (August) to 1.45 mm·d^{-1} (March). Baseflow recession at low flows is gradual, maintaining perennial flow at the catchment outlet. A hydrograph separation showed that the baseflow runoff proportion (i.e., the baseflow index) was 0.83, and represented 24% of precipitation (Aulenbach & Peters, 2018).

Streamflow contributions of each subcatchment and from the intervening ungaged area that includes the majority of the lower riparian area (Figure 2) were determined by utilizing temporary gages on the Eastern and Southeastern tributaries during 1992–1994 (a period with above average streamflow). The SW subcatchment containing the large Granodiorite Outcrop had 31% higher average streamflow per unit area than the E and SE subcatchments (Table 1). However, streamflow generation from the intervening ungaged area was much higher (6.51 mm·d^{-1}; for reference, precipitation during this period was 3.19 mm·d^{-1})—such that 58% of streamflow occurred from only 12% of the watershed. Not all runoff in the lower riparian area is from subsurface sources as saturated overland flow is observed in the flat, lowland near the confluence of the tributaries during very wet conditions.

Groundwater dynamics in the riparian aquifer provided insights into the role of groundwater flow. Continuous water level measurements in four riparian wells near the perennial stream showed seasonal variations of about 0.2 to 0.4 m, with additional rises during storms. A nest of piezometers and a single piezometer in the SW tributary channel near the confluence of the SE tributary showed that groundwater was flowing upward, suggesting this flat area was recharged from higher adjacent hillslopes. However, sustained head differences indicated that soils have low permeability and groundwater flow is correspondingly slow. Another possible recharge source to the lower riparian aquifer is subsurface flow from the riparian aquifer that sits below the intermittent stream in the SW subcatchment (i.e., above the Upper Gage), as indicated by the predominantly down-valley flow directions in the riparian area (van Meerveld et al., 2015; Figure 2 "C"). Seasonal baseflow dynamics may be explained by (subsurface) activation and connectivity of this area to the riparian aquifer (Figure 5).

The high baseflow contribution to total streamflow, combined with the limited extent of the riparian aquifer (along with considerations for high AET) requires substantial riparian recharge from either the hillslopes or runoff from the Granodiorite Outcrop. Several well transects were installed perpendicular to the stream channel in the SW subcatchment in 1988–1989 and in 1995–1996 to assess the fate of runoff from the Granodiorite Outcrop and to determine the dynamics of the riparian aquifer along this tributary. Well transects began near the hillslope base opposite the Granodiorite Outcrop and were installed across the riparian zone. Some extended across the lower hillslope below the outcrop and/or included a well in the

TABLE 1 Drainage areas and streamflow for PMRW and subcatchments in Figure 2

Area of watershed	Drainage area (ha)	Percentage of watershed (%)	Average streamflow, (l·s^{-1})	Portion of streamflow at outlet (%)	Streamflow per unit area (mm·d^{-1})
Eastern (E) subcatchment	8	20	0.60	9.2	0.65
Southeastern (SE) subcatchment	18	44	1.22	18.7	0.58
Southwestern (SW) subcatchment	10	24	0.92	14.1	0.79
Intervening ungaged area	5	12	3.77	57.9	6.51
Total	41	100	6.51	100.0	1.37

Note: Streamflow for 19-month period, September 1992 through May 1994; excluding October 1993 and March 1994 due to missing streamflow data at one or more gages. The intervening ungaged area is the remaining area ungaged by the three subcatchments.

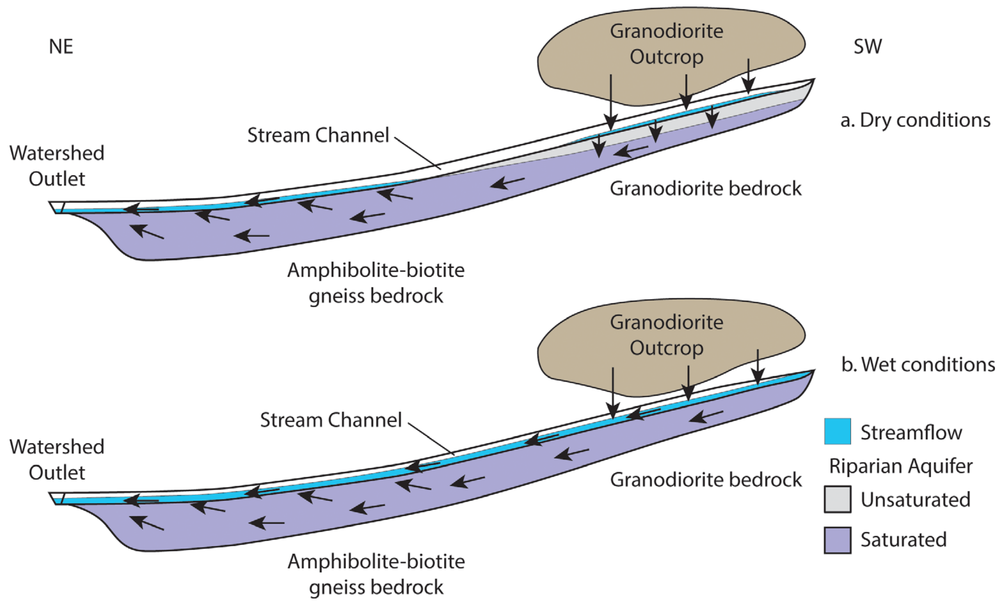

FIGURE 5 Profiles across the riparian area along the Southwestern tributary to the watershed outlet showing flow off the Granodiorite Outcrop, in the stream channel and in riparian aquifer during rainfall events for (a) dry and (b) wet hydrological conditions. The hillslopes also recharge the riparian aquifer as in Figure 4, but this is not shown

intermittent stream channel (Figure 2). The wells closest to the hillslope were mostly dry, except during rainfall events. Some wells closest to the stream channel became dry later in the growing season, but most sustained a water level about 2 m above the well bottoms for much of the dormant season (Peters, Freer, & Aulenbach, 2003). A water level rise of 1 to 2 m was often observed during rainfall events. These observations reflect abundant recharge of the riparian aquifer by runoff that infiltrates into the intermittent streambed during rainfall events (Burns et al., 2001). This is also clear from the losing stream at the outcrop base that is disconnected from the perennial stream (Figure 5a).

Peters, Freer, and Aulenbach (2003) showed that stormflow water yields at the outlet increased linearly with maximum event groundwater levels in the riparian well transects in the SW subcatchment when soil moisture at the deepest probe (70 cm) of a soil profile at hillslope “A” (Figure 2) exceeded a threshold. These hydrometric responses may incidentally occur with filling of the intermittently saturated aquifer and non-losing streamflow conditions on the intermittent tributary (Figure 5b), leading to more effective transmission of runoff from the Granodiorite Outcrop to the watershed outlet. Exceptions to this mechanism occur for very intense storms that can generate a floodwave from the Granodiorite Outcrop that exceeds the infiltration capacity of the streambed and moves down the channel as Hortonian overland flow (Burns et al., 2001). When the riparian aquifer is sufficiently filled, which typically occurs late in the dormant season, the stream connects and can sustain flow for several days, and for several months during the wettest winters (Figure 5b). This connectivity is consistent with the occurrence of lower baseflow magnesium concentrations when the SW intermittent tributary contributes to baseflow, because groundwater derived from areas with Panola Granite bedrock (SW subcatchment) has lower magnesium concentrations than groundwaters derived from areas with amphibolite-biotite gneiss bedrock (the perennial-stream riparian area; Burns et al., 2003).

Riparian aquifer recharge from the hillslopes is inferred from groundwater recharge on the hillslopes. Soil moisture responses from four profiles in different landscape positions indicate groundwater recharge when soils are sufficiently wet. Minimum groundwater recharge estimates from soil profile drainage over several years indicate sufficient recharge to support watershed baseflow and some portion of stormflow (Aulenbach & Riley, 2020), assuming this water is unavailable to contribute to AET. The aforementioned lack of hillslope-riparian zone connectivity (except during large events) of the hillslope at site “C” (Figure 2; van Meerveld et al., 2015) and high water losses to bedrock from the trenched hillslope during sprinkling experiments (Figure 2 “B”; Tromp-van Meerveld et al., 2007) indicate that most hillslope recharge to the riparian aquifer is through bedrock (Figure 4 “2”). Expected long transit times of flowpaths through the relatively impermeable bedrock is supported by older groundwater ages from samples in the riparian area of the lower part of the watershed (6–7 years old, 10–11 in deeper wells; Burns et al., 2003). Tromp-van Meerveld et al. (2007) used a simple four-component water balance calculation of catchment drainage areas, estimated average streamflow water yields of the riparian zone, hillslopes, and outcrops, and determined that subsurface contribution of flow through bedrock was at least 14%–21% of streamflow during a 1-year period.

Riparian storage dynamics along the intermittent tributary in the SW subcatchment is important in stormflow generation at the watershed outlet. Stormflow at the outlet is predominantly derived from the SW subcatchment, which contains the large Granodiorite Outcrop; stormflow from the other two perennial tributaries is minor. Semi-distributed perceptual runoff modelling at PMRW using dynamic TOPMODEL and 30-minute data indicated that three landscape units (bedrock outcrop, hillslope, and riparian zone) were required to adequately model streamflow responses (Peters, Freer, & Beven, 2003). However, infrequent connectivity to the hillslope during storms (Tromp-van Meerveld & McDonnell, 2006a; van Meerveld et al., 2015) indicates limited hillslope contribution to stormflow. Stormflow studies based on water chemistry (Peters et al., 1998; Peters & Ratcliffe, 1998) and mixing models (Burns et al., 2001; Hooper et al., 1988, 1990) indicate that riparian groundwater dominates stormflow during the latter part of the recession.

4.3 | An evolving perceptual model of catchment storage

Quantification of catchment storage was facilitated by advances in age dating techniques and the use of tracers. Burns et al. (2003) used chlorofluorocarbons and tritium/helium–3 data for 19 groundwater samples from wells in the riparian aquifer. These results indicated that apparent ages increased downvalley from modern to about 9 years old at the outlet, and also increased with depth below the surface. The mean age of stream baseflow was 3.2–4.1 years based on a piston flow distribution model and about 4.5 years based on an exponential distribution model (Burns et al., 2003). Peters et al. (2014) extended this analysis by relating tritium/helium–3 data to streamwater Si concentrations and calculated a volume-weighted mean stream water transit time (VW MTT) of ~4.7 years, but more than 10 years during dry years. Transit times were surprisingly long for a small headwater catchment, indicating substantial storage. A VW MTT of 4.7 years along with mean annual baseflow of ~212 mm implies a total watershed storage of ~1000 mm (cf., McGuire & McDonnell, 2006). Assuming a porosity of 0.4, this indicates an average watershed aquifer saturated thickness of 2.5 m. This is substantially larger than the storage expected based on soil plus regolith thicknesses, suggesting either a greater spatial extent of the thicker riparian aquifer than previously assumed, underestimated hillslope soil thicknesses, or substantial storage in bedrock.

The large total storage convinced us to quantify dynamic (active) storage. Dynamic storage of a catchment can be expressed by streamflow recession characteristics, but combining short segments of recession into a master recession curve is confounded at PMRW by highly variable ET and seasonally water-limiting conditions making AET estimates difficult. An alternate approach was developed by combining recession analysis with a daily water budget accounting scheme to adjust recessions for variations in AET. This approach was applied only during the dormant season when calculated PET ~ AET, while fitting the initial storage conditions for each year to obtain a single relationship (McNamara et al., 2011; Peters & Aulenbach, 2011). Dynamic storage was estimated from the derived baseflow-watershed storage relationships as 526 and 566 mm (WYs 1986–2015), depending on the variant relationship used (Aulenbach & Peters, 2018). Dynamic storage estimates were surprisingly large, representing 42% to 45% of annual average precipitation, and variations played a substantial role in the water budget, consistent with the large range in observed baseflow and annual runoff ratios. Differences between total (~1000 mm) and dynamic storage is also substantial (~450 mm). A detailed 1-m resolution topography supports a large area of relatively inactive storage in the lower portion of the riparian aquifer containing the perennial stream because much of the bottom portion of this aquifer lies near and below the elevation of the watershed outlet, which sits on bedrock and acts as a pour point that keeps the lower parts of the aquifer saturated (Figure 5).

5 | OPEN QUESTIONS AND FUTURE OPPORTUNITIES AT PMRW

Our current understanding of streamflow generation at PMRW indicates several future research opportunities to develop further insight into processes and related UPHs not yet fully understood. Recharge of the riparian aquifer via flowpaths from the hillslope in the saprolite and bedrock fractures requires further investigation to better define hillslope–riparian–stream–groundwater interactions. Recharge of the riparian aquifer and hillslope runoff generation in E and SE subcatchments needs better characterization and might also explain the large range in dynamic storage at the PMRW that appears excessive. Stream samples collected along the tributaries in these subcatchments exhibited high magnesium concentrations consistent with the amphibolite-biotite gneiss country rock suggesting that soils and geomorphology are likely dissimilar from those of the intensively studied SW catchment with the granodiorite bedrock. Quantifying the occurrence and magnitude of recharge in relation to precipitation magnitudes and frequencies and ET can help predict changes in storage and determine sensitivity and resilience to meteorological droughts. Further refinement of the baseflow-watershed storage relationship could elucidate differences in recession relationships when the intermittent streams are active, as indicated by Ghosh et al. (2016), and would improve interpretations of transit time distributions. Relationships between stormflow and hydrometric observations should be reevaluated in light of the roles of (1) filling of the riparian aquifer to convey runoff from the Granodiorite Outcrop, and (2) occasional connectivity of the hillslopes with the riparian area to generate stormflow.

6 | UNSOLVED SCIENTIFIC PROBLEMS IN HYDROLOGY AND INSIGHTS BEYOND THE IDIOSYNCRASIES OF PMRW

The presented observations, experimentation, and modelling help answer two Unsolved scientific Problems in Hydrology (UPH) at PMRW:

- UPH 8: Why do streams respond so quickly to precipitation inputs when storm flow is so old, and what is the transit time distribution of water in the terrestrial water cycle?
  The large riparian aquifer at PMRW dominates the catchment hydrologic response to storms. Granodiorite Outcrop runoff can efficiently generate stormflow but only when the riparian aquifer in the SW catchment is sufficiently filled and the intermittent stream becomes connected to the catchment outlet or during

intense storms when Hortonian overland flow moves down the channel (Figure 5). During large storms, the hillslope can connect with the stream and contribute to storm runoff, but contributions are small (Figure 4d).

We found surprisingly long residence times, a function of the volume and hydraulic properties of the riparian aquifer and its relation to the pour point. The hillslopes recharge this aquifer, but the process is slow enough that riparian groundwater is predominantly old water.

- UPH 12: What are the processes that control hillslope–riparian–stream–groundwater interactions and when do the compartments connect?

  Lateral hillslope flow depends on soil depth and is greatly affected by bedrock topography (Figure 4c, d) and catchments behaviour changes with hydrologic conditions. Saturation at the soil-bedrock interface occurs first in upper parts of the hillslope where soils are thinnest. When rainfall is sufficient, isolated saturated pockets become connected resulting in efficient down slope flow. Connectivity of these pockets down to the riparian zone can generate a quick water table rise in the riparian zone. Both macropore and matrix flow are important downslope transport mechanisms, but ultimately connectivity of the saturated zones determines the hillslope contribution to streamflow during storms. The dominant pathway that connects the hillslopes to the riparian zone and the stream is flow through bedrock.

The 35 years of research have taught us much about hydrology, not only at PMRW, but also what is generalizable to other locations. From a mechanistic viewpoint, the trench data have been applied in a series of modelling studies. Some of these examined whether a Richards equation-based model, such as Hydrus 3D (Hopp & McDonnell, 2009), Hydrogeosphere (Ameli et al., 2015), or CATHY (Camporese et al., 2020) could reproduce the threshold response. The observation of a threshold provided a strong test of finite element models—can the physics specified at the small scale (i.e., at the finite element scale) capture the emergent behaviour of a threshold response at the hillslope scale? The answer is yes, but the subsurface boundary, that is, the bedrock interface, has to be correctly specified to reproduce the threshold and to replicate internal pore pressures (Hopp & McDonnell, 2009), and soil core parameters have to be calibrated (as per the work with the TOUGH2 model by James et al., 2010). An important conclusion is that boundary conditions must be specified in far greater detail than was previously considered necessary. But representation of the bedrock does not have to be exact, provided variation in soil depth is represented (as shown by work with HillVi, Tromp-van Meerveld & Weiler, 2008). Indeed, if the important lower boundary is known, even a 2D shallow wave equation can be used to model PMRW hillslope fill-and-spill (Ameli et al., 2015).

The updated perceptual model at PMRW suggests that the roles of riparian areas and hillslopes in streamflow generation should be reconsidered. Beyond that, factors that determine hydraulic properties of the regolith, such as the lack of glaciation and the lithology of the site, are important. Thus, these results should apply to other water-limited non-glaciated terrains underlain by a similar lithology such as found throughout the Piedmont. Such comparisons could contribute to development of a classification system long sought by catchment scientists (e.g., McDonnell & Woods, 2004; Wagener et al., 2007).

After chasing storms at PMRW for decades, we now know that streamwater chemistry at the outlet largely reflects riparian zone dynamics. We cannot readily observe the hillslope chemical response to perturbations by examining chemical variations in streamwater during rainfall events, as initially assumed. Therefore, processes such as the impact of acid rain on hillslope soils (e.g., enhanced calcium leaching) must be studied at the hillslope scale. This finding has profound implications for modelling the response of catchments to nonpoint source pollutants. Most models infer parameters from variations in the stream chemistry at the catchment outlet and assume that all parts of the catchment contribute proportionally to the stream. We showed the fallacy of this assumption at PMRW.

Our understanding of the hydrological role of storage at PMRW has implications for understanding of the impacts of climate change and particularly meteorological droughts, in humid, seasonally water limited areas of the Southeastern United States. Hydrological droughts occurred only when storage at the end of the dormant season is below normal (Aulenbach & Peters, 2018). Groundwater recharge occurs predominantly in the dormant season. During the growing season recharge occurs only when antecedent conditions are sufficiently wet, and events are sufficiently large and/or frequent, otherwise, high AET reduces soil moisture between events. The effects of climate change, such as lengthening of the growing season, seasonal changes in the magnitude and frequencies of precipitation events, and increases in PET related to increasing temperatures, can result in reduced recharge, storage, and baseflow. This has implications for water availability and stream chemistry.

7 | LESSONS LEARNED ABOUT LONG-TERM MONITORING AND EXPERIMENTATION

Reflecting on our collective decades of research at PMRW, we offer the following lessons learned:

1. **Subsurface characterization is critical to process understanding**. Our initial assumptions about the subsurface, such as the topography of the soil-bedrock interface, aquifer depth, or mineralogic composition, based on inference from surface features were incorrect. Our initial assumption of non-transmissive bedrock was also mistaken. Geophysical measurements (and repeated augering for establishment of many wells) established a basic framework for understanding the hydrology of PMRW. Geochemical measurements enabled us to understand the sources of ambient tracers we utilized, allowing us to distinguish between weathering and cation exchange processes. Rainfall simulation experiments allowed quantification of leakage to bedrock.

2. **Environmental tracers complement hydrometric measurements**. Tracers provide qualitatively different information about water movement than hydrometric measurements. Taken together, we gained deeper insight into the processes controlling water movement at PMRW. Neither alone was sufficient.
3. **Age-dating of young groundwater is one of the most powerful tools in developing a perceptual model of the hydrology of a basin**. Whether by chlorofluorocarbons or tritium/helium, these relatively simple and inexpensive measurements provided powerful insight and should be one of the first measurements to characterize a site.
4. **Experimentation is necessary**. Small watersheds have long been manipulated to test hypotheses at the landscape scale. What we learned at PMRW could not have happened without the trench experiment, irrigation experiments, and applied tracers. The ability to perform experiments should be an important consideration for selection and operation of research watersheds.

Much of water movement occurs out of sight underground and must be inferred. Therefore, field studies are poorly constrained. Insufficient subsurface characterization and limited observations typically supports multiple hypotheses with repercussions for model equifinality. The overarching lesson learned from operating a long-term experimental watershed, beyond these four specific lessons, is the importance of an explicit perceptual model of the catchment, supported by mathematical models to explore competing hypotheses. What are the functional units of the catchment to address the research questions? How do each of these units operate and interact? These questions determine what, how, and where instruments are deployed. Repeatedly returning to the perceptual model with new data enables either refinement or rejection, requiring mathematical models to be updated. Studies rely on valid perceptual models, even as the focus of research changes.

Long-term studies have the potential to advance science precisely because we can accumulate measurements at a site to better constrain different interpretations or possibilities. Furthermore, observations are more likely to cover a greater range of climatic conditions with time. Yet, studies cannot be justified by simply waiting to see what happens. Continual progress of an evolving perceptual model requires compelling observations and experiments to test the model. The critical metric of success of a long-term study should be the assessment of how the perceptual model has evolved. Yet that question is seldom asked to justify continued operation when decisions are made for renewed funding.

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DATA AVAILABILITY STATEMENT

This is a review paper, and while previously unpublished observations have been incorporated herein, analysis in this paper relies predominantly on previously published research. Much of the storm response data at the experimental trenched hillslope (Figure 2 "B") is available from the data note by Tromp-van Meerveld et al. (2008). Data for PMRW water budgets are available from Aulenbach (2017).

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