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Key Points:
- During low snow years, perennial surface saturation is lost within the meadow, but streamflow is sustained year-round at the meadow's base
- Existence of these groundwater-fed meadows is related to regular surface saturation caused by downslope thinning of saprolite
- Together, this suggests that under continued snowpack decline, regular surface saturation may be lost in mountain meadow systems

Supporting Information:
Supporting Information may be found in the online version of this article.

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Influence of Critical Zone Architecture and Snowpack on Streamflow Generation Processes: A Mountain-Meadow Headwater System in a Mediterranean Climate

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Abstract Observations from a granitic watershed within a Mediterranean climate reveal the hydrologic and critical zone functioning of a perennial stream headwater and its upslope contributing area within a meadow system in the Sierra Nevada, California. Chemical analysis (diagnostic tools of mixing models, end member mixing analysis, tritium, etc.) and physical data (stream stage, piezometers, soil water, snowpack, etc.) indicate there are two primary pathways of water input into a headwater stream sourced from a mountain meadow. One input is a shallower and younger subsurface pathway with water that resembles snowpack chemistry, and the other a deeper and older subsurface pathway with water that reflects the chemistry of the groundwater derived from the contributing hillslopes. Multi-year observations reveal that regardless of snowpack amount, during the period of peak hillslope infiltration, shallow and deep pathways in the hillslope behave similarly to initiate headwater streams. However, during summer dry periods, similarities in active pathways within the meadow center are not maintained between high and low snowpack years. With less snow, perennial groundwater discharge within the meadow center is eliminated, becoming only a seasonal source at the meadow's outlet. At the meadow's edge, geophysically observed downslope thinning in saprolite thickness creates reduced lateral transmissivity and initiation points for headwater streams via enhanced groundwater discharge of upslope water. Combined, these findings suggest how loss of snowpack and critical zone structure can together mediate hydrologic function in a wet meadow system in a Mediterranean climate. Creating new understanding about the stability of hydraulic functioning in headwater wet-meadow systems under a changing climate.

Plain Language Summary A new combination of data sets collected over several years in the Sierra Nevada Mountains of California reveal how smaller wet meadows sustain headwater streamflow, or not, during years of higher or lower snowpack or drought. The location of streamflow generation at these sites may be strongly tied to the shape and characteristics of the weathered bedrock in the shallow subsurface. Findings from this study show how underground flow pathways of water can function to promote year-round headwater stream sources in mountain environments with wet-winter, dry-summer climates, when large snowpacks are present. However, long-term the prevalence of seasonal surface flooding in these headwater wet meadows may decrease as climate warms and snowpacks continue to decline and become more variable from year to year.

1. Introduction

Perennial headwater sites, where surface flows of water discharge from the subsurface year-round, are crucial for the provisioning of ecosystem and critical zone services both onsite and downstream, such as in-stream water resources, wetland habitat and increased montane species diversity, and the stabilization of sediment (Brauman et al., 2007; Field et al., 2015; Ratliff, 1985). Although perennial headwater sites comprise a relatively small fraction of the total landscape area, they provide a disproportionate amount of services for use by both humans and terrestrial and aquatic biota (Kattelmann & Embury, 1992; Purdy & Moyle, 2006). With changes in climate and land cover, reductions of dry season baseflow originating from perennial headwaters is becoming a greater concern in the western United States and other areas worldwide (Barnett et al., 2005). Considering these changes in climate, and the unique services these sites provide, these perennial headwater sites form a unique type of hydrologic refugia on the landscape that can allow some species to persist as the surrounding climate warms and causes the adjacent landscape to dry (McLaughlin et al., 2017; Stewart et al., 2005).

Perennial headwater sites within the Sierra Nevada often occur with a surrounding ecosystem of either unforested or forested riparian zones, depending in part, on whether near-surface saturation in the riparian subsurface occurs often enough to prohibit the growth of trees, forming a wet meadow (Crockett et al., 2016; Lubetkin et al., 2016). The factors that primarily control where on the landscape the initiation location of headwater streams occur are complex. Factors include influences from climate, topography, subsurface architecture, and the surrounding ecosystems (Dietrich & Dunne, 1993; Essaid & Hill, 2014; Hammersmark et al., 2008; Loheide et al., 2009; Montgomery & Dietrich, 1989, 1992, 2002). Critical zone science offers a lens by which to explore the interdisciplinary relationships between these multiple factors (Brantley et al., 2007).

Of these factors, the least is known regarding subsurface architecture (Riebe et al., 2016). Subsurface architectures has been shown previously to play a role in mediating where groundwater is discharged to the surface (Freer et al., 2002; Spence & Woo, 2003), and when occurring year-round, forming perennial headwater sites (Benedict & Major, 1982). Particular focus in the study of groundwater discharge locations and their role in forming perennial headwaters has been on wet meadow sites (Jin et al., 2012; Lord et al., 2011; Payn et al., 2012). Wet meadow systems are often comprised of highly permeable, deep alluvial basins that are in strong contrast to the shallow soils in the adjacent upslope area, and thus provide significant water storage in the subsurface (Wood, 1975). The role this accumulation of alluvial fill plays in the persistence of the perennial discharge of groundwater emanating from these headwater meadows is unclear, and these wet meadow systems have been the focus of previous hydrologic studies (Ciruzzi & Lowry, 2017; Hammersmark et al., 2008; Loheide et al., 2009; Lowry et al., 2010; Lucas et al., 2016; Tague et al., 2008). Riparian wet meadows in downstream locations have been shown to store water during overbank flooding, releasing it later during the dry season (Hammersmark et al., 2008; Ohara et al., 2014; Tague et al., 2008). Despite the value and diversity of these studies in wet meadow systems, limited understanding exists about the specific hydraulic functioning of hillslopes that feed small headwater meadow systems at the highest locations in watersheds. Uncertainty remains regarding whether these lowest-order headwater meadow sites still operate similarly to these lower meadows (Ciruzzi & Lowry, 2017), accumulating ephemeral surface flows during the wet season and snowmelt period and releasing water later during the dry season from storage in the unconsolidated sediment underlying the headwater meadow (Brown, 2013; Cornwell & Brown, 2008; Hammersmark et al., 2008; Loheide & Gorelick, 2007; Rodriguez et al., 2017). Instead it may be that these headwater mountain-meadow stream sources are located where groundwater accumulated in adjacent hillslopes during the wet season is eventually discharged as surface water due to lateral variations in critical zone structure, with saprolite thinning causing reduced transmissivity in the subsurface (Freer et al., 2002; Spence & Woo, 2003; Tromp-Van Meerveld & McDonnell, 2006). Then the unconsolidated sediment fill may only be co-occurring at these headwater initiation sites, but not facilitating their existence (Essaid & Hill, 2014; Lowry et al., 2010; Rodriguez et al., 2017; Wood, 1975).

This distinction between the enhanced subsurface storage present near these headwater meadow sites acting as either (a) storage and release systems for seasonal rain and snowmelt water (Brown, 2013; Cornwell & Brown, 2008; Hammersmark et al., 2008; Loheide & Gorelick, 2007; Rodriguez et al., 2017), or (b) simply co-occurring immediately upslope of the same saprolite thinning that cause the reduced lateral transmissivity and groundwater discharge (Freer et al., 2002; Spence, 2010; Spence & Woo, 2003; Tromp-Van Meerveld & McDonnell, 2006), is critical to understanding the long-term stability under a changing climate of streamflow emanating from these headwater meadow sites (Ciruzzi & Lowry, 2017), and the services these meadow sites provide (Field et al., 2015).

The need for understanding this distinction is particularly true within a Mediterranean climate where the highest seasonality between seasons of water availability and demand creates an end-member situation requiring the highest need in the critical zone to store water precipitated during the wet season, via snowpack and subsurface storage, and transfer it for vegetative use and surface streamflow during the dry season (Klos et al., 2018). This need to transfer water from wet to dry seasons in Mediterranean climates, and elsewhere, via subsurface storage is growing as snowfall and snowpack accumulation in the western U.S. and worldwide has been decreasing in recent decades due to global changes in climate (Hanson et al., 2005; Knowles et al., 2006; Mote et al., 2005), and is expected to further decrease in the decades to come with a continually higher proportion of precipitation occurring as rain, and a lower proportion as snow (Barnett et al., 2005; Klos et al., 2014).

Considering these decreases in snowpack, and the existing unknowns in both the function of the subsurface architecture underlying headwater meadow systems, and how this architecture will dictate the future stability of the

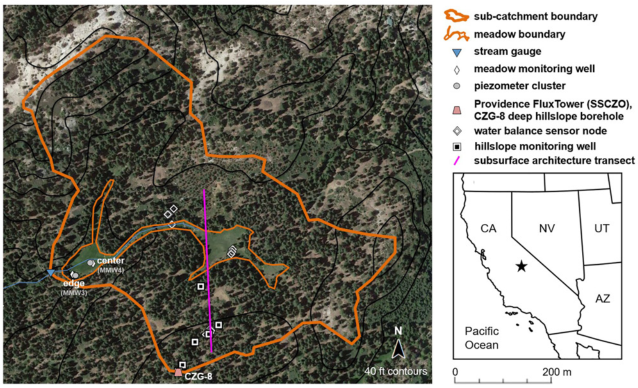

Figure 1. Map of study site with meadow and sub-catchment outlines overlaying aerial imagery. Only select monitoring wells, piezometer clusters, soil moisture and snowpack nodes, and the perennial stream sites that are used for the primary results and interpretations are highlighted. Relevant hillslope gradients in the primary area of study are shown in Figure 7, with the subsurface architecture (purple transect) based directly on geophysical findings from Holbrook et al. (2014).

services emanating from these headwater meadow sites, there is an increasing need to understand the pathways of water feeding these currently perennial sites (Essaid & Hill, 2014; Lowry et al., 2010; Rodriguez et al., 2017). Potential non-linear process thresholds controlling the activation of these pathways and seasonal timing of streamflow generation may exist (Ciruzzi & Lowry, 2017; Spence, 2010; Tromp-Van Meerveld & McDonnell, 2006; Uchida et al., 2005).

Quantification of surface and subsurface fluxes and stores of water, and the hydrologic partitioning of those into discrete processes and pathways, allows for this needed study of complex interactions between water and controls on it from climate, geology, and ecosystems in headwater settings (Brooks et al., 2015). Pairing physical measurements of volumetric fluxes and stores of water with measurements of water chemistry offers a robust methodological combination by which to partition watershed processes and pathways (McDonnell, 1990; McGlynn & McDonnell, 2003), expanding our current understanding of the ways subsurface architecture can influence the functioning of these headwater meadow systems under a changing climate, and expanding our understanding from what is known from lower, larger wet meadow systems (Ciruzzi & Lowry, 2017), and into the lowest-order headwater meadow systems. This partitioning of subsurface pathways and timing—relative to surface streamflow generation—provides insight into how the changes in precipitation regime will affect the provisioning of ecosystem and critical zone services emanating from perennial headwater systems.

Considering these needs and methodical opuntias to better quantity and predict the stability of these important perennial headwater meadow sites in montane environments with Mediterranean climates, especially in the context of continued warming and snowpack loss, and how this stability is mediated by subsurface architecture, we focused this study on the partitioning of a headwater meadow stream source at a site where an extensive knowledge of the subsurface architecture already exists (Holbrook et al., 2014). We used physical and chemical measurements collected over both high and low snowpack years to quantify the timing and influence of snowpack on upslope pathways feeding a headwater stream source emanating from a wet meadow in the Sierra Nevada of California. Our specific objectives were to: (a) quantitatively partition the inputs and pathways of water initiating a headwater wet-meadow stream source in a highly season Mediterranean climate across years of varying snowpack, (b) use this and other existing site information on critical zone architecture to understand why headwater meadow sources occur where they do in montane environments underlain by crystalline bedrock, and then (c) use this new understanding to help others better predict how meadow surface saturation and other services provided by these types of headwater meadow sources will be stable or transient in a changing climate with continued reductions in seasonal snowpack.

2. Methods

2.1. Site Description

This study was conducted in the upper portion of the Providence Creek watershed, P301 catchment (Latitude: 37.0692°, Longitude: −119.1979°), hereafter referred to as the sub-catchment (Figure 1), part of the United States Forest Service Pacific Southwest Research Station Kings River Experimental Watershed and the Southern Sierra Critical Zone Observatory. Vegetation consists of mixed conifers in the hillslope forests and grasses and sedges in the riparian wet meadow (Figure 1). At elevations around 1,850 m on the west slope of the Sierra Nevada the sub-catchment is in the rain-snow transition zone (Klos et al., 2014). Precipitation patterns in the sub-catchment are typical of a Mediterranean climate with cool, wet winters, and warm dry summers; at this elevation, winter precipitation is characterized by the seasonal accumulation of winter snowpack, and subsequent spring melt. The sub-catchment lies outside the boundaries of recent glaciation (Jessup et al., 2011). The subsurface architecture of the site, observed and described in high detail in Holbrook et al. (2014), is characterized by granodiorite that weathers into saprolite of varying thicknesses (up to 20 m), and is overlain by soils of highly variable thicknesses. Soils in the hillslope forests are comprised of loamy sands, sands, and gravels (Bales et al., 2011). The meadow

Table 1
Summary of Observational Measurement Types From Study Site

Measurement	Measurement tool	Physiographic location	Notes
Stream stage	Pressure transducer; salt tracer tests	Meadow outlet	
Hydrostatic head	Piezometer clusters; pressure transducers	Three clusters in meadow, varying from edge to center	Bottom 5 cm screened; in clusters of 3 at depths of 65, 120, and 260 cm
Barometric pressure	Pressure transducer	Top of hillslope (sub-catchment boundary)	
Terrestrial water balance	Ultrasonic snow depth sensors; air temperature and humidity sensors; soil moisture and temperature sensors	Five nodes in meadow; 20 nodes in adjacent hillslopes	Instrument clusters (nodes), combined into wireless network; soil sensors at depths of 10, 30, 60, and 90 cm
Stream water chemistry	Grab samples; automated sampler	Meadow outlet	
Groundwater chemistry	Monitoring wells; grab samples	Twelve wells in meadow; three wells in hillslope saprolite; deep geoprobe borehole in hillslope	Screened from well bottom to land surface; geoprobe borehole (CZG-8), 7.8 m deep, bottom 2 m screened
snowpack chemistry	Grab samples collected during snow survey	Distributed across sub-catchment	40 cm long tubes for vertical sampling

soil is characterized by a less than 10 cm thick peat layer underlain by high organic silts, silty loam, and loamy sands that transition into layers of sands and gravels that continue downward to depths greater than 2 m, typical for wet meadows in the region (Wood, 1975). Analysis of deeper (>2 m) subsurface lithology has been conducted via seismic refraction and resistivity surveys (Holbrook et al., 2014). The cross-sectional subsurface model of the sub-catchment presented by Holbrook et al. (2014) defines a soil layer that is approximately 1–2 m thick, below which several meters of saprolite and weathered bedrock exist before unweathered bedrock is encountered.

2.2. Physical Measurements

Stream stage (gauge location in Figure 1) was measured with *Solinst Gold Levelogger* pressure transducers (Table 1). Streamflow was determined with stage-flow relationships developed by determining streamflow with salt tracer tests and comparing flow to stage at the time of measurement. Groundwater elevation in the meadow was measured in 12 monitoring wells (select locations in Figure 1). Depth-specific hydrostatic head was measured in 12 piezometers associated with five of the monitoring wells in the meadow. Monitoring wells were constructed with 3.18 cm inner diameter schedule 80 PVC pipe, screened with 0.25 mm slotted screen from the bottom of the hole to as near as the ground surface as possible and the remaining length was equipped with blank casing. Piezometers were constructed with 5 cm of 0.25 mm slotted screen at the bottom of the hole and completed with blank casing. Piezometers were installed in clusters, with clusters containing piezometer depths of 65, 120, 260 cm (locations in Figure 1). Monitoring wells and piezometers were also equipped with *Solinst Levelogger Gold* pressure transducers (Table 1). Barometric pressure was recorded with a single pressure transducer (*Solinst Barologger Gold*) at the P301 eddy flux tower at approximately 1,900 m elevation. Twenty-five terrestrial water balance instrument clusters of snow depth, soil moisture and temperature, relative humidity and air temperature sensors were distributed across the catchment as part of a wireless network (Table 1). Five of these wireless sensor nodes are located within the meadow, and 20 wireless sensor nodes are distributed throughout the adjacent forested hillslopes (Figure 1). These instrument nodes are equipped with *Judd Communications* ultrasonic snow depth sensors, *Decagon Devices Echo-TM* soil moisture and temperature sensors deployed at 10, 30, 60, and 90 cm below ground surface, and *Sensirion SHT2x* humidity and air temperature sensors (Table 1).

2.3. Chemical Measurements

Water samples were collected from the stream water, groundwater monitoring wells, and snowpack (Table 1; Table S1 in Supporting Information S1). Grab samples were collected from monitoring wells and the stream at the meadow outlet (Figure 1) between 1 June 2011 to 15 October 2011 (17 samples) and between 30 May 2012 to 1 November 2012 (13 samples). Additionally, an automated sampler (*Teledyne Isco*) was used to collect samples from the meadow outlet between 23 June and 21 July 2012 (seven samples). For sampling, monitoring wells were purged—a total of three well volumes were pumped unless the well is purged dry before said volume is reached—and allowed to recover then sampled using a peristaltic pump. Groundwater samples were collected from multiple locations, including: (a) monitoring wells in the meadows, (b) shallow monitoring wells drilled into the saprolite in the upslope areas outside the meadow boundary, and (c) from a deeper geoprobe borehole (CZG-8) drilled upslope of the meadow to a depth of 7.8 m below ground surface (Table 1). The bottom 2 m of the casing placed in the borehole was screened. CZG-8 was purged until dry and allowed to recover before being sampled using a peristaltic pump. Snow samples were collected throughout the sub-catchment using cleaned 40 cm long and 5 cm diameter pipe pushed vertically into the snow pack during a snow survey on 13 and 14 March 2011—pipes were capped and sealed for transport to the lab. Once in the lab, snow samples were melted by running warm water over the sealed pipes. Liquid samples were poured into polyethylene sample bottles for major ion analyses and 40 ml glass vials with no headspace for stable water isotope analysis and stored at 4°C until further processing. All other water samples were collected in polyethylene sample bottles and 40 mL glass vials with no headspace and stored at 4°C until further processing. All major ion samples were filtered with *Millipore* 0.45 μm filters and divided for analysis with a *Dionex ICS-2000* ion chromatograph system. Major ion analysis was conducted for presence of F^-, Cl^-, SO_4^{2-}, NO_3^-, NH_4^+, Na^+, K^+, Mg^{2+}, and Ca^{2+}. Sample alkalinity was determined by titration on a *Radiometer Analytical Titralab* autotitration system. Select samples were analyzed for stable water isotopes on a *Los Gatos Liquid Water Isotope Analyzer*. Select samples (Table S2 in Supporting Information S1) were analyzed for tritium activity at Lawrence Livermore National Laboratory (Surano et al., 1992). Thanks to the 12.32 year half-life, tritium activity in surface water and groundwater can constrain the travel time (but this is young-biased without additional tracers) through the critical zone if the activity in precipitation is known (Harms et al., 2016; Vogel et al., 1974). Groundwater discharging at the meadow reflects the complex subsurface mixing of water with different ages (Visser et al., 2018). Without additional age tracer information available from the meadow piezometers, we calculate tritium ages (τ) assuming either piston flow ($\tau_{PF} = \ln(C_0/C)/\lambda$) or an exponential age distribution ($\tau_{EM} = (C_0/C - 1)/\lambda$), with an initial concentration C_0 of 13.5 pCi/L (Visser et al., 2018) and a decay constant $\lambda = 0.05626$ a^{-1}, to provide qualitative indicators of water travel times.

Diagnostic tools of mixing models (DTMM) developed by Hooper (2003) were used to determine which ion species behaved conservatively with end member mixing. NO_3^-, NH_4^+ were omitted from DTMM because many of the samples had values below detection limits not analyzed for that particular constituent. DTMM requires non-zero values for analysis. Missing values in the remaining constituent columns were filled with half of the lowest value measured above detection limit. Stable water isotope and tritium analyses were omitted from DTMM due to the lack of samples run for these constituents. DTMM is advantageous in that it distinguishes whether constituents are controlled by chemical equilibria or by mixing. DTMM also allows the user to determine the number of end members participating in mixing. End member mixing analysis (EMMA), as presented by Liu et al. (2008) was used to determine likely end members and percent contribution to streamflow from said end members.

3. Results

Water year 2011 was one of the wettest years on record (1901–2012) for the sub-catchment while water year 2012 was one of the driest years (Blankinship et al., 2014). The accumulated snow depths measured by the terrestrial water balance instrument clusters illustrates this difference between the two water years in the sub-catchment (Figure 2, created from published data sets: Hunsaker & Safeeq, 2017; Bales et al., 2018). A maximum of 250 cm snow depth was recorded in 2011 and a maximum of 140 cm in 2012 (Figure 2), with both from the same open canopy location in the sub-catchment (Figure 1). The reduced snowpack in 2012 resulted in earlier snowmelt (by 6 weeks), earlier drying out of the watershed soils (defined by the drop from a wet season VWC of ~30%), and reduced stream flow with an earlier peak compared to 2011 (Figure 2). However, these snowpack data sets may be limited by their spatial coverage and resolution, with some locations in the study area being over-represented in the final mean values, and others underrepresented, relative to the exact areas contributing most to snowmelt infiltration. This could be due to spatial heterogeneities in snowpack accumulation from drifting and other non-linear processes of terrestrial energy flux.

In synchronicity with snowmelt, vertical hydraulic gradients measured using piezometer clusters within the meadow (Table 1) follow two general patterns. The shallow hydraulic gradient, measured as the difference in total head between the shallow and middepth piezometers (spanning approximately 65–120 cm below ground surface) exhibits a negative gradient, indicating groundwater discharge, during snowmelt and moves to exhibit a positive gradient, groundwater recharge, as the growing season progresses (Figure 3). The timing of this change in groundwater gradient is dependent on the previous season's snowpack. Larger snowpacks melt out later and the transition from negative to positive groundwater gradient is observed later. The timing of this change in groundwater flow direction is also dependent on location in the meadow. The piezometer clusters near the edge of the meadow move from negative to positive gradient earlier than the clusters located in the center of the meadow (Figure 3), indicating that a groundwater discharge signal persists in the meadow center during the wet year (2011). Deeper hydraulic gradients (spanning approximately 120–260 cm below ground surface) at the meadow center exhibit a groundwater discharge signal throughout the growing season (Figure 3). In the relatively wet year, 2011, deep hydraulic gradients are most negative at the end of snowmelt in June. These gradient

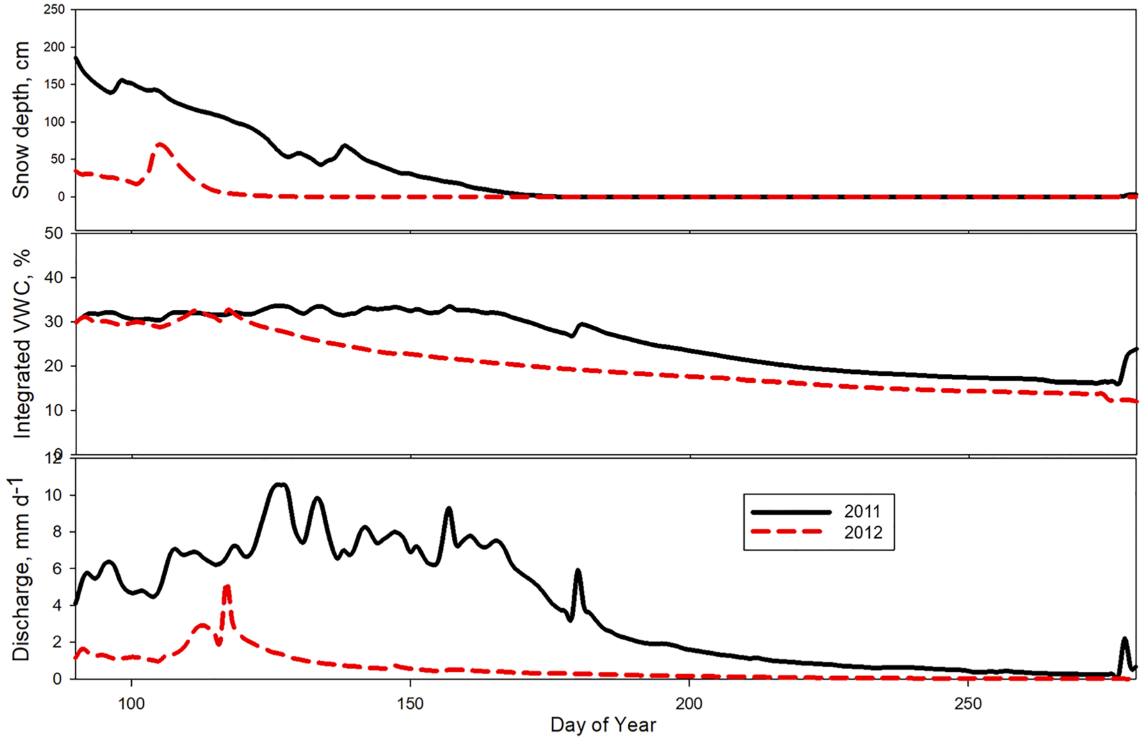

Figure 2. Snowmelt, soil moisture, and streamflow time-series from the snowpack melt periods and subsequent summer dry periods of 2011 and 2012. Locations of the specific snow depths and soil moisture measurements (water balance) nodes that were integrated and used, and the location of the outlet stream gauge used, are depicted in Figure 1.

signals are reduced in July and August and become stronger in September (Figure 3). Deep hydraulic gradients in the relatively dry year, 2012, are least negative in June and become more negative in the subsequent months (Figure 3). Horizontal hydraulic gradients calculated from the meadow monitoring wells indicate a steeper gradient during snowmelt than exhibited in the fall, consistent with the vertical hydraulic gradient patterns described above. These interpretations of hydraulic gradient in the wet meadow may be limited by a lack of uniform spatial coverage throughout the meadow environment. Alterative flow gradients, directions, and timing patterns may be occurring in other parts of the meadow outside the spatial and temporal coverage of our piezometer data set.

From chemical analysis, NO_3^- and NH_4^+ measured consistently near-zero values with concentrations in many samples below detection limits (Tables S1 and S2 in Supporting Information S1). Na^+ exhibited positive

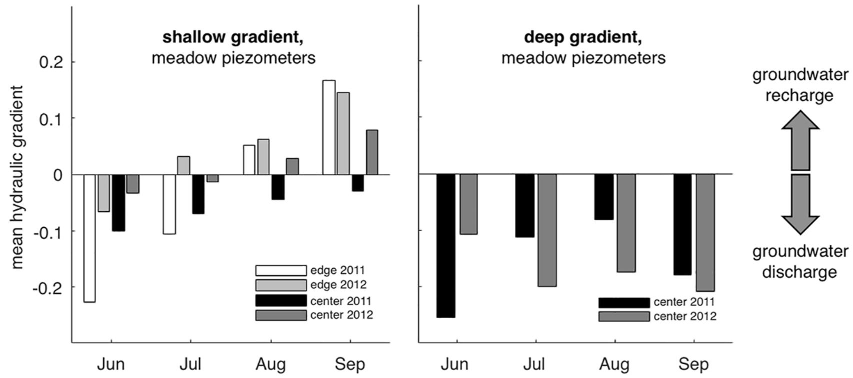

Figure 3. Mean monthly hydraulic gradients from piezometer clusters placed within the edge and center of the wet meadow. Shallow gradients are between 65 and 120 cm depth, and deep gradient represent hydraulic gradients between 120 and 260 cm depth. A negative gradient indicates groundwater discharge and a positive gradient indicates groundwater recharge. Locations are mapped on Figure 1.

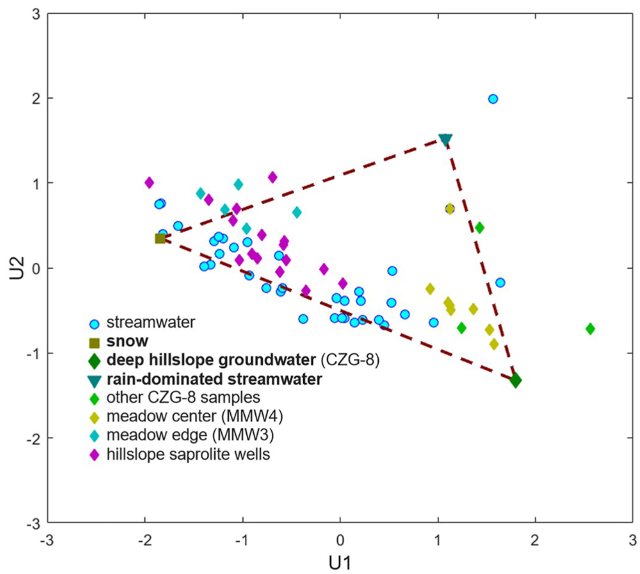

Figure 4. U-space diagram with determined end members: snow, deep hillslope groundwater, and rain plotted in relation to water from the stream outlet, hillslope saprolite, meadow edge, and meadow center.

correlation with concentrations of other major cations. Generally, stream water salinity increased from spring into summer and fall, with electrical conductivity more than doubling at the meadow outlet from June to September of 2011 (Table S2 in Supporting Information S1). Ca^{2+} concentrations in the stream generally increased from spring into summer and fall in both 2011 and 2012 (Table S2 in Supporting Information S1). Groundwater from the edge and middle meadow wells (MMW3, MMW4, respectively) show distinct ion concentration signatures with the groundwater from the meadow edge being more dilute than the meadow center. Groundwater samples collected from wells drilled into the saprolite in the hillslope above the meadow area are also more dilute than the meadow center (Tables S1 and S2 in Supporting Information S1). Groundwater samples from MMW4 at the meadow center had lower ^3H values than the groundwater sampled at the meadow edge (MMW3). Tritium-based analysis from the site gives an approximate age range of 6.2 years (τ_{PF}) to 7.5 years (τ_{EM}) for groundwater sampled from the meadow edge, and an approximate age range of 10.4 years (τ_{PF}) to 14.1 years (τ_{EM}) for groundwater sampled from the meadow center.

Water chemistry data were analyzed using diagnostic tool of mixing models (DTMM) for stream water samples and groundwater samples, including MMW3 (meadow edge) and MMW4 (meadow center). Conservative tracers were determined separately for stream and groundwater data sets. Ca^{2+}, K^+, Cl^-, and Alkalinity were all found to be conservative tracers. F^- residuals from the DTMM analysis exhibited a linear relationship. SO_4^{2-} residuals also exhibited a linear relationship in both 1D and 2D spaces for the meadow groundwater and in the 1D space in the stream water. Additionally, SO_4^{2-} concentrations were below detection limit for a number of both stream water and groundwater samples—thus making it a poor choice for EMMA. Na^+ was excluded in the EMMA consistent with Liu et al. (2013) considering Na^+ a non-conservative tracer in the surrounding Providence Watershed. Approximately 85% of the variance in the stream chemistry is explained by the first two eigenvectors of the principal component analysis compared to 60% of the variance in the groundwater data set described by the first two eigenvectors. In both data sets, at least a 2D mixing space with at least three endmembers are required to complete the end member analyses. EMMA was conducted for the stream water data set using Cl^-, Ca^{2+} and alkalinity as conservative tracers. Cl^- and K^+ were used for the mixing diagram constructed for meadow groundwater. Endmembers projected include snow, groundwater, and rain (Figure 4), consistent with Liu et al. (2013).

The snow end member is represented by the integrated snow sample collected near the Upper Providence met station on 13 March 2011. The met station reported snow depth of 173 and 79.8 cm of snow water equivalent (Hunsaker & Safeeq, 2018). The groundwater endmember for the data set was collected from the CZG-8 well just outside of the upper meadow (Figure 4) on 3 April 2013. The data set aligns well along an axis where the samples collected during snowmelt group closer to the snow end member and samples collected later in the summer and into the fall group closer to the respective groundwater endmember. As in Liu et al. (2013), deviation from this trend is captured by a streamflow sample collected in the fall shortly after a rain event on 15 October 2011.

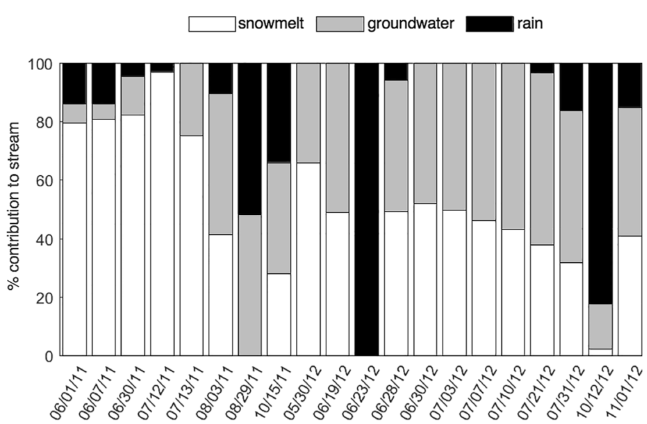

Figure 5. Time series of percent contributions to the stream water from end-member sources partitioned between: snowmelt, rain water, and deep hillslope groundwater.

Analysis was carried out as described by Liu et al. (2008) to determine the contribution of each end member to streamflow and meadow groundwater (Figures 5 and 6). In the stream, snowmelt contribution is highest in the spring and early summer and then decreases as the growing season progresses and snowmelt contribution is higher in 2011 than in 2012 (Figure 5). The tritium activity in stream water also trends from higher (10.4 pCi/L, less depleted) in February 2012 toward lower (7.6 pCi/L, more depleted) in November 2012, indicating a decreasing contribution of young water as the system moves from the period of peak infiltration (snowmelt) into the dry period. Analysis of end member contributions to meadow groundwater is split into groundwater sampled at the meadow edge and at the meadow center (Figure 6).

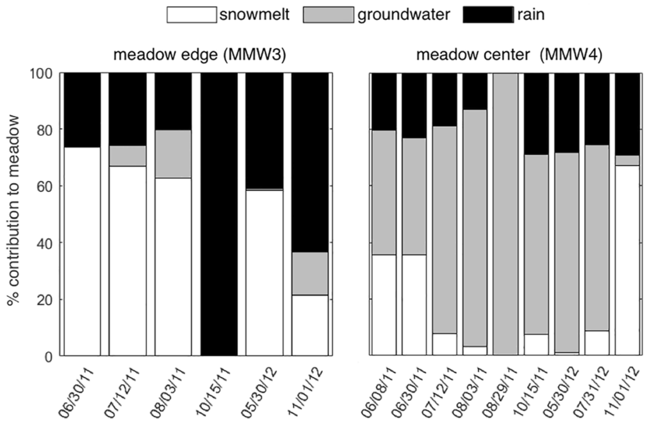

Figure 6. Time series of percent contributions to monitoring wells at the meadow edge and meadow center from end-member sources, partitioned between: snowmelt, rain water, and deep hillslope groundwater.

Groundwater at the meadow edge exhibits significant input from snowmelt in the spring and early summer and then decreases as the growing season progresses. At an annual scale more influence from snowmelt is observed in 2011 (40%–60%) than in 2012 (10%–20%) (Figure 6). The groundwater sample collected from the meadow edge well in October of 2011 is dominated by rain. This sample was collected shortly after a rain event in the catchment. The groundwater from the meadow center well has less of a snowmelt influence than the edge well and tends to be dominated more by groundwater. The highest percentage of snowmelt influence is observed in November of 2012. This is the same precipitation event that exhibited a strong rain contribution to the groundwater from the well at the meadow edge (Figure 6).

Interpretation of this water chemistry data may be limited by multiple factors, primarily a lack of all-year temporal coverage and limited spatial coverage. We provide the most robust data set we could acquire with our exiting funds and resources, but additional data, or re-analysis of existing data using alternative mixing models could yield alternative results. Despite this, we believe our methods and interpretations to be in-line with standards established by others (e.g., Liu et al., 2013), which can provide a logical and justifiable interpretation of water sources and ages useful for paring with our physical measurements to make a highly integrated and robust interpretation of hydrological processes in our study area.

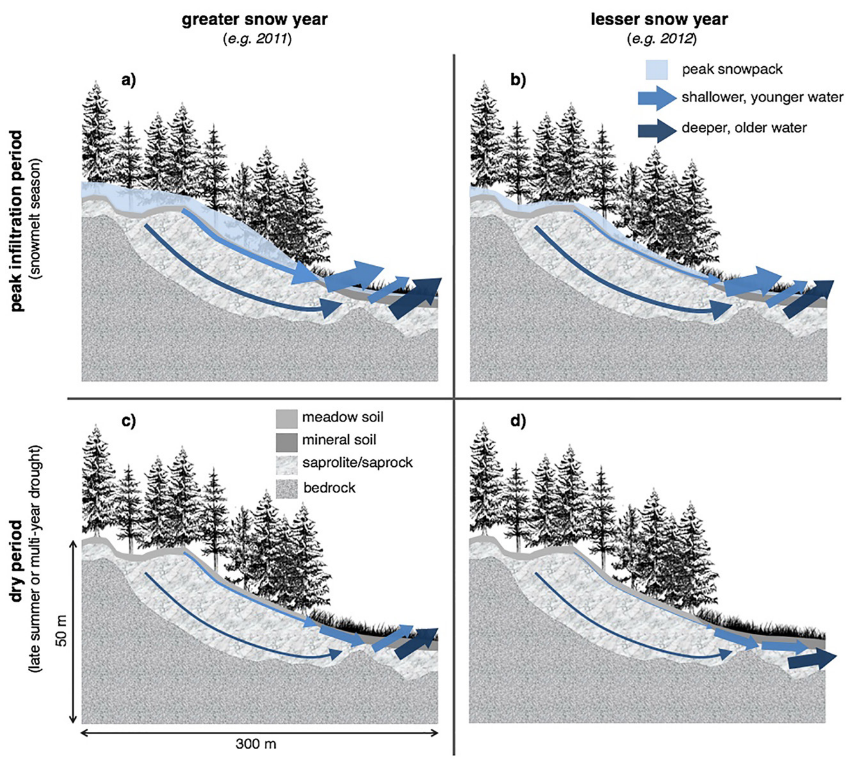

Figure 7. A cross-sectional comparison of hillslope flow pathways between years with greater (a and c) and lesser (b and d) snowpack for both the periods of peak infiltration (a and b) and greater (c) and complete (d) meadow dryness. Subsurface architecture is based directly on findings from Holbrook et al. (2014), where a 2 km s^{-1} seismic velocity threshold has been used by this study and others to decern saprolite from bedrock; with horizontal and vertical scales being approximate and not equal. Arrows depicting water flow paths are meant to be representational of observed processes occurring in the subsurface in different locations of the hillslopes and wet meadow of this study catchment, but are not meant to be exact spatial depictions in cross-section. Larger arrows denote greater hydraulic gradients and more flow, smaller arrows indicate lesser. Light blue indicates shallow, younger water derived of more recent snowmelt and rain water. Dark blue indicates deeper, older water derived from hillslope groundwater (derived from older infiltration of snowmelt and rain into the hillslope saprolite).

4. Discussion

4.1. Seasonal Headwater Partitioning in High Versus Low Snowpack Years

Through a combination of physical data indicating timing and direction of water flow (Figures 2 and 3), and chemical data suggesting water origin and age (Figures 4–6), our results suggest there are two major pathways of water input into the meadow system. The first is a relatively shallower subsurface pathway that contains younger water that resembles snowpack chemistry (and occasionally rainfall). The other is a deeper subsurface source that reflects the chemistry of the older groundwater derived from the surrounding hillslopes (Figure 7). This two-part system of faster, shallower, lateral flow paths, and deeper, slower flow paths is not unique to our site, and has been commonly found in hillslopes across varying climates and landscapes (e.g., Bishop et al., 2011; Newman et al., 1998; Uchida et al., 2005; Whipkey, 1965). The relative contribution of these hillslope sources, and their ability to saturate the surface of the meadow, varies over time and has a strong association with amount of snowmelt input.

In years where more snowpack accumulates in the catchment (e.g., 2011), the shallow hillslope pathway dominates the groundwater discharged into the edge of the meadow during the snowmelt period (Figure 7a) and is comprised primarily of snowmelt-derived water (Figure 6). During this period of peak hillslope infiltration, groundwater discharge to the surface at the meadow center is also high, indicated by hydraulic gradients (Figure 3), but instead of being derived primarily of snowmelt it contains a much higher proportion of deeper groundwater derived from the surrounding hillslopes (Figure 6). As the snowmelt periods ends, and the subsequent dry period arrives, the flow in the shallow pathways subsides significantly, with shallow water moving downwards and laterally at the meadow edge to help produce upward hydraulic gradients. This sustains surface saturation and groundwater discharge in the central regions of the meadow throughout the dry period (Figures 3, Figure 7c).

During years with less precipitation as snow (e.g., 2012), both shallow and deep pathways in the hillslope behave similarly during the period of peak hillslope infiltration (Figure 7b, compared to Figure 7a), though with lower hydraulic gradients (Figure 3). However, these similarities are not maintained as the hillslope and meadow transition into the dry period (Figure 7d, compared to Figure 7c). During these dry periods following a wet season of lesser snow accumulation (or, we assume, a multi-year drought), the meadow no longer can maintain groundwater discharge throughout its center. Deep hydraulic gradients are still moving upwards in the meadow center (Figure 3), but this deeper water sourced from the hillslope groundwater (Figure 6) does not make it to the near-surface within the meadow. Our evidence for this is in the shallow gradients (Figure 3) in the meadow edge and meadow center that are downwards, while the deeper gradients are upwards (Figure 7d), suggesting that flows are moving primarily laterally within the subsurface of the meadow, still supporting the perennial stream observed at the meadow's base, but not allowing groundwater discharge to occur at the surface within the meadow itself during these dry periods.

In Figure 6, we observe the deeper groundwater sourced from the adjacent hillslopes to be continuously input into the deeper sediments at the meadow center, even after an extended dry period, which reinforces the idea that groundwater around the meadow edge is dominated by a shallow, younger sub-surface source and the groundwater in the meadow center is dominated by a deeper, older groundwater source. We argue that this is further reinforced by tritium data, and although we cannot draw strong conclusions from the limited number of tritium samples run for this project (Table S2 in Supporting Information S1) due to limited funding and resources, our results do align with these trends and those depicted in Figure 7. We find water sampled at the meadow center to be more depleted in tritium than water sampled at the meadow edge. Based on this limited tritium analysis, groundwater collected at the meadow center is likely several years older than water collected at the meadow center. This supports the conceptualization of a two-part system with a shallower, younger flow pathway derived of more recent snowmelt and rain, and a deeper groundwater flow pathway derived of older snowmelt and rain that fell farther upslope, which spent longer in its transition through the near-surface saprolite/saprock aquifer as it moved toward the perennial headwater site. These findings regarding two process types dominating hillslope flow paths, one being the shallower, younger flows during peak infiltration periods, and the other being deeper, older flows sustaining dry period flow has been observed before (e.g., Bishop et al., 2011; Newman et al., 1998; Uchida et al., 2005; Whipkey, 1965). Near-surface lateral pipe flow has been studied in hillslopes worldwide, showing how higher transmissivity features in the shallow subsurface can facilitate rapid streamflow generation during precipitation and melt events (Newman et al., 1998; Uchida et al., 2005; Whipkey, 1965). And when travel times are considered in relation to these shallower and deeper hillslope flow pathways, evidence for the transmissivity feedback mechanism (Bishop et al., 2011) demonstrates how high infiltration events saturate the higher transmissivity surficial layers during periods of peak infiltration. This creates rapid lateral flow, since downward percolation is often limited by lower transmissivity deeper in the hillslope, though slower flow pathways in the fractured rock are still important for sustaining baseflow (Anderson, 2002; Montgomery & Dietrich, 1992). Our findings suggest similar process mechanisms, and we can now expand on this understanding by showing how the critical zone architecture of the deeper subsurface can influence where on the landscape these flow paths of varying ages and depths eventually make their way to the surface, and in conjunction with controls from higher versus lower seasonal snowpack years, we can better understand the formation and persistence of surface saturation in headwater meadow systems under a changing climate.

4.2. Role of Critical Zone Architecture on the Location of Perennial Headwater Sites

The hydrology of aquifers supports the assumption that where more impermeable subsurface material rises nearer to the surface, when also down gradient of a subsurface zone of higher permeability and storage, groundwater discharge to the surface can then be forced to occur at the surface as the cross-sectional capacity for subsurface flow is restricted creating reduced lateral transmissivity and saturation overland flow (Dietrich & Dunne, 1993). Therefore, for groundwater discharge to persist year-round, sustaining a perennial stream emanating from this sub-catchment site, even after several years of drought, a significant groundwater reservoir must exist within the sub-catchment or groundwater must be contributed from outside of the sub-catchment. Evidence for a significant subsurface storage reservoir in this sub-catchment is described by Holbrook et al. (2014), a study in which the depth and architecture of weathered bedrock was measured. Using geophysical analysis along a transect within the study site extending from the sub-catchment boundary to the meadow (Figure 7), Holbrook et al. (2014) found unconsolidated materials and weathered bedrock extending down to 10–35 m below ground surface, with the shallowest depth to competent bedrock along the transect being under the meadow edges (Figure 7). In the depiction of the subsurface architecture in Figure 7 the vertical axis has been exaggerated. Of important note in Figure 7 is the reduction in saprolite thickness that occurs at the upper boundary of the meadow. Though surface properties, such as, erosion, climate, and biology can control deep critical zone architecture in many ways (Riebe et al., 2016). Reduction in downslope saprolite thickness from less permeable bedrock (a.k.a. "solid bedrock") rising nearer the surface, or sometimes protruding and existing above the surface as well (e.g., hillslope tors), are not an uncommon feature in mountain environments (Anderson, 2002). Given the prevalence of spatial heterogeneities in saprolite thickness, we argue that these less permeable bedrock features—the "bedrock topography"—helps shape where on the landscape subsurface water is more likely to be forced onto, or near, the surface (Figure 8a), similar to the findings of others looking at the role of bedrock topography (Freer et al., 2002). However, this saprolite thinning cannot act alone in forcing water to the surface. An upslope hydraulic gradient in the subsurface is also required, and for this gradient to persist throughout the dry season or multi-year droughts, like we have found (Figure 7), a contributing upslope area forming a shallow subsurface aquifer of considerable size is needed. Therefore, for any thinning in saprolite in the hillslope architecture to act as a site of groundwater discharge to the surface and a perennial stream source, several factors need to exist: (a) a downslope thinning in saprolite needs to create reduced lateral transmissivity, (b) this reduction in downslope transmissivity needs to be great enough to allow surface saturation to occur year-round, which 3) is dependent on whether the location of thinned saprolite is low enough in the basin for a given rates of upslope precipitation, infiltration, and hydraulic conductivity of the hillslope saprolite aquifer. This perennial headwater site can be occurring with or without an associated wet meadow, with the occurrence of a wet meadow depending on the existence of 4) low angle topography immediately upslope promoting regular near-surface saturation (Figure 8).

Small basins of accumulated sediment frequently co-occur with these perennial groundwater discharge sites that contain wet meadows. We argue that our studied headwater meadow site, and sites similar too it with accumulated colluvium in similar headwater settings, exist where water in-transit down the hillslope transfers from groundwater to surface water due to reduced lateral transmissivity (Freer et al., 2002; Spence, 2010; Spence & Woo, 2003; Tromp-Van Meerveld & McDonnell, 2006). This is further supported by previous research showing that groundwater levels in wet meadows begin to rise in early fall as meadow evapotranspiration subsides, even though fall rains have yet to occur, together suggesting that continuous sources of upslope subsurface input must exist (Wood, 1975). Considering our findings and the findings of previous research from the region (Essaid & Hill, 2014; Lowry et al., 2010; Rodriguez et al., 2017; Wood, 1975), we argue that the presence of deeper unconsolidated sediment underneath our wet meadow site is only co-occurring with the locations of perennial

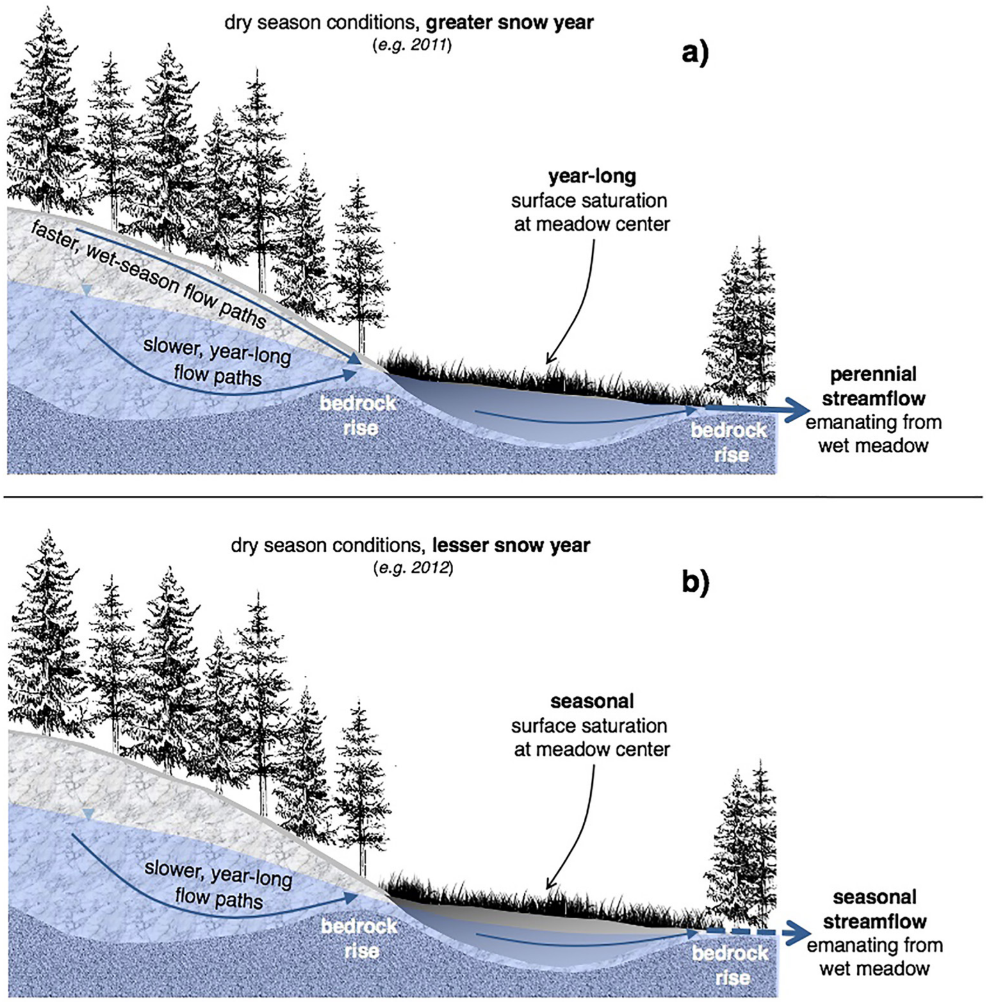

Figure 8. A conceptual model of how downslope thinning of saprolite moderates the influence of snowpack and topography on where perennial versus seasonal surface saturation forms in headwater wet meadows during the summer dry period. Mean annual water table elevation in the hillslope is represented in blue. This conceptual model is built from our data and findings presented in this study, as well as previous findings of hillslope and wet meadow subsurface architecture presented in Wood (1975) and Holbrook et al. (2014).

streamflow generation, and not directly causing perennial streamflow generation to occur. This is reinforced by our physical and chemical findings delineating hillslope pathways during snowmelt and the dry season, discussed above (Figures 7 and 8), which show that dry period and drought-year water (Figure 8b) is primarily sourced from the upslope regolith and not from the meadow aquifer (Figures 3 and 4). Therefore, only because of downslope thinning in saprolite thickness do these lateral subsurface flow pathways then become interrupted and the water pushed to the surface, forming surface saturation during the time of peak infiltration, and a wet meadow environment during high snowpack years (Figure 8a). The occurrence of sediment accumulation basins like these, with near-surface bedrock on both the upslope and downslope ends of the meadow sediment, is common in other mountain meadows observed in cross-section (Wood, 1975). As to why subsequent rises in more competent bedrock co-occur as you move downstream (either stochastically, or as related processes), and why they often form a basin of sediment accumulation like this, are both explanations beyond the scope of this study and are areas in need of additional research for Sierra Nevada. Worldwide above-ground observations of hillslope tors and the associated small scale heterogeneity in bedrock permeability and competence in many mountain settings, particularly with crystalline lithology, may provide insight on the reasons why saprolite thins in the locations that it does. Near-surface geophysical techniques offer one path forward assessing these small-scale changes in bedrock heterogeneity (Holbrook et al., 2014), as do other ways of possibly inferring bedrock characteristics from vegetation patterns (Hahm et al., 2014). Through this integration of data on subsurface architecture, hillslope flow pathways, and long-term changes in terrestrial water fluxes, better prediction can occur of where perennial headwater sites are more likely to persist through extended droughts and further climate change.

5. Conclusions

A combination of physical and chemical data support the findings that these mountain-meadow headwater systems are (a) supported by two primary hillslope pathways for streamflow generation, one being a seasonal, shallower pathway, and the other a deeper, continuous pathway, (b) existing where they are due to thinning in the saprolite aquifer, which (c) creates reductions in lateral transmissivity as water moves downslope in the subsurface, and (d) forcing saturation at the surface, which if common enough, creates the ecological conditions needed for a wet meadow environment to form. Findings from this study suggest that the timing and persistence of these physical processes may be more variable as climate continues to shift away from annually consistent snowpacks. Internal resilience and adaptations may help some ecosystems and their associated services persist temporarily at these sites, but the fundamental cause of many of these issues—primarily the extent of seasonal surface saturation from groundwater—will continue to change as climate warms and seasonal snowpacks continue to decline.

Data Availability Statement

Data produced from this study is available within the supplemental materials, and is published in Bales et al. (2018) and Hunsaker and Safeeq (2017), located at: https://doi.org/10.5194/essd-10-1795-2018 and https://doi.org/10.2737/RDS-2017-0037. This data, and additional data from the same study sites, and similar study sites nearby, can be found via an online data portal located at: https://criticalzone.org/data.

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