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Inferring Hillslope Groundwater Recharge Ratios From the Storage-Discharge Relation

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Key Points:

- Increases in hillslope groundwater storage can be quantified from storage-discharge relations
- Field measurements of groundwater and vadose zone (VZ) storage corroborate seasonality in recharge ratios (recharge per precipitation input)
- Recharge ratio increases with decreasing plant-driven VZ (soil and rock) storage deficits, reflecting spatial variations in storage

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Abstract

Accurate observation of hillslope groundwater storage and instantaneous recharge remains difficult due to limited monitoring and the complexity of mountainous landscapes. We introduce a novel storage-discharge method to estimate hillslope recharge and the recharge ratio—the fraction of precipitation that recharges groundwater. The method, which relies on streamflow data, is corroborated by independent measurements of water storage dynamics inside the Rivendell experimental hillslope at the Eel River Critical Zone Observatory, California, USA. We find that along-hillslope patterns in bedrock weathering and plant-driven storage dynamics govern the seasonal evolution of recharge ratios. Thinner weathering profiles and smaller root-zone storage deficits near-channel are replenished before larger ridge-top deficits. Consequently, precipitation progressively activates groundwater from channel to divide, with an attendant increase in recharge ratios throughout the wet season. Our novel approach and process observations offer valuable insights into controls on groundwater recharge, enhancing our understanding of a critical flux in the hydrologic cycle.

Plain Language Summary

Groundwater in hilly areas is an important source of water. The amount of rainfall that replenishes groundwater storage is known as groundwater recharge. Because groundwater recharge is challenging to measure directly, we applied a technique that makes it possible to use a more readily observable variable—streamflow, or the water flow in rivers and streams—to calculate how much water is stored in the hillslope as groundwater. This made it possible to use streamflow to estimate how much rainfall becomes groundwater recharge. By understanding the structure of the ground and how moisture is distributed, we were able to determine how the amount of recharge changes over the wet season. Our work improves understanding of how rainfall and plant water use affect groundwater recharge, which is important for managing water resources in mountain landscapes.

1. Introduction

Groundwater in upland landscapes generates stormflow and sustains baseflow, serving as a crucial water resource to ecological and municipal systems (Banks et al., 2009; Gburek & Urban, 1990; Salve et al., 2012; Shand et al., 2005). Groundwater recharge to hillslope aquifers must first travel through the overlying vadose zone, which is variably thick, and commonly composed of both soil and underlying weathered bedrock (Hahm, Rempe, et al., 2019; Rempe & Dietrich, 2018). The vadose zone's time varying moisture content mediates how much precipitation becomes groundwater recharge (Hahm et al., 2022; Heppner et al., 2007; Ireson et al., 2009; Rimon et al., 2007). However, the recharge process remains challenging to quantify: boreholes needed for direct observation are sparse and models require difficult to obtain parameters like bedrock hydraulic conductivity or spatially distributed tracer samples from aquifers (Cartwright et al., 2017; Jasechko et al., 2014; Kim & Jackson, 2012). Even when boreholes are available, recharge estimation relies on untested assumptions, such as a gently sloping water table. These challenges contribute to uncertainty in understanding how the precipitation and plant water use patterns that drive moisture dynamics in the vadose zone impact groundwater recharge and groundwater recharge ratios—that is, the fraction of precipitation that becomes recharge.

A promising approach for quantifying recharge relies on stream discharge dynamics as a catchment-integrated signal of water storage dynamics in the hillslopes supplying streamflow (Ajami et al., 2011; Kirchner, 2009). In upland landscapes, soil infiltration capacity typically greatly exceeds rainfall rates, and a reasonable assumption can be made that the hillslope groundwater aquifer is the storage reservoir that is hydraulically connected to and directly drives streamflow (Brutsaert & Nieber, 1977; Carrer et al., 2019; Dralle et al., 2018; Troch et al., 2003;

Wlostowski et al., 2021). Other components of water storage may be dynamic (e.g., water stored in the canopy, vadose zone, or as snowpack), but may not directly affect discharge from the hillslope.

Here, we advance an application of the storage-discharge relationship that enables the quantification of instantaneous hillslope groundwater recharge rates and recharge ratios. By comparing recharge ratios to hillslope storage observations at an intensively monitored site, we demonstrate how critical zone structure, in particular spatial patterns in weathered bedrock thickness and related vadose zone storage properties, explains the seasonal evolution of hillslope groundwater recharge.

2. Methods

2.1. Storage-Discharge and Groundwater Recharge

Stream recession behavior is used to empirically quantify how changes in catchment storage translate into changes in flow (Kirchner, 2009). Following Dralle et al. (2018), we assume that stream discharge (Q [L/T]) is a uniquely defined function of the catchment groundwater storage volume, S_{gw} (previously referred to as "direct storage" by Dralle et al. (2018) or "hydraulic storage" by Wlostowski et al. (2021) and Carrer et al. (2019)), which exclusively drives streamflow generation:

$$Q = f(S_{gw}). \tag{1}$$

The mass conservation equation for the groundwater storage reservoir is:

$$dS_{gw}/dt = R - Q - E_{gw}, \tag{2}$$

where R is a groundwater recharge term, E_{gw} is evapotranspiration sourced from groundwater storage, and Q is stream discharge, which solely originates from groundwater. Flow in streams that is driven by groundwater storage may originate from deeper/slower flowpaths (often called baseflow), or from shallow flowpaths (i.e., shallow subsurface stormflow). Distinguishing these modes of runoff generation is arguably somewhat arbitrary; both describe flow that is likely generated by a single hillslope aquifer, just at different times; "stormflow" when the water table is nearer the ground surface during rainfall events, and "baseflow" when the water table is deeper and draining more slowly between rainfall events. In addition to assuming that Q is sourced from groundwater, we also ignore any potential for inter-basin additions or losses of groundwater.

The key relationship required for linking the readily observable (streamflow) to the hidden (groundwater storage and recharge) is the catchment sensitivity function $g(Q)$, introduced by Kirchner (2009):

$$g(Q) = dQ/dS_{gw} = \frac{dQ/dt}{dS_{gw}/dt} = \frac{dQ/dt}{R - Q - E_{gw}}. \tag{3}$$

This sensitivity function is interpreted as the mathematical sensitivity of discharge to changes in S_{gw}. That is, $g(Q)$ quantifies how much discharge will change for a given change in storage. In general, the sensitivity function is difficult to determine without knowledge of all terms in Equation 3. However, there are times when E_{gw} and R are small relative to Q and thus negligible in the mass balance:

$$g(Q) = dQ/dS_{gw} \approx \frac{-dQ/dt}{Q} \quad \text{when} \quad R, E_{gw} \ll Q. \tag{4}$$

Once determined, the sensitivity function can then be applied during time periods for which recharge and evapotranspiration are not negligible. Kirchner (2009) used this approach to successfully model streamflow, precipitation and storage in a pair of small, groundwater-dominated, humid catchments in the UK. Storage-discharge functions have been applied in numerous hydrological modeling contexts, including a study of net mountain block recharge over a wet season by Ajami et al. (2011). Note that the presented storage term differs from the original formulation of Kirchner (2009), in that here the relevant storage is only the reservoir which drives streamflow (assumed to be groundwater), not the entire dynamic catchment storage, which also includes reservoirs which in some landscapes may not directly drive streamflow, such as snowpack or vadose zone storage. Quantification of the recharge term here also differs from the approach taken by Ajami et al. (2011), who took the difference between inferred storage between two timesteps to quantify the minimum average groundwater recharge rate over an entire wet season. Here, the instantaneous, time-varying recharge term is explicitly solved by re-arranging the mass conservation equation and substituting the sensitivity function for the change in storage when evapotranspiration from groundwater is negligible:

$$\frac{dS_{gw}}{dt} = \frac{dQ/dt}{g(Q)}, \tag{5}$$

$$R = \frac{dQ/dt}{g(Q)} + Q. \tag{6}$$

Equation 6 is mathematically equivalent to Equation 22 in Kirchner (2009), but the physical interpretation of $g(Q)$ as discharge sensitivity to the hillslope groundwater aquifer (rather than total catchment dynamic storage) implies that the inferred flux is groundwater recharge, not precipitation. Evapotranspiration losses from S_{gw} are also assumed negligible, which Kirchner (2009) argues is a reasonable assumption because most recharge will occur during precipitation events when evapotranspiration is depressed.

Once the recharge flux is estimated via Equation 6, recharge ratios can be quantified. Recharge ratios are defined as the volume of recharge divided by the volume of precipitation over a time period (Jasechko et al., 2014). However, it can be challenging to analyze recharge ratios over short timescales. For example, recharge ratios are not defined during precipitation-free periods, and identification of individual storms can be subjective in implementation (Grande et al., 2022, e.g.). To overcome this, it is advantageous to analyze a cumulative form of recharge versus precipitation:

$$R_\Sigma = f(P_\Sigma), \tag{7}$$

where the Σ subscript indicates the running sum of the flux, and where the instantaneous recharge ratio can be calculated as the derivative:

$$\text{Recharge ratio} = \frac{dR_\Sigma}{dP_\Sigma}. \tag{8}$$

The convenience of the cumulative form is that the function $R_\Sigma = f(P_\Sigma)$ is straightforward to smooth over different-sized windows to perform analysis of recharge processes over different timescales (e.g., weekly, monthly, seasonally).

2.2. Field Site

We apply the recharge inference method at an intensively monitored catchment, Elder Creek, where deep drilling and monitoring of vadose zone and groundwater storage dynamics, and documentation of channel-to-ridge weathering patterns in the subsurface CZ, enable process-based interpretation and validation of results. Elder Creek is a 16.8 km^2 catchment in the Eel River watershed in the Northern California Coast Ranges. The regional climate is Mediterranean-type with warm, dry summers and cool, wet winters (most precipitation arrives between November and April). Elder Creek is underlain by the Coastal Belt of the Franciscan Complex, composed of steeply dipping turbidite sequences, volumetrically dominated by argillite (Blake & Jones, 1974; Lovill et al., 2018; McLaughlin et al., 1994). The watershed is vegetated by an old-growth forest consisting of Douglas-fir *Pseudotsuga menziesii*, madrone *Arbutus menziesii*, live oak *Quercus* spp. and tanoak *Notholithocarpus densiflorus*.

The United States Geological Survey (USGS) has conducted discharge monitoring in Elder Creek since 1967. An intensively studied hillslope dubbed "Rivendell" is situated 200 m upstream of the mouth of Elder Creek, and contains a thin soil layer (30–75 cm thick) overlying weathered, fractured bedrock whose thickness varies systematically from about 4 m at the base of the hillslope to over 20 m at the ridge (Oshun et al., 2016; Rempe & Dietrich, 2014; Salve et al., 2012). Fresh, perennially saturated unweathered bedrock lies beneath the weathered bedrock, acting as an aquiclude to meteoric water. This structured critical zone (CZ) establishes a recurring annual cycle of water dynamics, as revealed by field monitoring.

The deep hillslope weathering profiles result in large water storage capacity in the subsurface, most of which is unsaturated storage in a thick vadose zone that includes soil, saprolite, and weathered bedrock. This unsaturated reservoir can hold more than 300 mm of seasonally dynamic water storage, equal to over one quarter of annual wet season precipitation during dry years (Rempe & Dietrich, 2018). This large dynamic storage in the vadose zone is the primary water source for the productive, dense conifer-hardwood evergreen forests found in the Coastal Belt (Hahm, Rempe, et al., 2019).

A typical wet season (October through April) at Elder Creek proceeds as follows. At wet season onset, incoming rains gradually increase moisture content in the upper layers of soil, saprolite, and fractured weathered rock. All incoming precipitation first transits vertically through the unsaturated zone; overland flow is not observed. After approximately 300–600 mm of cumulative seasonal rainfall, the vadose zone's moisture content no longer increases. Additional rainfall likely travels vertically along fractures, recharging a hillslope water table situated upon the underlying fresh bedrock boundary (Salve et al., 2012). Above this boundary, groundwater moves laterally through a network of fractures, eventually reaching the stream via seeps and springs (Lovill et al., 2018). The groundwater reservoir can store upwards of 200 mm of dynamic, drainable groundwater (in addition to the catchment-averaged 300 mm of dynamic storage in the unsaturated soils and rock) that supports year-round cold baseflows and a thriving salmon population (Dralle et al., 2018; Dralle, Rossi, et al., 2023; Rempe & Dietrich, 2018).

2.3. Data Sets

All datasets and code used in this paper are publicly available and hosted in the accompanying data repository (Dralle, Hahm, & Rempe, 2023).

Streamflow in Elder Creek is monitored by the USGS (gauge ID: 11475560). In the storage-discharge analysis, we use flow data from 2017 to 2021, over which time processed groundwater data is available for the Rivendell hillslope. This time period also incorporates a record wet year (2017) and a period of prolonged drought (2019–2021), which should capture any potential contrasting storage patterns resulting from climatic variability.

Rempe and Dietrich (2018) quantified the typical dynamic storage (maximum to minimum amount observed) of the soil via time domain reflectometry probes, and of the weathered bedrock vadose zone using downhole neutron probe. Reported vadose zone storage capacities fall between 200 and 700 mm. Storage capacities that are typically fully depleted at the end of the dry season are subsequently reliably refilled in the wet season (Hahm, Dralle, et al., 2019).

Local precipitation is measured with a Campbell Scientific Model TB4 tipping bucket rain gauge. Average precipitation over the 2017 to 2021 period is 1956 mm.

Groundwater levels are reported for six groundwater wells that penetrate to the depth of fresh bedrock across the Rivendell hillslope, where both vadose zone storage capacity and first seasonal groundwater responses were reported in Rempe and Dietrich (2018). Well positions along the Rivendell hillslope are plotted in Figure 4. Groundwater wells were cased with slotted PVC pipes and instrumented with submersible pressure transducers to monitor water level dynamics. Additional details on installation and instrumentation can be found in Salve et al. (2012) and Rempe and Dietrich (2018).

2.4. Identifying and Applying the Sensitivity Function

To estimate a functional form for $g(Q)$, the flow recession analysis procedures of Kirchner (2009) and Dralle et al. (2018) are followed. Timeseries are resampled to the daily timestep, and the following conditions are imposed to identify data suitable for fitting the sensitivity function: (a) precipitation-free days, (b) days following a dry period of at least a day, (c) days when flows are decreasing ($dQ/dt < 0$), and (d) days that fall from November through March. Conditions (a), (b), and (c) ensure that the sensitivity function is estimated only on days when precipitation and thus recharge are negligible. Although precipitation is only a proxy for recharge, Rempe (2016) showed the average lag-to-peak time between a rainfall event centroid and peak groundwater response is approximately 30 hr across all wells on the Rivendell hillslope. Since groundwater peak storage likely occurs after peak recharge fluxes (e.g., Kirchner et al., 2020), requiring an additional dry day to pass after the cessation of rainfall and the start of the recession analysis is a conservative approach for identifying recession periods with minimal recharge. Condition (d) ensures the sensitivity function is being estimated when evapotranspiration from groundwater is low. It is unlikely that evapotranspiration significantly impacts groundwater storage dynamics during the November - March period. The portion of the vadose zone over which ET-driven storage dynamics are observed is shallower (typically less than 5 m) than the observed depth (typically greater than 5 m) of the groundwater table (Rempe & Dietrich, 2018). Even in the unlikely case that some ET is sourced from groundwater, average flows are >5 mm/day during the November to March period, whereas average potential evapotranspiration (PET, the maximum possible ET rate) is only 1.25 mm/day (Dralle et al., 2018). Put another way, the site is energy limited during the winter months, with a seasonal aridity index (average potential evapotranspiration divided by precipitation from November through March) equal to approximately 0.14. Wlostowski et al. (2021) introduce a method that can account for ET water withdrawals in calculation of the sensitivity function, but the method requires a priori specification of the fraction of ET taken from "hydraulic storage" (the term Wlostowski et al. (2021) use for S_{gw}), which can only be guessed at in most contexts.

Using flow data on days that satisfy conditions (a)–(d), we calculate flow derivatives using a forward difference, and follow the binning and fitting procedure of Kirchner (2009) to obtain a sensitivity function that is quadratic in logs (Equation 9 in Kirchner (2009)):

$$\ln(g(Q)) = \ln\left(\frac{-dQ/dt}{Q}\right) \approx c_1 + c_2 \ln Q + c_3 (\ln Q)^2, \tag{9}$$

with $c_1 = -3.127 \pm 0.014$, $c_2 = 1.439 \pm 0.025$, and $c_3 = 0.063 \pm 0.014$ by polynomial least-squares regression. When using the sensitivity function to infer recharge (Equation 6), there is some extrapolation in Q that is unavoidable (i.e., some values of Q used to evaluate $g(Q)$ fall outside the range of Q values used to determine $g(Q)$), as recession analysis (and thus sensitivity function fitting) cannot be performed during peak flows. However, fit quality is high with $R^2 = 0.98$, and most uncertainty/noise in the regression data occurs for smaller values of Q. Additional methodological details can be found in commented code (that can be run in any web browser) in the accompanying data supplement (Dralle, Hahm, & Rempe, 2023).

3. Results

Figure 1 shows that rainfall occurs before significant groundwater response and recharge are observed. This initial rainfall contributes to vadose zone (VZ) storage, not directly to groundwater recharge. Over the course of the wet season, recharge ratios generally exhibit a gradual increase (blue curve in Figure 2; also visualized in Figure 1a as the relative size of recharge pulses in blue vs. precipitation pulses in gray). Figure 1b shows that in the subsurface, groundwater "awakens" first near the channel, followed by the ridge. Despite the overall gradual increase in groundwater response seen in Figure 2, the system is characterized by high dynamism, with considerable inter-storm variation in recharge ratios. For example, after prolonged dry periods (e.g., the storm on 1 February 2019), recharge ratios appear much lower (R relatively much less than P) than after prolonged wet periods. This observed decline in recharge ratio between storm events can be attributed to evapotranspiration during dry periods, which increases the storage deficit in the upper vadose zone, and potentially to continued inter-storm drainage from the vadose zone into groundwater, which may increase deficits in the lower vadose zone. Consequently, precipitation from the first storm following a dry period primarily serves to replenish vadose zone storage rather than contribute to recharge.

The cumulative formulation of recharge in Figure 2 reveals a steady and inter-annually consistent seasonal increase in recharge ratios (blue curve) with increasing cumulative seasonal precipitation at Elder Creek. Inter-storm variability is not entirely obscured; e.g., as discussed in Figure 1, recharge efficiency temporarily drops after prolonged dry periods, appearing as short, relatively flat runs of points in Figure 2. Additionally, some small negative recharge values (likely numerical error) result in small decreases in the otherwise upward trajectory. Recharge ratios eventually plateau at a value of around 0.8. If all precipitation went to recharge, the recharge ratio would be 1 (and the cumulative trends would be parallel to the 1:1 lines). The difference of 0.2 is likely attributable to interception and inter-storm evapotranspiration (Salve et al., 2012). Similar water year trajectories of cumulative recharge with cumulative precipitation are consistent with prior work that shows that there is a similar year-to-year drawdown of vadose zone storage (due to evapotranspiration) in spite of highly variable winter precipitation (Rempe & Dietrich, 2018), and the observation that seasonal water storage is limited by storage capacity of the subsurface, rather than by the amount of total wet season precipitation (Hahm, Dralle, et al., 2019).

The cumulative precipitation amounts needed for the first significant seasonal response of groundwater at various locations across a hillslope profile (x-axis of Figure 3) align with the independently quantified dynamic storage capacity of the overlying soil and weathered bedrock vadose zone (y-axis of Figure 3). This indicates that water storage deficits in the root zone must be replenished before groundwater recharge can take place (Rempe & Dietrich, 2018).

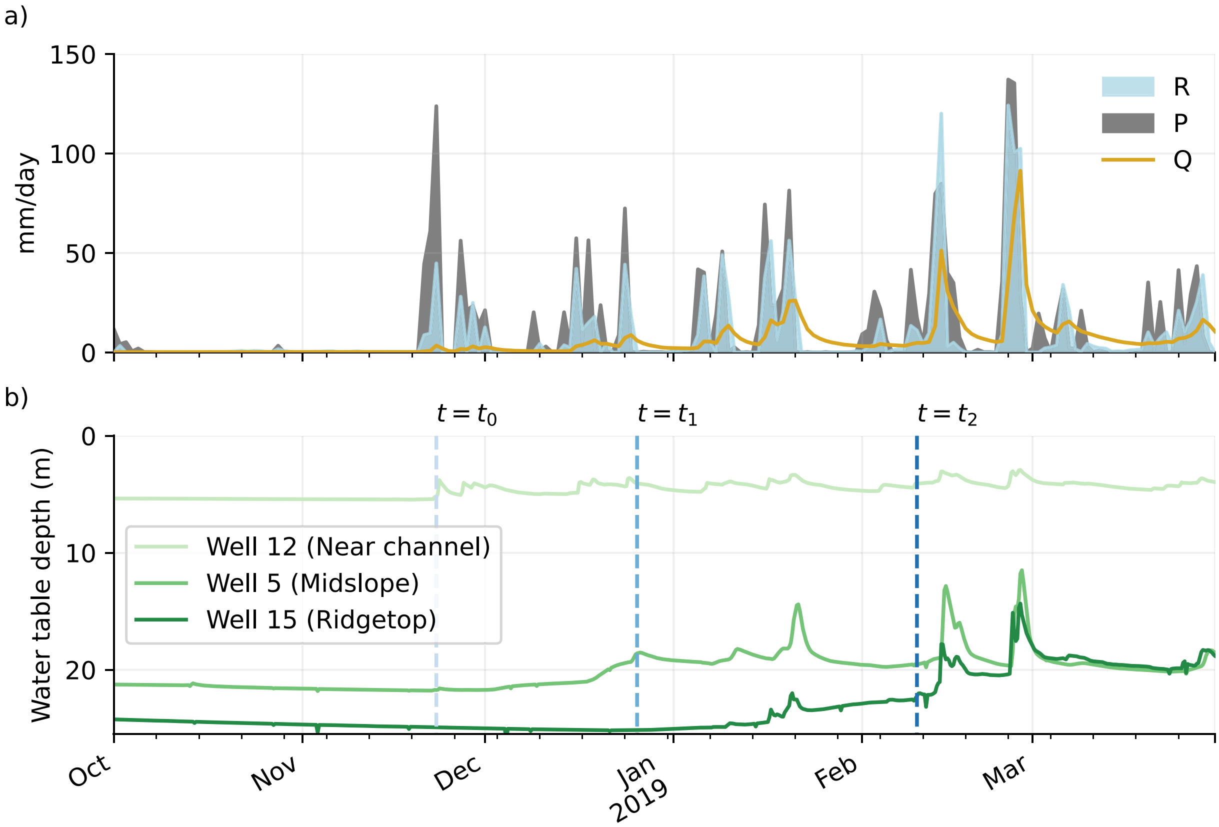

Figure 1. Flow, precipitation, and inferred (positive) groundwater recharge fluxes over the 2019 water year (a). Early season rains do not result in significant recharge because most incoming precipitation is stored in the vadose zone. Groundwater time series at three hillslope positions (b). Near channel groundwater responds fastest due to small vadose zone storage capacity downslope, versus the delayed response at the ridge where storage capacity in the vadose zone is largest. Representative time points (t_0, t_1, t_2) correspond to groundwater profiles in Figure 4.

Furthermore, there is a spatial pattern to the magnitude of deficit that must be replenished, with a steady increase from the channel to the divide (colorbar in Figure 3). As a result, groundwater tables initially respond in the lower parts of the hillslope (e.g., Well 12 is closest to the stream), with groundwater at the ridge (Well 15) responding last.

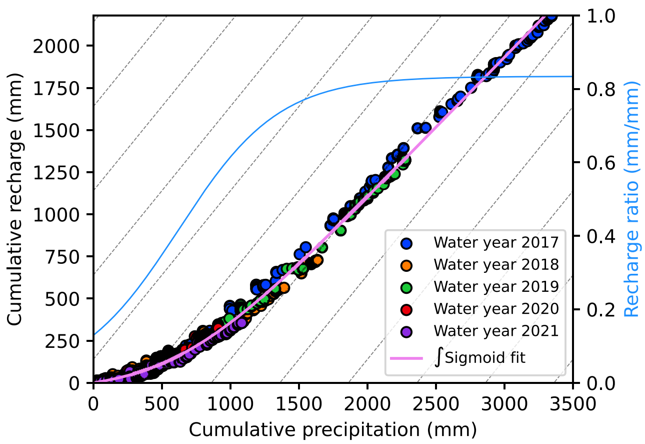

Figure 2. Cumulative recharge plotted against cumulative precipitation for five individual wet seasons (October through April) from 2017 to 2021. The pink curve is the best fit across all years of data, and the blue sigmoidal curve (which is the derivative of the pink curve) is the time-varying recharge efficiency, which steadily increases with increasing cumulative precipitation.

Figure 4 illustrates that the thickness of weathered bedrock (and, by association, the root-zone storage capacity) increases toward the divide. Consequently, over the course of the wet season, the hillslope aquifer is first recharged in downslope positions. At time $t = t_0$, Figure 1 reveals that near-channel Well 12 (mapped in Figure 4) activates before all other wells. With additional seasonal precipitation at time $t = t_1$, mid-slope wells (e.g., Well 5) are activated. Finally, ridge-top groundwater (Well 15) activates last at $t = t_2$. These observations, along with the hillslope profile, offer a process-based explanation for how subsurface critical zone (CZ) structure and spatially varying water storage deficits contribute to a steady, gradual increase in recharge ratios with seasonal cumulative precipitation. This demonstrates how threshold-like processes at a single point can result in gradual phenomena when integrated over space.

4. Discussion

4.1. Approaches for Estimating Groundwater Recharge

Quantifying recharge magnitude and seasonality is crucial for monitoring freshwater sustainability under climate and land-use change (Aeschbach-Hertig & Gleeson, 2012; Foley et al., 2011; Scibek &

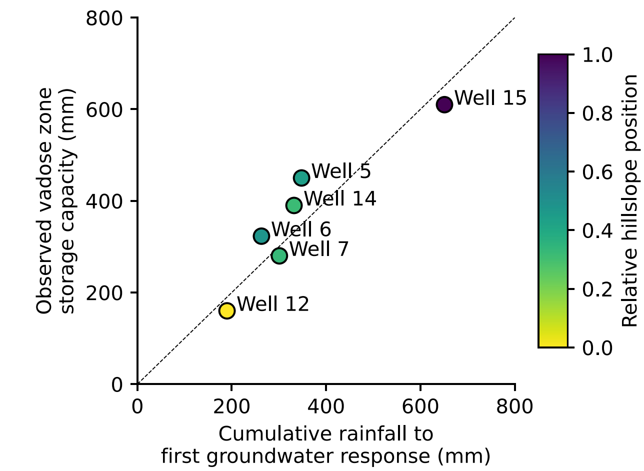

Figure 3. Root zone storage capacity (y-axis) estimated in individual boreholes scales with the cumulative rainfall to first groundwater response (x-axis), as well as hillslope position (colorbar; 1 = ridgetop, 0 = channel). Data taken from Rempe and Dietrich (2018).

Allen, 2006). While precipitation and evapotranspiration are recognized as primary drivers of recharge processes (Kim & Jackson, 2012), most studies have estimated recharge through either process-based hydrological models (Portmann et al., 2013; Wada et al., 2014, e.g.), which prove challenging to parameterize and validate in upland bedrock aquifer landscapes (Mirus & Nimmo, 2013, e.g.), or mass balance-based mixing models and tracers, which necessitate distributed and difficult-to-obtain groundwater isotope estimates (Berghuijs et al., 2022; Jasechko et al., 2014). With some exceptions (Pangle et al., 2014; Jasechko et al., 2014, e.g.), most recharge studies also typically only provide annual or seasonal mean recharge behavior rather than intra-seasonally resolved dynamics. The presented method helps to address some of these challenges; it is computationally simple, accounts for seasonality, avoids complex model parameterization, and relies on (relatively) accessible streamflow data. Although we applied our method to a single, seasonally dry watershed, the cumulative approach (Equation 8) for determining time-varying recharge ratios is adaptable and extendable over flow records of any length. However, the sensitivity function approach for estimating storage-discharge dynamics may not be applicable in certain settings. For example, where ecosystems rely heavily on groundwater storage, vegetation water withdrawals must either be directly estimated or the sensitivity function must be computed when ET is significantly less than Q. In other catchments—for example, semi-arid catchments where Hortonian overland flow is the dominant mode of runoff production—groundwater storage state may not uniquely map to discharge magnitude.

4.2. Process Controls on Recharge Ratios

We proposed a process-based explanation for observed recharge dynamics based on spatial variations in weathered bedrock thickness and plant water use. Although a number of studies have explored threshold mechanisms

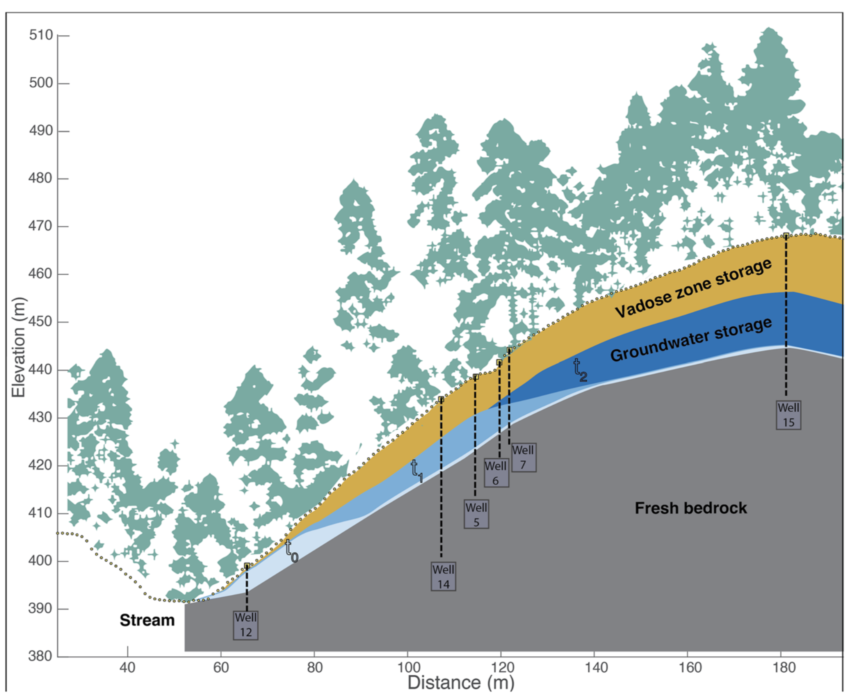

Figure 4. Cross-section reveals structure of the weathering profile along the Rivendell hillslope. Representative time points (t_0, t_1, t_2) correspond to groundwater time series in Figure 1. Green points are LiDAR returns classified as vegetation. Soil is approximately the thickness of the dotted line along the hillslope surface. Fresh bedrock is exposed in the channel and found at approximately 30 m depth at the divide.

for recharge and runoff generation at hillslope and catchment scales (Ali et al., 2015; Lapides et al., 2022; Nanda & Safeeq, 2023; Scaife & Band, 2017; Tromp-van Meerveld & McDonnell, 2006; van Meerveld et al., 2015, e.g.), few have leveraged direct observations of storage dynamics throughout the entire weathering profile to definitively attribute groundwater recharge fluxes (and subsequent flow generation) to storage dynamics in the overlying soil and bedrock vadose zone (Hahm et al., 2022; McNamara et al., 2005; Oshun et al., 2016; Rempe & Dietrich, 2018; Salve et al., 2012). Comparison of time-varying recharge ratio in the Elder Creek watershed to independent measurements of groundwater and vadose zone storage demonstrate that the seasonal evolution of recharge ratio can be explained by spatial variation in weathered bedrock thickness. This upslope thickening (and attendant increase in root zone storage capacity) is likely a common feature of uplands landscapes (Rempe & Dietrich, 2014; Riebe et al., 2017), possibly significantly impacting along-slope rooting patterns (Fan et al., 2017). However, the observed evolution of the recharge ratio throughout the wet season could also occur, for example, under a constant-thickness vadose zone. This would require that the vadose zone drainage rate steadily increases with storage, rather than exhibiting a threshold-like drainage response after deficits are replenished. A uniformly increasing vadose zone drainage efficiency does not appear to be the primary driver of the recharge ratio behavior at Elder Creek, as we would have observed spatially uniform activation of groundwater along the slope. Instead, the initiation of groundwater recharge was shown to be threshold-like, only occurring at a particular hillslope position once vadose zone storage (which varied systematically, increasing from a minimum near the channel to a maximum near the ridge) at that position reached capacity. Because the storage-discharge approach operates on lumped, catchment-integrated discharge which cannot capture spatial variability in the recharge signal, field data are likely needed to discern between different mechanisms leading to temporal variations in recharge ratio. Nonetheless, the recharge ratio shows clear sensitivity to the observed hillslope recharge dynamics. Further research is needed to determine the applicability of these methods in disentangling the influence of spatial heterogeneity in vadose zone properties on groundwater recharge processes.

5. Conclusion

In this study, we advanced an application of the storage-discharge relationship to quantify instantaneous hillslope groundwater recharge rates and recharge ratios. Our findings demonstrate that spatial patterns in weathered bedrock thickness and evapotranspiration-driven water storage deficits can explain the dynamics of recharge ratios. This insight was made possible by a cross-hillslope borehole network for monitoring vadose zone moisture and groundwater. Our research contributes to a better understanding of how precipitation and plant water use patterns, which drive moisture dynamics in the vadose zone, impact groundwater recharge processes in headwater catchments.

Data Availability Statement

All data and code are published in an accompanying repository (Dralle, Hahm, & Rempe, 2023).

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