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Groundwater dominates snowmelt runoff and controls streamflow efficiency in the western United States

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Climate change in seasonally snow-covered mountain catchments is reducing water supply and decreasing streamflow predictability. Here, we use tritium age dating to show that contrary to the common assumption that snowmelt quickly contributes to runoff, streamflow during snowmelt in western US catchments is dominated by older groundwater. The average age of streamwater during snowmelt runoff (5.7 ± 4.3 years) was intermediate to the average age of groundwater (10.4 ± 4.5 years) and recent precipitation, indicating that 58% (±34%) of snowmelt runoff was derived from groundwater. Water ages, streamflow, and groundwater storage were mediated by bedrock geology: low-permeability hard rock/shale catchments exhibited younger ages, less storage, and more efficient streamflow generation than high-permeability sandstone/clastic catchments. Our results demonstrate that snowmelt runoff is the result of multiple prior years of climate mediated by groundwater storage. Including these interactions will be crucial for predicting water resources as climate and landscape changes accelerate.

Snowmelt-driven streamflow and groundwater recharge from mountain watersheds of the western US are the primary water sources for 70 million people across ten states[1,2] and semi-arid regions around the globe[3–9]. In the US, this water supports municipal, industrial, agricultural, hydropower, and natural ecosystems powering a $9.8 trillion economy, trailing only the entire US and China in global economic activity[2]. Air temperatures in these mountain "water towers" are increasing at twice the rate of the globe as a whole[3,8,10,11], resulting in changes in snow fall and snowpack accumulation, ablation, streamflow timing and amount, and atmospheric water demand[12–14]. These ongoing water supply challenges are further exacerbated by a record-setting, two-decade drought in much of the region[15,16].

Compounding the changes in climate are widespread forest mortality due to fire, insects, and droughts. Studies report contradictory responses to these disturbances; both increases and decreases in streamflow have been observed[17,18], suggesting that the processes controlling streamflow response are variable in space and/or time. In contrast, operational water resource models almost uniformly predict that widespread forest mortality increases streamflow[17,18], highlighting the need to determine why models fail to capture observed variability[19]. Further, the western US has one of the fastest-growing populations nationally[1] resulting in new demands from urban and industrial uses as warming temperatures simultaneously increase agricultural water requirements[20]. Policy makers and resource managers working at scales from the Colorado River Basin to regional conservation districts and local agencies are struggling to adapt to these challenges using laws, policies, infrastructure, and operational models developed decades ago[5].

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Central to addressing these challenges is the ability to accurately predict annual and longer-term water supplies to support equitable and efficient management. Surface water supplies in the western US, which enable development and support current populations, originate primarily in high-elevation snowmelt-dominated headwaters comprising 10% to 15% of the region's area[9,16]. Similarly, regional groundwater is sourced from these headwater catchments through mountain block and mountain front recharge[21]. Remote locations, complex terrain, and minimal observing infrastructure led to the development of a water supply predictive framework built on statistical relationships between snowpack at relatively sparse snow course and/or SNOTEL stations and stream gages[22]. Statistically distributed climate data from these observations, combined increasingly with remote sensing[23] have been used to model snow accumulation, ablation, and streamflow. However, historical relationships between climate, snowpack, and streamflow used to develop and evaluate these models are becoming less representative of current and future conditions in the region[14,24].

Substantial effort has been made in obtaining observations and developing physical, process-based models to address the shortcomings in relying on historical relationships, including: developing improved spatial and temporal resolution of near surface mass and energy fluxes[25,26], improved spatial data on snow fall and snowpack[27,28], and increased monitoring and modeling of the influence of soil moisture hydrological partitioning[29,30]. In almost all cases however, these advances in understanding the near-surface climate and environmental forcing have been used to predict surface water supply using simplified models of streamflow generation. Watershed scale models that rely on fast streamflow generation processes (e.g. overland flow and shallow subsurface flow) are ubiquitous in both application and research[6,7,27,29]. The implicit assumptions in these models are that: (1) shallow soil overlies low permeability, near surface bedrock resulting in minimal groundwater storage in mountain catchments and (2) annual water balance closure can be approximated by assuming minimal change in groundwater storage between years[31].

In contrast, a growing body of research from multiple subdisciplines of hydrology, geophysics, and geochemistry suggests that mountain groundwater stores are large and variable[32–40]. For example, widespread observations of hydrochemistry and hydrochemical mixing models suggest potentially large contributions of subsurface water stores during snowmelt runoff[36,37,40]. Similarly, ecohydrological research suggests that mountain groundwater stores are large enough to allow forests to survive multiple, sequential years of drought[41–44]. Related studies suggest that soil moisture alone is not sufficient to support forest growth in mountain systems invoking groundwater subsidy to explain evapotranspiration[33–35], carbon uptake, and biomass accumulation[41–47]. Recently, several studies have identified regionally coherent, quasi-decadal patterns in groundwater storage driven by multiple years of climate[48] and that groundwater storage is positively related to runoff efficiency in the mountains of Utah and the Upper Colorado River Basin[9,48].

Disparate observations from catchment hydrochemistry, ecohydrology, groundwater modeling, and empirical streamflow response to climate all suggest that mountain groundwater stores are potentially large and actively contribute to both streamflow and plant water use. To date however, there have been no consistent, large-scale observations describing how mountain groundwater storage influences snowmelt-derived water resources. The presence of large and variable groundwater storage would represent a fundamental change[49–51] in how we conceptualize and model climate influence on snowmelt-derived water resources. Specifically, this change requires relaxing assumptions of annual water balance closure and developing methods to include antecedent water storage in predictive models. Making this change requires addressing the question: How old is mountain streamflow? This is a prerequisite for predicting how, and over what time scales, mountain hydrology will respond to climate or land use change.

We addressed this question using tritium ($t_{1/2} = 12.32$ yr) in water molecules as a proxy for mean transit times (age dating) and water stable isotopes for inferences on seasonal precipitation contributions to surface and groundwater. We focused our work on 42 catchments throughout the interior western US (Fig. 1) that have been gaged either as part of long-term catchment research studies (28 catchments), by the US Geological Survey (USGS)[9], or by Colorado Division of Water Resources[5]. We collected samples in mid-winter when discharge was low, stable, and both hydrometric and hydrochemical analyses indicate stream water is derived from groundwater storage[36,37] and sampled again during snowmelt runoff in spring and early summer. Following two decades of drought, winter baseflow was at or near record low levels at many of the sites.

Results

Our 42 study catchments represent headwaters of five major western US drainages (Fig. 1). Tritium-derived age data of these samples indicated that the mean age of winter baseflow (groundwater) across all sites was 10.4 (SD = 4.5) years, suggesting that baseflow integrates many years of climate. The mean age of snowmelt runoff was younger than winter baseflow in almost all sites. Perhaps most surprising was the observation that the mean age of snowmelt runoff was 5.7 (SD = 4.3 years), indicating large contributions of longer residence time groundwater to streamflow even during peak runoff. A simple, two-component linear mixing model using tritium units (TU) values in winter baseflow and estimated TU in precipitation as end members indicates that snowmelt runoff is composed of 58 (SD = 34) percent old water (defined as precipitation that fell one or more years before sampling) across these catchments.

Large variability in both baseflow and snowmelt runoff ages led us to evaluate both climate and catchment characteristics as drivers. In spite of a study domain that spans ~1300 km from east to west and ~800 km from north to south with regional differences in elevation, aspect, radiation, and the amount and seasonality of precipitation (SI Table 1), there were no clear differences in either baseflow or runoff ages when comparing the five Hydrologic Unit Code-2 (HUC-2) regions (SI Tables 1 and 2). Somewhat surprisingly, neither baseflow nor runoff ages within or across HUC-2 regions were strongly related to climate, elevation, area, latitude, or longitude. Cluster analysis (log-likelihood = −108.1608, $N = 40$, DF = 4, BIC = −231.0771) of baseflow water ages identified a bimodal distribution (SI Fig. 1a) breaking our dataset into two groups centered around water ages of ~5 and ~14 years, respectively. Consistent with a bimodal age distribution, changepoint analysis on ranked ages indicated a significant change in slope between these peaks at a baseflow age of 8.3 years. In contrast, cluster analysis (log-likelihood = −97.37147, $N = 34$, DF = 2, BIC = −201.7957) on runoff age indicated a unimodal distribution with a right skew (SI Fig. 1b).

Sites with younger baseflow are underlain by hard rock and shale, characterized by low permeability and conductivity. In contrast, sites with older baseflow are underlain by sedimentary and clastic rocks with orders of magnitude higher permeability and hydraulic conductivity (SI Table 3). Catchments underlain by high permeability sedimentary/ clastic geology had significantly ($t^2 = 10.3234$, $p < 0.0001$) older baseflow ($M = 14.0$, SD = 3.0 years) than sites with hard rock/ shale substrate ($M = 6.5$, SD = 1.5 years). Similar to winter baseflow, snowmelt runoff samples from high permeability sedimentary/ clastic catchments ($M = 8.0$, SD = 4.9 years) were significantly ($t^2 = 3.0827$, $p = 0.0036$) older than those from low permeability hard rock/ shale catchments ($M = 3.6$, $SD = 2.4$ years).

Runoff age was significantly ($R^2 = 0.68$, $p < 0.0001$) related to baseflow age at sites with baseflow in high permeability sandstone/ clastic catchments (Fig. 2a). In contrast, there was no correlation between baseflow age and runoff age in low permeability hard rock/ shale catchments. Neither precipitation, aridity, catchment size, nor elevation were significant predictors of water ages within either group (SI Fig. 2). The only significant relationship between climate variables and water age was an inverse relationship ($R^2 = 0.27$, $p = 0.016$) between snow persistence and baseflow age on samples from catchments with high permeability sandstone/clastic geology (Fig. 2b).

Catchment geology also influenced the fundamental partitioning of precipitation to streamflow or evapotranspiration through mediating the age and amount of water storage. Mean annual runoff efficiency, defined as

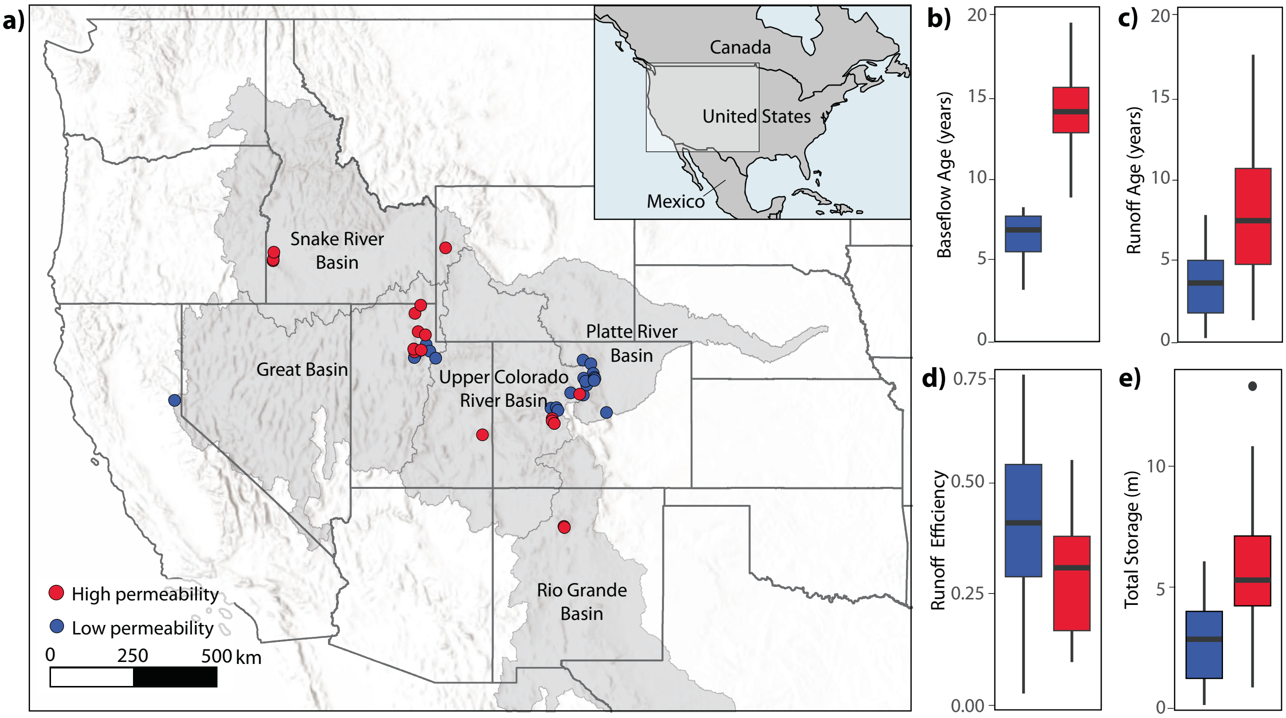

Fig. 1 | Locations and select hydrological characteristics of 42 headwater catchments sampled for this work. Catchments were distributed across five major drainage basins of the intermountain western North America (**a**). Tritium-derived water ages for winter baseflow (**b**) and spring snowmelt (**c**) were older in high permeability sedimentary catchments than in low permeability hard rock/ shale catchments. Mean annual runoff efficiency (**d**) and calculated catchment water storage (**e**). Red and blue points correspond with high- and low-permeability catchment, respectively. Box plots show the minimum, first quartile, median (solid line), third quartile, and maximum values.

the annual volume of streamflow divided by annual volume of precipitation, was inversely related to baseflow age in both hard rock/ shale and sedimentary/clastic catchments (Fig. 3). The negative relationship between baseflow age and runoff efficiency suggests that a larger fraction of precipitation is partitioned to evapotranspiration in sites with longer water residence times and greater storage. The relationship is stronger and the decrease in streamflow with age is steeper in hard rock/shale catchments than in sedimentary/clastic catchments (Fig. 3a). In general, climate (aridity (PET/P) or snow persistence) is more strongly (larger R^2) related to streamflow generation in high permeability sedimentary/clastic catchments than in low permeability hard rock/shale. In contrast, hard rock/shale catchments are more sensitive (steeper slopes) to changes in climate than sedimentary/clastic sites (Fig. 3b, c).

Water stable isotopes also indicated a difference in how precipitation is partitioned in catchments underlain by hard rock/ shale or sedimentary/ clastic substrates (SI Fig. 3). Water samples from low permeability hard rock/ shale sites exhibited a signature consistent with evaporative enrichment relative to the global meteoric water line (GMWL) during both baseflow ($^2H = 6.443{*}^{18}O - 16.05$) and snowmelt ($^2H = 6.705{*}^{18}O - 12.56$). In contrast, water samples from high permeability sedimentary/ clastic sites closely followed the GMWL during winter baseflow ($^2H = 7.790{*}^{18}O + 5.632$) and snowmelt ($^2H = 8.066{*}^{18}O + 11.54$). These relationships suggest that although longer residence time leads to larger total evapotranspiration losses (i.e. lower runoff efficiency) in high permeability sedimentary/clastic catchments, evaporation is a larger fraction of evapotranspiration in low permeability hard rock/shale catchments, possibly due to rapid and/or deeper infiltration in sedimentary/clastic catchments.

The negative relationships between water age and runoff efficiency, combined with stable isotopes of baseflow and snowmelt runoff, suggest considerable overlap in the age distributions of water contributing to streamflow and evapotranspiration. Based on this assumption, calculated catchment water storage in high permeability sedimentary/clastic catchments ($M = 5.82$ m; SD = 3.49 m) is significantly larger ($p = 0.005$; df = 22, t-stat = 3.138) than in low permeability hard rock/shale catchments ($M = 2.78$ m; SD = 1.80 m).

Discussion

Our finding that snowmelt runoff is, on average, 5.7 years old directly contrasts with the majority of research addressing mountain hydrology that assumes annual water balance closure. Although continued advancement in observations and modeling has improved the quantification of the role of water stored as soil moisture on streamflow and evapotranspiration, the time scales of soil moisture storage are days to months with little to no carryover between years, and the volume of water storage primarily is limited by shallow soil depths[6,7,19,30]. The focus on soil water storage is partially due to the long-recognized importance of soil moisture on hydrological processes, but also due to the fact that soils are relatively easy to measure and monitor compared to deeper groundwater. Further, only within the last decade has there been a focus on observing the complex structure of the critical zone between soil surface and bedrock capable of storing water[52–54]. Current operational models primarily rely on parameterizations of soil moisture to predict streamflow using overland flow or fast shallow subsurface flow processes[6,7,30] (Fig. 4a). Undoubtedly, soil moisture is important for hydrological prediction, but the groundwater and streamflow ages observed in this study indicate the storage of much larger volumes than could be held in shallow mountain soils. Streamflow generation, and response to climate or disturbance, in mountain catchments is better represented by a subsurface with greater capacity for water storage (Fig. 4b). Quantifying the volume of actively cycling water within these deeper stores is critical to understanding and predicting hydrologic response to climate change, drought, and land disturbance[8,9,48,53].

Calculated storage volumes are 8.1 times larger than mean annual precipitation in high permeability sedimentary/clastic catchments and 3.4 times larger than mean annual precipitation in low permeability hard rock/ shale catchments. These calculations assume that precipitation is equally likely to contribute to streamflow or evapotranspiration, consistent with a

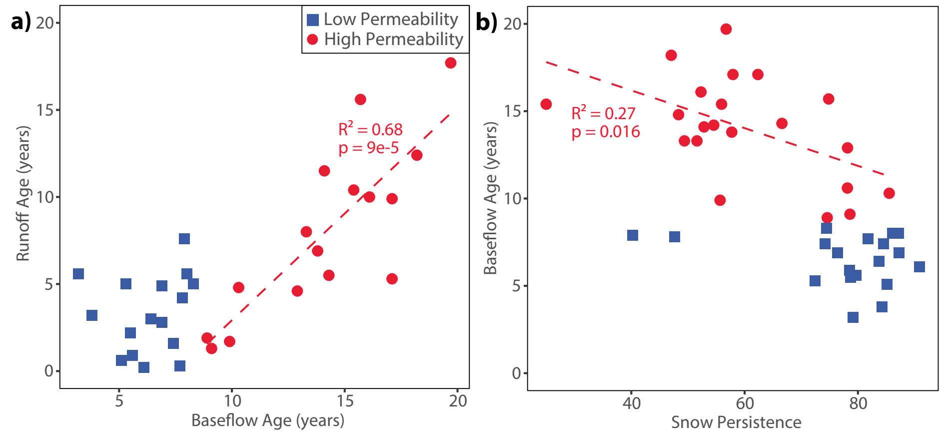

Fig. 2 | Stream water ages and climate. The age of stream water during winter baseflow (groundwater) was significantly ($R^2 = 0.68$, $p < 0.0001$) related to the age of snowmelt runoff in high permeability sedimentary/ clastic catchments (red circles) but not in catchments underlain by low permeability hard rock/ shale geology (blue squares) (**a**). The only climate or landscape variable significantly ($R^2 = 0.27$, $p = 0.016$) related to baseflow/groundwater age was snow persistence in high permeability sedimentary/clastic catchments (red circles) (**b**).

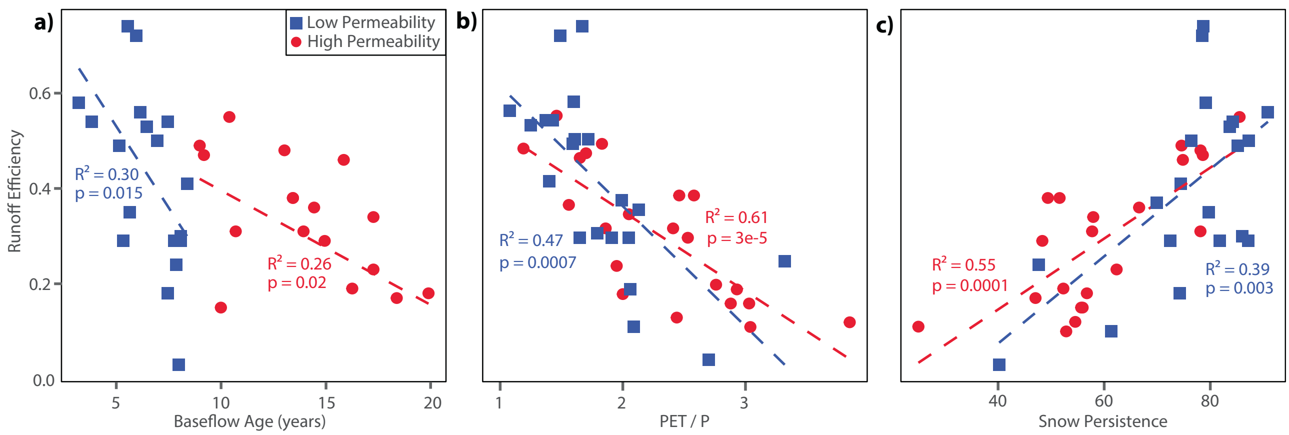

Fig. 3 | Runoff efficiency as a function of baseflow age, climate, and geology. Baseflow age (**a**) is significantly related to mean annual runoff efficiency in both hard rock/shale (blue squares) and sedimentary/clastic catchments (red circles). Catchment geology also mediates runoff efficiency response to both aridity (PET/P) (**b**) and snow persistence (**c**). These climate characteristics are more strongly related to runoff efficiency in sedimentary/clastic catchments (red circles) than hard rock/ shale catchments (blue squares).

growing body of research that suggests considerable overlap in the sources of water contributing to streamflow and evapotranspiration[53,55–57]. Vegetation exhibits plasticity in when and where it obtains water, a fact noted by Horton's observation in 1933[58] that "the natural vegetation of a region tends to develop to such an extent that it can utilize the largest possible proportion of the available soil moisture supplied by infiltration". Other work however suggests a distinction between water sources contributing to streamflow and evapotranspiration with younger water preferentially partitioned to evapotranspiration[40,53]. The mean water ages during baseflow and snowmelt runoff, combined with an inverse relationship between age and runoff efficiency, are consistent with source waters for evapotranspiration and streamflow having substantial overlap. More broadly, this study highlights the need for focused research to accurately quantify how much water is stored in these headwater catchments, where this water is stored, and the drivers of spatial and temporal variability in storage. Although research using stable isotopes of water is beginning to answer these questions[54,55], the ages of water identified here highlight the utility of other tracers, like tritium, to unambiguously determine transit times of more than a season or two.

The water ages and storage volumes calculated here are sufficient for water chemistry to come into equilibrium with subsurface mineral sources, helping to explain why stream chemistry more closely resembles groundwater than recent precipitation, while the difference in water ages and volumes associated with geology provide potential explanations for why hydrochemistry remains variable in time and space[36,37]. Large volumes of actively cycling subsurface water, with mean residence times of several years, also are consistent with recent findings that forests rely on stored water during consecutive years of drought[41–43]. Similarly, forest water status, which often is related in modeling frameworks to soil moisture, is driven instead by atmospheric water demand and unrelated to soil moisture suggesting that plant water sources likely include large contributions from groundwater[44–47]. Inferences that mountain forests depend on stored groundwater are consistent with recent work that documents interannual variability in mountain groundwater storage is positively related to several years of antecedent precipitation and negatively related to antecedent temperature[45]. With both evapotranspiration and streamflow generation linked to multiyear catchment water storage, modeling the time scales of water balance, including both streamflow generation and evapotranspiration will require modeling frameworks capable of representing deeper storage[44,49–53,56,57,59]. An expansion of tritium age and transit time analyses could provide the ages and volumes of stored water to constrain these models that include explicit representations of large and variable groundwater stores in mountain systems, including the potential for groundwater fluxes out of catchments that vary based on geology[32,34,47,50,60,61].

Although much remains to be learned about how and where these catchments store water, our findings have immediate implications for managing mountain water resources. (1) Biannual tritium sampling in winter and during snowmelt could provide water managers with both the age and volume of stored water providing additional calibration metrics to evaluate if and when operational streamflow models are getting the right answer for the right reasons. (2) Similarly, repeat winter tritium sampling

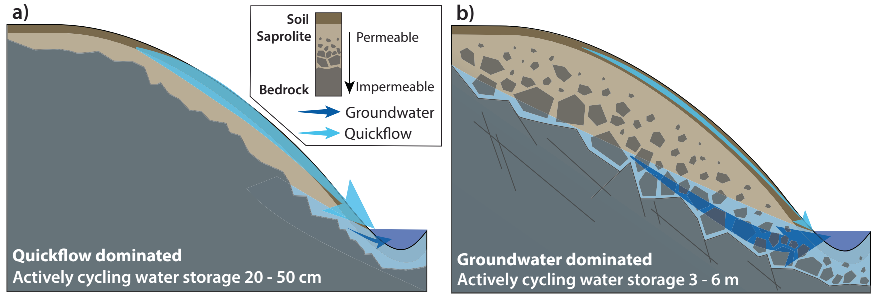

Fig. 4 | Conceptual models of streamflow generation in mountain catchments. Most common conceptual and numerical models of mountain hydrology include a shallow active soil layer (~1 m in depth) capable of storing 20–50 cm of water overlying bedrock with minimal storage (**a**). As shallow soils approach saturation, precipitation or snowmelt is routed quickly to surface water. **b** In contrast, our data support emerging conceptual models of mountain hydrology that include large saprolite and bedrock water storage underlying these soils. Our age dating of baseflow and snowmelt runoff suggests that an order of magnitude more of actively cycling water is stored in these headwater catchments.

could allow resource managers to track groundwater recharge and recovery following drought. (3) The knowledge that streamflow during melt is dominated by groundwater suggests that variability in groundwater storage should be related to interannual variability in runoff efficiency. Our recent work covering 40 catchments in the Great Basin and Upper Colorado Basin demonstrates this relationship by using a simple metric of groundwater storage, obtained during winter baseflow, to reduce uncertainty in streamflow prediction the following spring by ~50%[8,9]. Perhaps most importantly, simple tools based on this information are available months before snowmelt facilitating long-term planning by water managers. We have been providing these tools to local water managers in the Great Basin and are beginning to expand into the Upper Colorado River Basin. (4) Even in the absence of additional water sampling or data collection, resource managers can use the differences in water storage volume, age, and cycling that result from catchment geology to anticipate responses to disturbance. For example, vegetation in hard rock/ shale catchments with lower permeability and total storage may be more sensitive to drought than vegetation in sedimentary/clastic catchments with larger subsurface water storage. These are just a few examples that represent the need and utility of explicitly including multiyear time scales when calculating catchment water balance and managing water resources. All of these examples represent a fundamental change from historical approaches that, often implicitly, assume minimal carryover of water storage from one year to the next.

Methods

Study sites

We sampled 42 catchments across the western US for winter baseflow and snowmelt runoff during the 2022 water year (Fig. 1) including intensively studied catchments with ongoing, active research and long-term U.S. Geological Survey (USGS) and Colorado Division of Water Resources gaging locations. The annual cycle of streamflow in these catchments is typical for montane snowmelt systems with peak discharge in spring and early summer, annual minima in late summer when evapotranspiration is high, a slow rebound in fall and winter as plants senesce, followed by stabilization in mid-winter. Catchments were delineated using geographic information system (GIS) software tools (Esri ArcGIS Pro, hydrology toolset https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/an-overview-of-the-hydrology-tools.htm) using USGS digital elevation models (DEMs) at 10 m resolution. Catchment geological characterizations were obtained from USDA-USGS Mineral Resources (http://pubs.usgs.gov/of/2005/1351/), USGS (e.g. https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html), the Utah Geological Survey (https://geomap.geology.utah.gov/), and the Critical Zone Network (https://criticalzone.org/). Representative permeability and hydraulic conductivity values based on geology were taken from Freeze and Cherry[59].

Sample collection and analysis

All 42 catchments were sampled at least once although logistics of sample collection and transport were challenging with winter access limited by snow and ice, and runoff access limited by high water. Our final dataset included winter baseflow samples from 40 sites and snowmelt runoff from 38 sites. All tritium and stable isotope data are available in SI Table 3 and on Hydroshare (http://www.hydroshare.org/resource/7c29732b61f2414b96188d19748e9054). Winter baseflow samples, collected between December and early March when precipitation is accumulating in the snowpack rather than contributing to soil moisture or streamflow, is indicative of groundwater age. Snowmelt runoff samples were collected between late March and July when discharge was two to three orders of magnitude higher than winter baseflow. Samples were collected in prewashed, pre-rinsed bottles following three rinses with sample water. Water stable isotope samples were collected ensuring no head space.

Samples from 36 of the 42 sites were analyzed in the EarthCore and SIRFER laboratory facilities at the University of Utah. Water stable isotopes were measured using Laser Water Isotope Analyzer (Picarro L2130i Analyzer) and tritium was measured using the ^{3}He ingrowth method to ±0.05 TU[62]. Samples from the additional six locations had stable isotope ratios measured by isotope ratio mass spectrometry at the USGS Reston Stable Isotope Laboratory[63,64] and tritium concentrations measured at the U.S. Geological Survey Menlo Park Tritium Laboratory by electrolytic enrichment and gas proportional counting to ±0.3 TU[65]. Precipitation tritium values were derived from spatial interpolation of measured values[66,67].

Streamflow consists of a spectrum of transit times, the mean of which can be calculated as:

$$\text{age} = \frac{-\text{Ln}\left(\frac{C_{\text{meas}}}{C_{\text{precip}}}\right)}{\lambda} \quad (1)$$

where:

C_{meas} = measured tritium value (TU)

C_{precip} = annual average tritium value in precipitation (TU)

λ = tritium decay constant (0.05626 yr^{-1})[68].

Equation 1 implies that the average annual tritium in precipitation is constant which is approximately true for North America since 2000[69], and the age represents a minimum for waters recharged prior to 2000[70]. Assuming a piston flow model, Eq. 1 approximates the mean for a mixture of ages because the relationship between age and time is approximately linear over 25 years[71].

Climate and streamflow metrics were calculated on a water year basis for the period 2000 through 2022 and are presented as mean annual values. The average period of record for discharge across sites is 17 years. Daily stream discharge data for USGS sites were downloaded from USGS water data dashboard[72]. Daily stream discharge data from Critical Zone research catchments was obtained from HydroShare (https://www.hydroshare.org/search/). Discharge data for Utah research catchments was obtained from Salt Lake City Department of Public Utilities (SLCDPU https://www.slc.gov/utilities/grama/) and from the Logan River Observatory (https://uwrl.usu.edu/lro/data). Water year total precipitation and reference evapotranspiration (ET) were computed from daily gridMET data[73] at 4 km resolution. Snow persistence was calculated as the percentage of days with snow cover from January 1-July 3 at 500 m resolution[74]. For precipitation (P) and potential evapotranspiration (PET) we summed the daily values for each water year and grid cell then extracted the mean water year total values for all grid cells within each drainage area.

We calculated the contribution of stored groundwater to snowmelt runoff using a two-component mixing model of measured TU values in winter baseflow, indicative of groundwater, and estimated TU values in precipitation as end members.

$$\mathrm{f(GW)} = \frac{(TU_{(S)} - TU_{(P)})}{(TU_{(GW)} - TU_{(P)})} \quad (2)$$

where:

$f_{(GW)}$ = the fractional contribution of groundwater to snow-melt runoff

$TU_{(S)}$ = the tritium content of snowmelt

$TU_{(GW)}$ = the tritium content of groundwater from winter baseflow samples

$TU_{(P)}$ = the tritium content of precipitation

We calculated the volume of catchment water storage using the measured ages of snowmelt runoff (SI Table 2) and mean annual precipitation (SI Table 1).

$$\mathrm{S} = \mathrm{P} * \mathrm{Age}_{(s)} \quad (3)$$

where:

S = calculated storage volume (mm)

P = mean annual precipitation (mm)

$\mathrm{Age}_{(S)}$ = tritium-derived age of snowmelt

This calculation assumes a well-mixed storage reservoir that is not increasing or decreasing over the 22 period of record and overlapping residence time distributions for annual streamflow and for evapotranspiration.

We initially calculated basic descriptive statistics for hydroclimate metrics and tritium-derived ages of both baseflow and runoff for the entire dataset in R[75]. Preliminary plots of baseflow age data suggested a bimodal distribution leading us to computed the Hartigan's dip test statistic for unimodality/ multimodality (https://doi.org/10.32614/CRAN.package.diptest) on stream water ages confirming a non-unimodal distribution of baseflow water ages ($D = 0.039474$, p-value = 0.9764). Gaussian finite mixture modeling (https://doi.org/10.32614/CRAN.package.mclust) identified two clusters in baseflow age data (log-likelihood = −108.1608 40; $n = 40$; df = 4; BIC = −231.0771; ICL = −231.8121). Subsequent analysis using a multiple changepoint algorithm PELT with a nonparametric cost function (https://doi.org/10.32614/CRAN.package.changepoint.np) identified a breakpoint at a groundwater age of 8.3 years. Based on these results, we recalculated basic descriptive statistics and performed all subsequent analyses for each grouping individually. The presence of two distinct groups of groundwater ages, associated with fundamental difference in catchment geology, led us to recalculate basic statistics for each catchment type. Differences in individual metrics were analyzed using T-tests assuming unequal variances.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All tritium and stable isotope data are available on Hydroshare (http://www.hydroshare.org/resource/7c29732b61f2414b96188d19748e9054). Daily stream discharge data for USGS sites is available on the USGS water data dashboard (https://dashboard.waterdata.usgs.gov). Daily stream discharge data from Critical Zone research catchments was obtained from HydroShare at listings for individual catchments (https://www.hydroshare.org/search/). Discharge data for Utah research catchments was obtained from the Logan River Observatory (https://uwrl.usu.edu/lro/data) and from Salt Lake City Department of Public Utilities (https://www.slc.gov/utilities/grama/). Catchment climate data were computed from daily gridMET data[73] at 4 km resolution.

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Author contributions

P.D.B. and D.K.S. designed the study. P.D.B. led the analyses and wrote the paper. S.K., S.W., C.B., A.H., G.T.C., H.R.B., K.L., B.N., D.B., and M.S. contributed to data analyses and interpretation of hydroclimatic data. J.C., J.M., R.W.H.C., F.M., and M.W. provided considerable comments and contributed to interpretation.

Competing interests

The authors declare no competing interests.

Additional information

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