Multi-year Controls on Groundwater Storage in Seasonally Snow-Covered Headwater Catchments

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Key Discoveries:

- Interannual changes in groundwater storage inferred from baseflow in 10 headwater catchments exhibit coherent 2-5 and 12-15 year periodicity.
- Interannual variability in groundwater storage is related to 1-4 years of antecedent precipitation (+) snowmelt rate (+) and temperature (-).
- Groundwater storage in warmer/drier catchments is related to longer periods of antecedent climate than cooler/wetter catchments.

Abstract:

Seasonally snow-covered catchments in the western United States supply water to growing populations as both annual snowmelt-driven streamflow and multi-year groundwater recharge. Although interannual variability in streamflow is driven largely by precipitation, runoff efficiency (the ratio of streamflow to precipitation) in individual catchments varies by 50% or more. Recent work suggests that interannual variability in groundwater storage, inferred from winter baseflow, is a primary control on runoff efficiency, highlighting a need to quantify both the time scales on which groundwater storage varies and the hydro-climatic drivers of storage. Using over a century of daily stream discharge data from ten seasonally snow-covered catchments in northern Utah, we find that temporal variability in winter baseflow, an index of groundwater storage, measured from mean daily January discharge, exhibits a 2-5- and 12-15-year periodicity, driven by regional precipitation patterns and snowmelt dynamics. Specifically, multiple linear regression (MLR) modeling using antecedent hydro-climatic variables demonstrates that winter baseflow (groundwater storage) was positively related to 3-4 years of antecedent annual precipitation, negatively related to the previous year's mean annual temperature, and positively related to 1-4 antecedent years of snowmelt rate and duration. Because antecedent baseflow (groundwater storage) is strongly related to runoff efficiency, these results suggest that more frequent and longer droughts in a future climate will reduce surface water supplies faster than otherwise expected. More broadly, these results highlight the importance of including the influence of antecedent climate on groundwater storage when modeling and managing water supplies from seasonally snow-covered catchments.

1. Introduction

Snowmelt from mountainous headwater catchments is the primary water supply for adjacent lowlands in the western United States (Dettinger et al., 2015; Mote et al., 2005; Viviroli et al., 2020). Interannual variability, defined here as the annual change relative to the historic mean, in total annual streamflow is controlled primarily by precipitation, especially winter snowfall (Bales et al., 2006; Harpold et al., 2012; McCabe et al., 2007). Snowmelt-generated total annual streamflow is characterized by high interannual variability, where average snow years can result in significantly below- or above-average annual total streamflow (Bales et al., 2006; Brooks et al., 2021; Miller & Piechota, 2011; Mote, 2006; Woodhouse et al., 2016). Variability in annual total streamflow is expected to increase in a changing climate, as a result of warmer temperatures increasing evaporation and transpiration (Barnett et al., 2005; Goulden & Bales, 2014; Harpold & Brooks, 2018; Sexstone et al., 2018), snowmelt beginning earlier and progressing more slowly (Barnhart et al., 2016; Musselman et al., 2017), and decreasing the fraction of precipitation falling as snow (Barnett et al., 2005; Barnhart et al., 2016; Milly et al., 2018; Mote, 2006; Musselman et al., 2018). Changes in snowmelt rate influence the fraction of precipitation that makes it to streamflow (runoff efficiency) with earlier and slower melt associated with reduced runoff efficiency (Barnhart et al., 2016; Musselman et al., 2017; Painter et al., 2018). Interannual variability in runoff efficiency complicates streamflow prediction, highlighting a need to understand how and why snowmelt-generated streamflow will change in the future (Bryant et al., 2013; Gordon et al., 2022; Milly et al., 2008). Understanding headwater catchment response to climate change is critical in the drought-prone western U.S. (Williams et al., 2022), especially as the population grows and water demand increases (Viviroli et al., 2020).

Recent work indicates that interannual variability in snowmelt dynamics interacts with multi-year cycles of antecedent groundwater storage to control annual runoff efficiency (Brooks et al., 2021). Statistical models incorporating these interactions reduce uncertainty in streamflow prediction to less than 5% (Brooks et al., 2021). Although most models of hydrologic partitioning in headwater catchments assume minimal carryover of storage from year to year, an increasing body of literature indicates that the volume of water stored in headwater catchments may be large (Arnoux et al., 2020; Carroll et al., 2019; Frisbee et al., 2011; McNamara et al., 2011). Hydrochemical analysis suggests that stored water maintains flows before and after seasonal snowmelt (Frisbee et al., 2017; Hayashi, 2020), and buffers or exacerbates how much snowmelt is routed to streamflow (Dierauer et al., 2018; Huntington & Niswonger, 2012; Jefferson et al., 2008). Multiple catchments in the western U.S. exhibit chemostatic behavior, suggesting that the chemical composition of streams change very little (chemostasis) even during peak snowmelt, when a rapid increase in streamflow occurs, the majority of streamflow is still sourced from stored groundwater (Godsey et al., 2009; Kirchner, 2003). Stored water also supports vegetation in arid environments, especially during drought (Christensen et al., 2021; Hahm et al., 2019; Tai et al., 2020). Although both catchment hydrology and ecohydrological research have identified the importance of large and potential variable groundwater storage in headwater systems, research on the effects of climate change on streamflow generation typically does not explicitly consider stored water (Cochand et al., 2019; Dunn et al., 2008; Rodgers et al., 2005; Soulsby et al., 2006).

It is unknown how climate change will specifically influence groundwater storage in individual headwater catchments, critical to streamflow and forest health. This is due in part to the challenges involved with quantifying sub-surface storage in complex topographic terrain in headwater catchments (Kampf et al., 2020). Multiple approaches have been employed to identify the streamflow component derived from stored water, including recession analysis, chemical tracers, mixing models, and physically based hydrologic models (Wittenberg, 1999; Godsey et al., 2009; Miller et al., 2014 ; Carroll et al., 2019; Rumsey et al., 2020). Physical hydrologic models can be used to evaluate dynamic groundwater storage using known periods of low flows representative of a streams' baseflow (Brutsaert, 2008). To quantify historical contributions of stored water to streamflow, physical models that quantify baseflow (measured from streamflow) as a metric to understand groundwater influx to streams, allow for analysis of an extended period of record of dynamic storage variability over time, due to the relatively long records available for daily streamflow measurements compared to other metrics (Brutsaert, 2008; Staudinger et al., 2017; Wittenberg, 1999). Using baseflow as a metric for dynamic groundwater storage, recent studies in the Upper Colorado River Basin suggest baseflow will be reduced due to climate change as a result of decreased input from snow (Miller et al., 2021). These findings suggest that variability in baseflow is controlled by regional climate forcings (Chikamoto et al, 2020). However, there is still high uncertainty on what specific climate factors lead to above or below average groundwater storage (baseflow) and how these factors may vary under differing climatic and geologic settings.

We address what specific hydro-climatic factors control changes in groundwater storage using over a century of streamflow data from ten snowmelt-dominated catchments in Northern Utah with the same regional climate but with variable mean annual temperature, total precipitation, and runoff efficiency across a range of geologic regimes. We ask, how has groundwater storage in these headwater catchments, inferred from winter baseflow, varied over the last century? And what are the hydro-climatic factors that control variability of groundwater storage, inferred from winter baseflow, within a catchment?

2. Data and Methods

2.1 Study Sites

Ten snow-dominated headwater catchments of the Jordan and Weber Rivers in northern Utah (Figure 1) were selected for the study based on the length of the streamflow measurement record and minimal diversions and impoundments. These catchments are uniquely suited to address our questions, having a relatively long period of record (between 76 and 118 years), especially for montane environments; they have similar climate regimes relative to other intermountain catchments, each with distinct precipitation and temperatures driven by elevation and other geographic factors. Distributed across the Wasatch and Uinta Mountains of northern Utah, the ten catchment areas range from 19 to 643 km^{2,} with mean elevation ranging from 1963-2759 m (Table 1). Seven catchments contain tributaries of the Jordan River (J) including: City Creek (J C.C.), Red Butte Creek (J R.B.), Emigration Creek (J E.C.), Parleys Creek (J P.C.), Mill Creek (J M.C.), Big Cottonwood Creek (J B.C.), and Little Cottonwood Creek (J L.C.). Three headwater tributaries were selected from the Weber River, including the South Fork of the Ogden River (W O.S.), Chalk Creek (W C.C.), and the Weber Headwaters at Oakley (W O.). These catchments represent the diverse watersheds found throughout the intermountain western U.S. characterized by relatively cool and wet winters with hot and dry summers (Harpold et al., 2012; McCabe et al., 2018). Spatial variability in precipitation is high where Uinta Mountain catchments (although higher elevation) receive less precipitation than Wasatch Mountain catchments due to orographic placement out of line/ in alignment with storm tracks. The 10 catchments are lithologically and structurally complex with bedrocks ranging from Precambrian quartzites and shales to Tertiary igneous intrusions. The annual cycle of streamflow in these catchments is typical for snowmelt systems, with peak discharge in spring during snowmelt, reduction in streamflow in late summer when evapotranspiration is high, followed by relatively stable flows in mid-winter (Bales et al., 2006; Frisbee et al., 2011). These tributaries are major water sources to either Salt Lake City Public Utilities (SLCDPU) or the Weber Basin Water Conservancy District (WBWCD), together providing water for over 1 million residents in northern Utah.

2.2 Hydro-climate data

Historical monthly mean precipitation(mm) and air temperature (°C) were extracted from 4km resolution grids developed by the Parameter-elevation Regression on Independent Slopes Model (PRISM) climate record (PRISM Climate Group, 2018) from 1901-2018. Gridded PRISM data were clipped to the boundary of each catchment, then the catchment average for each metric was calculated. Monthly precipitation and temperature data were aggregated to the annual timestep. Daily streamflow records were obtained from SLCDPU 2018 (https://www.slc.gov/utilities/grama/) or the United States Geological Survey (USGS, 2018) (https://waterdata.usgs.gov/ut/nwis/). Daily streamflow discharge was converted from ft^3/s to mm/day, giving a one-dimensional unit normalized to the watershed area, facilitating comparisons between precipitation and stream discharge and between catchments. All streamflow and climatic metrics were calculated on a water year basis (October 1st-September 30th). Annual runoff efficiency (RE), also termed fractional water yield, was calculated by dividing total annual discharge (Q (mm/year)) by total annual precipitation (P (mm/year)). Variability was presented as either standard deviation from the mean (SD), coefficient of variation (CV; SD/mean), or standardized to a z-score by subtracting the mean and dividing by the standard deviation to compare values between catchments. Long term trends are analyzed using linear regression, and change points are detected using Pettitt change point analysis (Pettitt, 1979).

2.3 Statistical Analysis and Processing

A change in winter baseflow (ΔWBF) calculated using mean daily streamflow in January in mm/day from each year is used as an index of interannual variability in groundwater storage. Daily streamflow discharge in mid-winter in these snowmelt dominated streams are typically low and steady, (SD ≤ 0.03) (SI Figure 1), with very little influence from rain, or episodic melt, with mean catchment January temperatures ranging from(-3°C to -7°C). We assume here that these mid-winter (January) steady flows are an index of antecedent catchment groundwater storage. A broad range of studies infer groundwater storage from baseflow (Brooks et al., 2021; Cooper et al., 2018; Miller et al., 2014; Rumsey et al., 2020; Safeeq et al., 2014) and here we are using baseflow to infer the relative change from year to year in groundwater storage. To address the few instances where January rains occur or episodic melt occurs, each year was screened and in the event of high daily variability (SD>0.03 from mean), that year's value was removed. Additional years were removed if daily streamflow went to zero, indicative of ice dams or gage malfunction. Between 3 and 11 years were removed from each catchment. W C.C. (3 years removed), J E.C. (6 years removed), J P.C.(6 years removed), J R.B. (3 years removed), J M.C. (6 years removed), W O.S. (11 years removed), J C.C. (6 years removed), J B.C. (5 years removed), W O. (3 years removed), J L.C.(4 years removed). We acknowledge here that the daily fraction of streamflow composed of baseflow will vary throughout the year, however we do not address variable baseflow contributions to the stream throughout the year.

Periodicity in winter baseflow was analyzed using wavelet power analysis, which identifies periodicity in a data set using Morelet wavelet analysis. Wavelet analysis quantifies the amplitude and frequency of positively correlated wave signals over a time series. We used the Roesch and Schmidbauer, WaveletComp: Computational Wavelet Analysis in R (Roesch and Schmidbauer, 2018). Statistical significance was evaluated using *t* tests assuming one degree of freedom per water year.

2.4 Derived variables

We considered antecedent hydro-climatic influence on Δwinter baseflow at a wide range of temporal scales, including seasonal and annual variability from up to 10 years in the past. The following metrics were calculated: antecedent fall precipitation (F.P.) (total precipitation from October-December), annual total precipitation (P), mean annual temperature (T), snowmelt rate (M.R.), and snowmelt duration (M.D.). Each of these variables were standardized to a z-score.

Snowmelt rate and snowmelt duration were calculated using the start and end date of bulk seasonal snowmelt attenuated in the stream hydrograph. This approach is consistent with a multitude of studies inferring melt timing and duration from stream hydrographs (Cayan et al. 2001, Clow. 2010, Stewart et al., 2005). The start of the snowmelt was identified when the daily stream hydrograph deviated distinctly from winter baseflow conditions. This distinct deviation was quantified using a threshold metric (equation 1), which addresses when the snowmelt signal exceeds daily winter baseflow variability.

$$Threshold = \frac{\sigma Q_b}{Peak\ Q - Q_b} \tag{1}$$

Where σQ_b is the mean standard deviation of winter baseflow across all years, Peak Q is the mean peak discharge across all years, and Q_b is the mean of winter baseflow across all years in the given watershed. The threshold value explains the potential variability associated with winter streamflow; threshold values range from 0.01 (J C.C.) to 0.03 (J M.C.). The threshold value of 0.03 was determined to be the value that was applicable in every catchment as it included all lower threshold values as well (Brooks et al, 2021). This threshold indicates that daily discharge is greater than 3% of the difference between the peak discharge of that year ($Peak\ Q(n)$) and baseflow for that year ($Q_b(n)$) ensuring that the snowmelt controlled phase of the hydrograph was elevated above baseflow conditions. Snowmelt start was calculated using equation (2)

$$Q_d > Q_b(n) + (Threshold * (Peak\ Q(n) - Q_b(n))) \qquad (2)$$

where Q_d is daily streamflow, Qb is baseflow, Threshold = 0.03, $Peak\ Q$ is annual peak discharge, and n is water year. The day of snowmelt start was calculated as the first day when the snowmelt onset equation (equation 2) is satisfied for the first day of a 25 consecutive day period in which each subsequent day also is above the threshold value. Snowmelt end date was calculated when the slope (rate of change) of the falling limb of the hydrograph decreased from a rapidly declining slope to a flat slope, identifying the end of the snowmelt runoff phase of the hydrograph, where streamflow begins to transition back to baseflow conditions. The falling limb of the hydrograph was smoothed using a Savitsky-Golay filter from the Matlab 'smooth' function. The Savitsky-Golay filter fits 2nd degree polynomials to the data using least-squares regression. Then a change point test (Killick et al., 2012) was used to find the point where the slope of the falling limb of the hydrograph (from peak flow until end of water year) changed the most significantly, indicating a return to baseflow conditions (Cayan et al., 2001; Painter et al. 2018). Snowmelt duration was calculated as the day of melt start subtracted from the day of melt end.

Snowmelt rate was calculated using equation 3.

$$Snowmelt\ Pulse\ Rate = \frac{melt\ volume}{melt\ pulse\ duration} \tag{3}$$

Snowmelt volume is the summation of daily streamflow, normalized for catchment area, during the snowmelt season in millimeters, yielding snowmelt rate in units of mm/day. Because snowmelt rate and duration are correlated with the total winter snowpack, we calculated normalized snowmelt rate (normMR) and duration (normMD). We normalized these values by taking the linear regression between winter precipitation (December-March) and snowmelt rate and duration. We took the residual value of each individual year from the regression to normalize for the influence of snow input, and restrain the relative fast or slow snowmelt rate, or the long or short snowmelt duration attenuated in the stream hydrograph (SI Figure 2).

Using the metrics described above, we evaluated the individual control that each previous year (up to 10 years in the past) had on the annual change in catchment groundwater storage, quantified using a change in winter baseflow between years indicated as ΔWBF(wy), where (wy) represents the water year when winter baseflow is predicted. A change in winter baseflow for each year was predicted using a multiple linear regression (MLR) model. We included Fall P(wy), antecedent precipitation P(wy-i), antecedent temperature T(wy-i), antecedent normMR(wy-i), and antecedent normMD(wy-i), where i denotes the lag in year. For example P(wy-2) means that total annual precipitation from two water years previous was included as a control. The multiple linear regression model used to predict ΔWBF(wy) includes antecedent hydr-climatic variables whose regression coefficients (β) can be distinguished from zero at the 95% confidence level. To measure how well our model predicts changes in winter baseflow, we compared the observed ΔWBF with the predicted ΔWBF.

3. Results

Mean annual precipitation across catchments ranged from 558mm/year (W C.C.) to 1293mm/year (J L.C.); mean annual temperature ranged from 2.6°C (W O) to 6.9°C (J R.B.); mean annual discharge ranged from 94mm/year (W C.C.) to 807mm/year (J L.C.); mean annual runoff efficiency (RE) ranged from 0.17(W C.C.) to 0.62 (J L.C.) (Figure 2; Table 1). Interannual precipitation variability within each catchment was consistent across the study area (CV= 0.2) (Table 1). Streamflow in each catchment was characterized by a seasonally driven pulse from spring snowmelt, with annual peak streamflow occurring from April-June, receding in July-August, and returning to baseflow conditions through the fall and winter. Each catchment's total annual streamflow displayed high interannual variability (CV=0.3-0.7) (Table 1).

Mean winter baseflow across ten sites ranged from 0.08 to 0.51 mm/day (28.8-184.9 mm/year) (Figure 2; Table 1). Winter baseflow was not significantly correlated with either precipitation or temperature in January in seven of the ten catchments (SI table 2). Small, statistically significant correlations were observed between January precipitation and winter baseflow in J B.C. ($r^2 = 0.05$; $p = 0.02$) and W.O. ($r^2 = 0.03$; $p = 0.05$), and between January temperature and winter baseflow in J B.C. ($r^2 = 0.03$; $p = 0.05$) and J M.C. ($r^2 = 0.05$; $p = 0.03$) (SI Table 2). Interannual winter baseflow varied significantly over the last century (CV = 0.2-0.7) (Table 1). Mean winter baseflow was positively correlated with the long-term mean annual catchment precipitation, where wetter catchments had higher winter baseflow compared to drier catchments ($r^2 = 0.75$; $p < 0.001$) (Figure 3). In contrast, winter baseflow was not significantly correlated with mean annual temperature, although warmer catchments generally had lower winter baseflow than colder catchments (Figure 3).

Winter baseflow exhibited temporally coherent long-term variability over the last century across all sites (SI Figure 3). Wavelet analysis revealed two primary peaks in periodicity, one from 2-5 years (wavelet power= 0.23) and a second at 12-15 years (wavelet power= 0.29) (Figure 4), wavelet power values describe the correlation intensity between peaks. The 2-5-year periodicity (p = 0.1) was observed over the entire century, and the 12-15 year periodicity was statistically significant (p = 0.05) from 1960-2002 (Figure 4). Inter-annual variability in winter baseflow was significantly and positively related to annual changes in runoff efficiency across all catchments (slopes ranging from 0.45 to $.76$ with $p<0.001$)(SI Table 3). In warmer (mean annual T> °6) and drier (mean annual P <900mm/year) catchments, runoff efficiency is more sensitive Δwinter baseflow(slope>0.6) compared to cooler (mean annual T< °6), and wetter catchments (mean annual P >900mm/year) (SI Figure 4).

MLR models demonstrated that inter-annual variability in winter baseflow values were significantly related to a number of antecedent hydro-climatic variables over the previous four years ($0.29 \leq r^2 \leq 0.87$; $p<0.05$) (Figure 5; Table 2). Winter baseflow was significantly related to the concurring water year's fall precipitation (9/10 catchments), 1- 4 years of antecedent precipitation (all catchments), 1-3 years of previous snowmelt rate and/or duration (9/10 catchments), and 1 year of antecedent temperature (8/10 catchments) (Table 2). No catchment exhibited significant relationships between hydro-climatic variables and a change in winter baseflow more than four years in the past. In addition, the strength of the relationship decreased as the number of years previous increased. These results informed our model to only include antecedent hydro-climatic variables from up to 10 years prior. The number of variables retained as significant in each regression ranged from as few as two (J L.C.) to as many as 10 (J C.C.) (Table 2, SI Figure 5). The strongest predictors of Δwinter baseflow in all catchments was the concurring year's fall precipitation (β= 0.14-0.56), the previous year's annual precipitation (β= 0.14-0.57), or the previous year's melt rate (β= 0.07-0.44) (Table 2).

The MLR models better predicted Δwinter baseflow in lower-runoff efficiency, warmer, and drier catchments, (r^2>0.70 for W C.C., J P.C., J R.B., J M.C.) than in higher-runoff efficiency, cooler, and wetter catchments (0.70>r^2> 0.46 (W O.S., J C.C., J B.C., W.O., and J L.C.) (Table 2). In catchments with higher predictiability (W C.C., J P.C., J R.B., J M.C.) bedrock geology is primarily sedimentary (carbonates and clastics) in W C.C., J P.C., J R.B., J M.C., and higher number of antecedent variables are included in these regressions. In catchments with fewer number of variables included in the MLR, and lower predicitability of Δwinter baseflow, catchment bed rock geology includes igneous (intrusive) bedrock, such as in J.L.C. which has only 2 antecedent predictors (antecedent Fall P and antecedent total annual precipitation from 1 year prior). There was no significant relationship between area or elevation and Δwinter baseflow predictabilty. J E.C. was an exception to this overall pattern. Although J E.C. is relatively low elevation, warm and dry with a low runoff efficiency =0.18, and sedimentary bedrock, predictability of Δwinter baseflow was low (r^2=0.29) compared to catchments with similar climate regimes (Table 2).

4. Discussion

4.1 Periodicity in winter baseflow

In headwater catchments in Northern Utah, we found a coherent pattern of inter-annual variability in catchment groundwater storage inferred from winter baseflow over the last century. The century long 2-5 year periodicity (p-val = 0.10) and half century long 12-15 year periodicity (p-val = 0.05) observed in Δwinter baseflow suggest that the inter-annual variability in catchment storage associated with mountain precipitation inputs are susceptible to change and respond to climatic variance on timescales longer than one water year. Regional patterns in precipitation on 12-15 year time scales have been identified for Northern Utah and the Great Basin driven by Interdecadal Pacific Oscillation (**Wang**s et al. 2010, Wang et al. 2012, **Wise 2010**). Wise 2010 also highlights that Northern Utah falls within the transition zone of El Nino Southern Oscillation (ENSO) influence on precipitation, where some years ENSO leads to high precipitation and other years ENSO has little influence on precipitation. The shifting of this transition phase on weather ENSO has a relative impact on precipitation in Northern Utah is modulated by PDO (Pacific Decadal Oscillation, and AMO (Atlantic Multi-Decadal Oscillation). Tree ring records suggest this 12-15 year periodicity has been present for 500+ years in the region (DeRose et al. 2014). Masbruch et al. 2016 link observed 11-13 year variability in valley groundwater in Northern Utah from 1960-2013 to the 12-15 year precipitation anomalies identified for Northern Utah. The relatively shorter periodicity observed at 2–5-year timescale in mountain catchments has yet to be identified, however most catchments exhibit significant relationships to antecedent hydro-climate up to four-years prior. Tracking the dynamics of groundwater storage in mountain environments is rare (McNamara et al., 2011) even though recent studies highlight that variable change in headwater catchment storage explains a large portion of year-to-year variability in annual runoff efficiency (Arnoux et al., 2020; Brooks et al., 2021; Carroll et al., 2019; Hayashi, 2020). Previous studies have identified physical characteristics that may control spatial differences in catchment storage, including (but not limited to) catchment geology and topography that control flow path routing and depth of permeation (Aishlin & McNamara, 2011; Dailey, 2016; Hood & Hayashi, 2015; McNamara et al., 2011; Rumsey et al., 2020). In contrast, relatively few studies quantify interannual temporal changes in individual catchment storage beyond soil moisture (Hayhoe et al., 2007; Wooldridge et al., 2003). Other studies specifically highlight the climatic controls on low flows, specifically within one water year, highlighting the importance of wintertime precipitation and summertime evaporative demands on storage (Cooper et al., 2018; Godsey et al., 2014; Goulden & Bales, 2014).

4.2 Mechanisms supporting how catchment storage predispose catchments for high/low runoff efficiency

The geologic, topographic, and physical characteristics of a catchment are essential to understand differences in catchment runoff efficiency, recharge amount, and groundwater storage size, these factors will likely remain stable on human time scales; however, climate is expected to continue to change (Dettinger et al., 2015; Nogués-Bravo et al., 2007) with impacts on catchment storage (Price, 2011). Consecutive wet/dry periods will result in increased/ decreased baseflow conditions and subsequently control runoff efficiency on a timescale longer than one water year. The mechanisms underlying the strong, statistical relationships between antecedent winter baseflow and runoff efficiency are unknown, but are consistent with the growing body of hydrochemical research that suggests headwater catchments are able to store and rapidly release large volumes of water (Neal et al., 1997, Neal and Kirchner 2000,, Kirchner 2003, Godsey et al., 2009). For example, J RB is a USGS hydrologic benchmark location (Cobb and Biesecker, 1971) which exhibits chemostatic behavior during snowmelt (Godsey et al., 2009). Specifically, the concentrations of solutes derived from host rock weathering in streamflow changes very little while streamflow varies several orders of magnitude indicative of large amounts of stored ground or subsurface water. The relationship between antecedent winter baseflow, our index of stored groundwater, and runoff efficiency suggests that as the amount of storage changes the sources and routing of snowmelt to streamflow change. Potential mechanisms underlying these changes include preferential routing of melt to subsurface storage when antecedent storage is low, similar to fill and spill (McDonnell et al, 2021, Tromp van Meerveld et al, 2015), transmissivity feedbacks resulting in greater flow through near surface soils with higher hydraulic conductivity when storage is high (Bishop et al., 1990), more rapid soil saturation and increased overland flow when storage is higher (Wu et al., 2021), or greater activation of piston pumping or macropore flow (Detty and McGuire (2010)) when storage is higher. These mechanisms are not exclusive however but all suggest that a greater fraction of incoming snowmelt being partitioned to storage when antecedent catchment storage is low, and increased runoff efficiency when storage is high.

4.3 Climatic Controls on Winter Baseflow:

4.3.1 Antecedent Precipitation Controls on Δwinter baseflow

Our findings that fall precipitation is related to Δwinter baseflow across all catchments is consistent with recent work indicating that fall precipitation is more readily partitioned to recharge than evapotranspiration compared to spring or summer precipitation (Dailey, 2016; Goodrich et al., 2000; Rungee et al., 2018). The fall season in semiarid catchments is typically when plants senesce, energy availability decreases as the sun angle gets lower and temperatures decrease. Fall season decreases in plant activity result in reduced atmospheric demands for water (Rungee et al., 2018). The decrease in evaporative/atmospheric demand may allow for precipitation to more readily be partitioned to stored water rather than to the atmosphere, increasing winter baseflow.

We find that multiple years of antecedent precipitation (of which the majority falls as snow) are positively and significantly related to above or below average winter baseflow up to 4 years later. This is consistent with past work suggesting that seasonal snowmelt contributes to both streamflow generation (Julander & Clayton, 2018; Liu et al., 2008; Miller et al., 2020; Mote et al., 2018) and groundwater recharge (Arnoux et al., 2020; Carroll et al., 2019; Cochand et al., 2019; Dailey, 2016; Schilling et al., 2021). Other work in the region suggests that the 12-15 year patterns observed in winter baseflow are also observable in the Northern Utah Valley/ Great Basin groundwater levels measured from the 1960-2013. This study found that five large groundwater recharge events were identified with a frequency of about 11–13 years driven by above-average annual precipitation (Masbruch et al. 2016). The patterns observed in the first half of the century vs the second and the regional climatic drivers of these patterns remain un-explained. Our findings suggest that faster/slower snowmelt rates from 1-4 years in the past increases/decreases winter baseflow. The number of years important to controlling ∆winter baseflow varies from catchment to catchment, where ∆winter baseflow in cooler and wetter catchments is typically controlled by climatic conditions on shorter timescales (1-2 years), and warmer and drier catchments respond at a 3-4 year timescale. We also observe that in cooler and wetter catchments, year to year changes in runoff efficiency are controlled to a lesser degree by changes in winter baseflow, suggesting that runoff efficiency in these catchments may respond to climate at a faster timescale with annual precipitation primarily being routed to streamflow in that water year. Despite mean winter baseflow values typically being higher in cooler and wetter catchments (Figure 3), their relative influence on runoff efficiency is smaller (SI Figure 2).

4.3.2 Antecedent Temperature Controls on Δwinter baseflow

Under future climate scenarios, temperatures are expected to continue to increase, especially in mountain environments which are expected to warm at two to three times the average rate of warming during the 20th century (Christensen et al., 2021; McCabe et al., 2007; Nogués-Bravo et al., 2007). In 7/10 catchments, temperature is negatively and significantly related to Δwinter baseflow. These findings suggest that if the previous year's mean annual temperature was above/below average, the following water year's Δwinter baseflow was below/above average. Increasing temperatures will lead to increasing evapotranspiration (evaporation and transpiration), decreasing both recharge and discharge (Christensen & Lettenmaier, 2007; Christensen et al., 2004; Cooper et al., 2018; Goulden & Bales, 2014; Miller et al., 2021; Miller & Piechota, 2011; Milly et al., 2018; Rungee et al., 2018). Similar to these findings, we suggest that in warmer years/ warmer catchments, seasonal precipitation will preferentially partition to atmospheric water demands, rather than to recharging groundwater storage. In the two coolest and wettest catchments (J L.C. and W.O.), antecedent temperature is not related to Δwinter baseflow and in J B.C., temperature is positively related to Δwinter baseflow. These three catchments (J B.C. J L.C., W.O.), where higher antecedent temperatures do not reduce Δwinter baseflow, have the highest annual and winter precipitation, highest runoff efficiency, the mean elevation is over 500m higher than other catchments, and are characterized by host rocks consisting of Precambrian quartzites and Tertiary igneous intrusions while other catchments are underlain by sedimentary and clastic bedrock (Brooks et al. 2021). Presumably, the combination of colder, wetter conditions, shorter growing seasons, and limited storage resulting from subsurface geology give rise to shorter climatic memory in these catchments.

4.3.3 Antecedent Snowmelt Dynamics Controls on WBF

We found that faster antecedent snowmelt rates result increased winter baseflow in all catchments except for J L.C. This finding is supported by recent research, in which Barnhart et al. (2016) suggest that faster melt rates allow for greater infiltration below the root zone of plants, leading to a greater fraction of snowmelt partitioned to streamflow generation or recharge as opposed to evapotranspiration. Many studies suggest that under future/ warmer climate scenarios, snowpack ablation (snowmelt + sublimation) will likely start earlier and extend over a longer period (Barnhart et al., 2016; Musselman et al., 2017; Regonda et al., 2005), as a result of increasing energy input into snowpacks. This shift in timing of snowmelt may lead to increasing atmospheric vapor transport and reduced partitioning of the snowpack to recharge/storage (Biederman et al., 2014; Carroll et al., 2019; Dailey, 2016; Earman et al., 2006; Gustafson et al., 2010; Harpold & Brooks, 2018; Hood et al., 1999; Petersky & Harpold, 2018; Pomeroy et al., 1998).

4.3 Spatial Trends across catchments

Our findings suggest that multi-year cycles of Δwinter baseflow will become more important to regulating runoff efficiency as the climate warms because in warmer and drier catchments, Δwinter baseflow typically plays a larger role in buffering/exacerbating runoff efficiency increases/decreases (SI Figure 2), and Δwinter baseflow is controlled over longer timescales in these catchments. In a warmer and more variable precipitation future, cooler and wetter catchments may see higher year-to-year variability associated with direct seasonal snowpack inputs. ΔWinter baseflow may buffer streamflow to a larger degree than expected; however, without multiple years of above-average snow accumulation, storage contributions to streamflow will decrease (Barnett et al., 2005; Marshall et al., 2019). Warming may also reduce

Δwinter baseflow volumes in the future through 1) increased evapotranspiration (Goulden & Bales, 2014; Rungee et al., 2018) and 2) changes in snowmelt rates (Barnhart et al., 2016). Longer-term declining trends in winter baseflow may be more apparent under changing climate conditions, specifically during long-term drought scenarios observed in the last two decades in the western U.S. (Udall & Overpeck, 2017). Long term reductions in winter baseflow will reduce runoff efficiency over time.

5. Conclusions

In our study of northern Utah headwater catchments, we observed a consistent periodicity in catchment groundwater storage based on changes in winter baseflow, despite differences in climate, elevation, and catchment specific-geology. We found that a shorter 2-5 year periodicity is influenced by hydro-climatic variability from up to four years in the past, while a longer 12-15 year periodicity is driven by previously identified regional precipitation anomalies.

Using multiple linear regression (MLR), we examined how antecedent precipitation, snowmelt rate, and temperature affect interannual variability in winter baseflow as an indicator of groundwater storage. Our results show that groundwater storage is more sensitive to these factors over longer timescales (up to four years) in warmer and drier catchments, with groundwater storage primarily affected by the previous 1-2 years of antecedent conditions in cooler and wetter catchments. We also discovered that changes in groundwater storage have a greater impact on runoff efficiency in warmer and drier catchments. These findings highlight the influence of groundwater storage on streamflow generation over several years, with a potential for an increasingly important role in moderating or reducing streamflow in a warmer future.

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Open Research:

All data used in these analyses are freely available either from PRISM Climate Group, Oregon State University (https://prism.oregonstate.edu/), United States Geological Survey(USGS) (https://waterdata.usgs.gov/ut/nwis/), or Salt Lake City Department of Public Utilities (SLCDPU) (https://www.slc.gov/utilities/grama/).

References

Aishlin, P., & McNamara, J. P. (2011). Bedrock infiltration and mountain block recharge accounting using chloride mass balance. *Hydrological Processes*, *25*, 1934-1948. https://doi.org/10.1002/hyp.7950

Arnoux, M., Halloran, L. J. S., Berdat, E., & Hunkeler, D. (2020). Characterizing seasonal groundwater storage in alpine catchments using time-lapse gravimetry, water stable isotopes and water balance methods. *Hydrological processes*, *34*(22), 4319-4333. https://doi.org/10.1002/hyp.13884

Bales, R., C., Molotch, N., P., Painter, T., H., Dettinger, M., D., Rice, R., & Dozier, J. (2006). Mountain hydrology of the western United States. *Water resources research*, *42*(8), W08432-n/a. https://doi.org/10.1029/2005WR004387

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303-309. https://doi.org/10.1038/nature04141

Barnhart, T. B., Molotch, N. P., Livneh, B., Harpold, A. A., Knowles, J. F., & Schneider, D. (2016). Snowmelt rate dictates streamflow. *Geophysical research letters*, *43*(15), 8006-8016. https://doi.org/10.1002/2016GL069690

Biederman, J. A., Harpold, A. A., Gochis, D. J., Ewers, B. E., Reed, D. E., Papuga, S. A., & Brooks, P. D. (2014). Increased evaporation following widespread tree mortality limits streamflow response. *Water resources research*, *50*(7), 5395-5409. https://doi.org/10.1002/2013wr014994

Bishop, K.H., Grip, H. and O'Neill, A., (1990). The origins of acid runoff in a hillslope during storm events. *Journal of Hydrology*, 116: 35~31. https://doi.org/10.1016/0022-1694(90)90114-D

Brooks, P. D., Gelderloos, A., Wolf, M. A., Jamison, L. R., Strong, C., Solomon, D. K., . . . Stewart, J. (2021). Groundwater-Mediated Memory of Past Climate Controls Water Yield in Snowmelt-Dominated Catchments. *Water resources research*, *57*(10), n/a. https://doi.org/10.1029/2021WR030605

Bryant, A. C., Painter, T. H., Deems, J. S., & Bender, S. M. (2013). Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin: DUST IN SNOW IMPACT ON STREAMFLOW. *Geophysical research letters*, *40*(15), 3945-3949. https://doi.org/10.1002/grl.50773

Carroll, R. W. H., Deems, J. S., Niswonger, R., Schumer, R., & Williams, K. H. (2019). The Importance of Interflow to Groundwater Recharge in a Snowmelt-Dominated Headwater Basin. *Geophysical research letters*, *46*(11), 5899-5908. https://doi.org/10.1029/2019gl082447

Chikamoto, Y., Wang, S. Y. S., Yost, M., Yocom, L., & Gillies, R. R. (2020). Colorado River water supply is predictable on multi-year timescales owing to long-term ocean memory. *Communications earth & environment*, *1*(1), 1-11. https://doi.org/10.1038/s43247-020-00027-0

Christensen, L., Adams, H. R., Tai, X., Barnard, H. R., & Brooks, P. D. (2021). Increasing plant water stress and decreasing summer streamflow in response to a warmer and wetter climate in seasonally snow-covered forests. *Ecohydrology*, *14*(1), n/a. https://doi.org/10.1002/eco.2256

Christensen, N. S., & Lettenmaier, D. P. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and earth system sciences*, *11*(4), 1417-1434. https://doi.org/10.5194/hess-11-1417-2007

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. *Climatic change*, *62*(1-3), 337-363. https://doi.org/10.1023/b:clim.0000013684.13621.1f

Clow, D. W. (2010). Changes in the Timing of Snowmelt and Streamflow in Colorado. *Journal of Climate* 23.9, 2293-306 https://doi.org/10.1175/2009JCLI2951.1

Cobb, E. D., Biesecker, J.E. (1971). The national hydrologic bench-mark network. USGS report, Circular 460-D https://doi.org/10.3133/cir460D

Cochand, M., Christe, P., Ornstein, P., & Hunkeler, D. (2019). Groundwater Storage in High Alpine Catchments and Its Contribution to Streamflow. *Water resources research*, *55*(4), 2613-2630. https://doi.org/10.1029/2018wr022989

Cooper, M. G., Schaperow, J. R., Cooley, S. W., Alam, S., Smith, L. C., & Lettenmaier, D. P. (2018). Climate Elasticity of Low Flows in the Maritime Western U.S. Mountains. *Water resources research*, *54*(8), 5602-5619. https://doi.org/10.1029/2018WR022816

Dailey, K. R. (2016). Streamflow and groundwater response to precipitation variability in a snow-dominated, subalpine headwater catchment, Colorado Rocky Mountains, USA. In: ProQuest Dissertations Publishing.

DeRose, R. J., Wang, S.-Y., Buckley, B. M., & Bekker, M. F. (2014). Tree-ring reconstruction of the level of Great Salt Lake, USA. *The Holocene*, *24*(7), 805–813. https://doi.org/10.1177/0959683614530441

Dettinger, M., Udall, B., & Georgakakos, A. (2015). Western water and climate change. *Ecol Appl*, *25*(8), 2069-2093. https://doi.org/10.1890/15-0938.1

Detty, J. M., and McGuire, K. J. (2010). Threshold Changes in Storm Runoff Generation at a Till-mantled Headwater Catchment. *Water Resources Research* 46.7 https://doi.org/10.1029/2009WR008102

Dierauer, J. R., Whitfield, P. H., & Allen, D. M. (2018). Climate Controls on Runoff and Low Flows in Mountain Catchments of Western North America. *Water resources research*, *54*(10), 7495-7510. https://doi.org/10.1029/2018WR023087

Dunn, S. M., Bacon, J. R., Soulsby, C., Tetzlaff, D., Stutter, M. I., Waldron, S., & Malcolm, I. A. (2008). Interpretation of homogeneity in δ18O signatures of stream water in a nested sub-catchment system in north-east Scotland. *Hydrol. Process*, *22*(24), 4767-4782. https://doi.org/10.1002/hyp.7088

Earman, S., Campbell, A. R., Phillips, F. M., & Newman, B. D. (2006). Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States. *J. Geophys. Res*, *111*(D9), D09302-n/a. https://doi.org/10.1029/2005JD006470.

Frisbee, M. D., Phillips, F. M., Campbell, A. R., Liu, F., & Sanchez, S. A. (2011). Streamflow generation in a large, alpine watershed in the southern Rocky Mountains of Colorado: Is streamflow generation simply the aggregation of hillslope runoff responses? *Water Resour. Res*, *47*(6), n/a. https://doi.org/10.1029/2010WR009391

Frisbee, M. D., Tolley, D. G., & Wilson, J. L. (2017). Field estimates of groundwater circulation depths in two mountainous watersheds in the western U.S. and the effect of deep circulation on solute concentrations in streamflow: GROUNDWATER CIRCULATION DEPTHS. *Water resources research*, *53*(4), 2693-2715. https://doi.org/10.1002/2016WR019553

Godsey, S. E., Kirchner, J. W., & Clow, D. W. (2009). Concentration – discharge relationships reflect chemostatic characteristics of US catchments. *Hydrological Processes*, *1864*, 1844- 1864. https://doi.org/10.1002/hyp

Godsey, S. E., Kirchner, J. W., & Tague, C. L. (2014). Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA. *Hydrological processes*, *28*(19), 5048-5064. https://doi.org/10.1002/hyp.9943

Goodrich, D. C., Scott, R., Qi, J., Goff, B., Unkrich, C. L., Moran, M. S., . . . Ni, W. (2000). Seasonal estimates of riparian evapotranspiration using remote and in situ measurements. *Agricultural and forest meteorology*, *105*(1), 281-309. https://doi.org/10.1016/S0168-1923(00)00197-0

Gordon, B. L., Brooks, P. D., Krogh, S. A., Boisrame, G. F. S., Carroll, R. W. H., McNamara, J. P., & Harpold, A. A. (2022). Why does snowmelt-driven streamflow response to warming vary? A data-driven review and predictive framework. *Environ. Res. Lett*, *17*(5), 053004. https://doi.org/10.1088/1748-9326/ac64b4

Goulden, M. L., & Bales, R. C. (2014). Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. *Proc Natl Acad Sci U S A*, *111*(39), 14071-14075. https://doi.org/10.1073/pnas.1319316111

Gustafson, J. R., Brooks, P. D., Molotch, N. P., & Veatch, W. C. (2010). Estimating snow sublimation using natural chemical and isotopic tracers across a gradient of solar radiation. *Water Resources Research*, *46*(12). https://doi.org/10.1029/2009WR009060

Hahm, W. J., Rempe, D. M., Dralle, D. N., Dawson, T. E., Lovill, S. M., Bryk, A. B., . . . Dietrich, W. E. (2019). Lithologically Controlled Subsurface Critical Zone Thickness and Water Storage Capacity Determine Regional Plant Community Composition. *Water resources research*, *55*(4), 3028-3055. https://doi.org/10.1029/2018WR023760

Harpold, A. A., Brooks, P. D., Rajagopal, S., Heidbuchel, I., Jardine, A., & Stielstra, C. (2012). Changes in snowpack accumulation and ablation in the intermountain west. *Water resources research*, *48*(11), n/a. https://doi.org/10.1029/2012wr011949

Harpold, A. A., & Brooks, P. D. (2018). Humidity determines snowpack ablation under a warming climate. *Proc Natl Acad Sci U S A*, *115*(6), 1215-1220. https://doi.org/10.1073/pnas.1716789115

Hayashi, M. (2020). Alpine Hydrogeology: The Critical Role of Groundwater in Sourcing the Headwaters of the World. *Ground Water*, *58*(4), 498-510. https://doi.org/10.1111/gwat.12965

Hayhoe, K., Wake, C. P., Huntington, T. G., Luo, L., Schwartz, M. D., Sheffield, J., . . . Wolfe, D. (2007). Past and future changes in climate and hydrological indicators in the US Northeast. *Climate dynamics*, *28*(4), 381-407. https://doi.org/10.1007/s00382-006-0187-8

Hood, E., Williams, M., & Cline, D. (1999). Sublimation from a seasonal snowpack at a continental, mid-latitude alpine site. *Hydrological Processes*, *13*(12-13), 1781-1797. https://doi.org/10.1002/(SICI)1099-1085(199909)13:12/13<1781::AID-HYP860>3.0.CO;2-C

Hood, J. L., & Hayashi, M. (2015). Characterization of snowmelt flux and groundwater storage in an alpine headwater basin. *Journal of hydrology (Amsterdam)*, *521*, 482-497. https://doi.org/10.1016/j.jhydrol.2014.12.041

Huntington, J. L., & Niswonger, R. G. (2012). Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: An integrated modeling approach: SW AND GW INTERACTIONS ON STREAMFLOW. *Water resources research*, *48*(11). https://doi.org/10.1029/2012WR012319

Jefferson, A., Nolin, A., Lewis, S., & Tague, C. (2008). Hydrogeologic controls on streamflow sensitivity to climate variation. *Hydrol. Process*, *22*(22), 4371-4385. https://doi.org/10.1002/hyp.7041

Julander, R. P., & Clayton, J. A. (2018). Determining the proportion of streamflow that is generated by cold season processes versus summer rainfall in Utah, USA. *Journal of Hydrology: Regional Studies*, *17*, 36-46. https://doi.org/https://doi.org/10.1016/j.ejrh.2018.04.005

Kampf, S. K., Burges, S. J., Hammond, J. C., Bhaskar, A., Covino, T. P., Eurich, A., . . . Willi, K. (2020). The Case for an Open Water Balance: Re-envisioning Network Design and Data Analysis for a Complex, Uncertain World. *Water resources research*, *56*(6), n/a. https://doi.org/10.1029/2019WR026699

Killick, R., Fearnhead, P., & Eckley, I. A. (2012). Optimal Detection of Changepoints With a Linear Computational Cost. *Journal of the American Statistical Association*, *107*(500), 1590-1598. https://doi.org/10.1080/01621459.2012.737745

Kirchner, J. W. (2003). A double paradox in catchment hydrology and geochemistry. *Hydrological Processes*, *17*(4), 871-874. https://doi.org/10.1002/hyp.5108

Liu, F., Bales, R. C., Conklin, M. H., & Conrad, M. E. (2008). Streamflow generation from snowmelt in semi-arid, seasonally snow-covered, forested catchments, Valles Caldera, New Mexico. *Water Resour. Res*, *44*(12), W12443-n/a. https://doi.org/10.1029/2007WR006728

Marshall, A. M., Abatzoglou, J. T., Link, T. E., & Tennant, C. J. (2019). Projected Changes in Interannual Variability of Peak Snowpack Amount and Timing in the Western United States. *Geophysical research letters*, *46*(15), 8882-8892. https://doi.org/10.1029/2019GL083770

Masbruch, M. D., Rumsey, C. A., Gangopadhyay, S., Susong, D. D., & Pruitt, T. (2016). Analyses of infrequent (quasi-decadal) large groundwater recharge events in the northern Great Basin: Their importance for groundwater availability, use, and management. Water Resources Research, 52(10), 7819-7836. https://doi.org/10.1002/2016WR019060

McCabe, G. J., Clark, M. P., & Hay, L. E. (2007). Rain-on-Snow Events in the Western United States. *Bulletin of the American Meteorological Society*, *88*(3), 319-328. https://doi.org/10.1175/bams-88-3-319

McCabe, G. J., Wolock, D. M., & Valentin, M. (2018). Warming is Driving Decreases in Snow Fractions While Runoff Efficiency Remains Mostly Unchanged in Snow-Covered Areas of the Western United States. *Journal of hydrometeorology*, *19*(5), 803-814. https://doi.org/10.1175/JHM-D-17-0227.1

McDonnell, J. J., Spence, C., Karran, D. J., van Meerveld, H. J., & Harman, C. J. (2021). Fill-and-Spill: A Process Description of Runoff Generation at the Scale of the Beholder. *Water resources research*, *57*(5), n/a. https://doi.org/10.1029/2020WR027514

McNamara, J. P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N. E., . . . Hooper, R. (2011). Storage as a Metric of Catchment Comparison. *Hydrol. Process*, *25*(21), 3364-3371. https://doi.org/10.1002/hyp.8113

Miller, M. P., Susong, D. D., Shope, C. L., Heilweil, V. M., & Stolp, B. J. (2014). Continuous estimation of baseflow in snowmelt-dominated streams and rivers in the Upper Colorado

River Basin: A chemical hydrograph separation approach. *Water resources research, 50*(8), 6986-6999. https://doi.org/10.1002/2013wr014939

Miller, O. L., Miller, M. P., Longley, P. C., Alder, J. R., Bearup, L. A., Pruitt, T., . . . McKinney, T. (2021). How Will Baseflow Respond to Climate Change in the Upper Colorado River Basin? *Geophysical research letters*, *48*(22), n/a. https://doi.org/10.1029/2021GL095085

Miller, S. A., Lyon, S. W., & Miller, S. N. (2020). Quantifying contributions of snowmelt water to streamflow using graphical and chemical hydrograph separation. *Hydrological processes*, *34*(26), 5606-5623. https://doi.org/10.1002/hyp.13981

Miller, W. P., & Piechota, T. C. (2011). Trends in Western U.S. Snowpack and Related Upper Colorado River Basin Streamflow. *Journal of the American Water Resources Association*, *47*(6), 1197-1210. https://doi.org/10.1111/j.1752-1688.2011.00565.x

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Climate change - Stationarity is dead: Whither water management? *Science*, *319*(5863), 573-574. https://doi.org/10.1126/science.1151915

Milly, P. C. D., Kam, J., & Dunne, K. A. (2018). On the Sensitivity of Annual Streamflow to Air Temperature. *Water resources research*, *54*(4), 2624-2641. https://doi.org/10.1002/2017wr021970

Mote, P. W. (2006). Climate-Driven Variability and Trends in Mountain Snowpack in Western North America. *Journal of climate*, *19*(23), 6209-6220. https://doi.org/10.1175/jcli3971.1

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western north America. *Bulletin of the American Meteorological Society*, *86*(1), 39-+.

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., & Engel, R. (2018). Dramatic declines in snowpack in the western US. *NPJ climate and atmospheric science*, *1*(1), 1-6. https://doi.org/10.1038/s41612-018-0012-1

Musselman, K. N., Lehner, F., Ikeda, K., Clark, M. P., Prein, A. F., Liu, C., . . . Rasmussen, R. (2018). Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature climate change*, *8*(9), 808-812. https://doi.org/10.1038/s41558-018-0236-4

Musselman, K. N., Molotch, N. P., & Margulis, S. A. (2017). Snowmelt response to simulated warming across a large elevation gradient, southern Sierra Nevada, California. *The cryosphere*, *11*(6), 2847-2866. https://doi.org/10.5194/tc-11-2847-2017

Neal, C., Wilkinson, J., Neal, M., Harrow, M., Wickham, H., Hill, L., Morfitt, C. (1997). The hydrochemistry of the River Severn, Plynlimon, Wales. *Hydrology and Earth System Sciences* **1**: 583– 617. https://doi.org/10.5194/hess-1-583-1997

Neal, C., Kirchner, J.W. (2000). Sodium and chloride levels in rainfall, mist, streamwater and groundwater at the Plynlimon catchments, Mid-Wales: inferences on hydrological and chemical controls. *Hydrology and Earth System Sciences* 4: 295–310. https://doi.org/10.5194/hess-4-295-2000

Nogués-Bravo, D., Araújo, M. B., Errea, M. P., & Martínez-Rica, J. P. (2007). Exposure of global mountain systems to climate warming during the 21st Century. *Global environmental change*, *17*(3-4), 420-428. https://doi.org/10.1016/j.gloenvcha.2006.11.007

Painter, T. H., Skiles, S. M., Deems, J. S., Brandt, W. T., & Dozier, J. (2018). Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust

Radiative Forcing in Snow. *Geophysical research letters*, *45*(2), 797-808. https://doi.org/10.1002/2017gl075826

Petersky, R., & Harpold, A. (2018). Now you see it, now you don't: a case study of ephemeral snowpacks and soil moisture response in the Great Basin, USA. *Hydrology and earth system sciences*, *22*(9), 4891-4906. https://doi.org/10.5194/hess-22-4891-2018

Pettitt, A. N. (1979). A non-parametric approach to the change-point problem. *Applied Statistics*, *28*(2), 126-135. https://doi.org/10.2307/2346729

Pomeroy, J. W., Gray, D. M., Shook, K. R., Toth, B., Essery, R. L. H., Pietroniro, A., & Hedstrom, N. (1998). An evaluation of snow accumulation and ablation processes for land surface modelling. *Hydrological Processes*, *12*(15), 2339-2367.

Price, K. (2011). Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. *Progress in physical geography*, *35*(4), 465. https://doi.org/10.1177/0309133311402714

PRISM Climate Group, Oregon State University (2018). *Parameter-elevation Regression on Independent Slopes Model*. [Dataset] https://www.prism.oregonstate.edu/

Regonda, S. K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal Cycle Shifts in Hydroclimatology over the Western United States. *Journal of climate*, *18*(2), 372-384. https://doi.org/10.1175/jcli-3272.1

Rodgers, P., Soulsby, C., Waldron, S., & Tetzlaff, D. (2005). Using stable isotope tracers to assess hydrological flow paths, residence times and landscape influences in a nested mesoscale catchment. *Hydrology and earth system sciences*, *9*(3), 139-155. https://doi.org/10.5194/hess-9-139-2005

Roesch, A., Schmidbauer, H (2018). WaveletComp: Computational Wavelet Analysis. R package version 1.1. https://CRAN.R-project.org/package=WaveletComp

Rumsey, C. A., Miller, M. P., & Sexstone, G. A. (2020). Relating hydroclimatic change to streamflow, baseflow, and hydrologic partitioning in the Upper Rio Grande Basin, 1980 to 2015. *Journal of hydrology (Amsterdam)*, *584*, 124715. https://doi.org/10.1016/j.jhydrol.2020.124715

Rungee, J., Bales, R., & Goulden, M. (2018). Evapotranspiration response to multiyear dry periods in the semiarid western United States. *Hydrological processes*, *33*(2), 182-194. https://doi.org/10.1002/hyp.13322

Safeeq, M., Guillaume, S. M., Gordon, E. G., Ivan, A., Alan, F. H., & Se-Yeun, L. (2014). Comparing Large-Scale Hydrological Model Predictions with Observed Streamflow in the Pacific Northwest: Effects of Climate and Groundwater. *Journal of hydrometeorology*, *15*(6), 2501-2521. https://doi.org/10.1175/JHM-D-13-0198.1

Schilling, O. S., Parajuli, A., Tremblay Otis, C., Müller, T. U., Antolinez Quijano, W., Tremblay, Y., . . . Therrien, R. (2021). Quantifying Groundwater Recharge Dynamics and Unsaturated Zone Processes in Snow-Dominated Catchments via On-Site Dissolved Gas Analysis. *Water resources research*, *57*(2), n/a. https://doi.org/10.1029/2020WR028479

Sexstone, G. A., Clow, D. W., Fassnacht, S. R., Liston, G. E., Hiemstra, C. A., Knowles, J. F., & Penn, C. A. (2018). Snow Sublimation in Mountain Environments and Its Sensitivity to Forest Disturbance and Climate Warming. *Water resources research*, *54*(2), 1191-1211. https://doi.org/10.1002/2017WR021172

SLCDPU (2018), Salt Lake City Public Records Department. Historical streamflow data. [Dataset] https://www.slc.gov/utilities/grama/

Soulsby, C., Tetzlaff, D., Rodgers, P., Dunn, S., & Waldron, S. (2006). Runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment: An initial evaluation. *Journal of Hydrology*, *325*(1-4), 197-221. https://doi.org/10.1016/j.jhydrol.2005.10.024

Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M., & Stahl, K. (2017). Catchment water storage variation with elevation. *Hydrological processes*, *31*(11), 2000-2015. https://doi.org/10.1002/hyp.11158

Stewart, I.T, Cayan, D.R., and Dettinger, M.D.(2005). Changes toward Earlier Streamflow Timing across Western North America. *Journal of Climate*, 18.8, 1136-1155. https://doi.org/10.1175/JCLI3321.1

Tai, X., Anderegg, W. R. L., Blanken, P. D., Burns, S. P., Christensen, L., & Brooks, P. D. (2020). Hillslope Hydrology Influences the Spatial and Temporal Patterns of Remotely Sensed Ecosystem Productivity. *Water resources research*, *56*(11), n/a. https://doi.org/10.1029/2020WR027630

Tromp van Meerveld, H. J., Seibert, J., & Peters, N. E. (2015). Hillslope-riparian-stream connectivity and flow directions at the Panola Mountain Research Watershed: Hillslope-Riparian-Stream Connectivity and Flow Directions at Panola. *Hydrological processes*, *29*(16), 3556-3574. https://doi.org/10.1002/hyp.10508

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water resources research*, *53*(3), 2404-2418. https://doi.org/10.1002/2016WR019638

USGS. (2018), USGS Water Data For Utah. *National Water Information System.* [Dataset] https://waterdata.usgs.gov/ut/nwis/

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature sustainability*, *3*(11), 917-928. https://doi.org/10.1038/s41893-020-0559-9

Williams, A. P., Cook, B. I., & Smerdon, J. E. (2022). Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature climate change*, *12*(3), 232-234. https://doi.org/10.1038/s41558-022-01290-z

Wittenberg, H. (1999). Baseflow recession and recharge as nonlinear storage processes. *Hydrological Processes*, **13**(5), 715– 726. https://doi-org.ezproxy.lib.utah.edu/10.1002/(SICI)1099-1085(19990415)

Woodhouse, C. A., Pederson, G. T., Morino, K., McAfee, S. A., & McCabe, G. J. (2016). Increasing influence of air temperature on upper Colorado River streamflow. *Geophysical research letters*, *43*(5), 2174-2181. https://doi.org/10.1002/2015GL067613

Wooldridge, S. A., Kalma, J. D., & Walker, J. P. (2003). Importance of soil moisture measurements for inferring parameters in hydrologic models of low-yielding ephemeral catchments. *Environmental modelling & software : with environment data news*, *18*(1), 35-48. https://doi.org/10.1016/S1364-8152(02)00038-5

Wu, S., Zhao, J., Wang, H., & Sivapalan, M. (2021). Regional patterns and physical controls of streamflow generation across the conterminous United States. Water Resources Research, 57, e2020WR028086. https://doi.org/10.1029/2020WR028086

Brutsaert, W. (2008). Long-term groundwater storage trends estimated from streamflow records: Climatic perspective. Water Resources Research, 44, W02409. https://doi.org/10.1029/2007WR006518

Chikamoto, Y., Wang, S. Y. S., Yost, M., Yocom, L., & Gillies, R. R. (2020). Colorado River water supply is predictable on multi-year timescales owing to long-term ocean memory. Communications earth & environment, 1(1), 1-11. https://doi.org/10.1038/s43247-020-00027-0

Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M., & Peterson, D. H. (2001). Changes in the onset of spring in the western United States. Bulletin of the American Meteorological Society, 82(3), 399-415. https://doi.org/10.1175/1520-0477(2001)082<0399:CITOOS>2.3.CO;2

Wang, S., R. R. Gillies, J. Jin, and L. E. Hipps, 2010: Coherence between the Great Salt Lake Level and the Pacific Quasi-Decadal Oscillation. J. Climate, 23, 2161–2177, https://doi.org/10.1175/2009JCLI2979.1.

Wang, S.Y.; Gillies, R.R.; Reichler, T. Multidecadal drought cycles in the Great Basin recorded by the Great Salt Lake: Modulation from a transition-phase teleconnection. J. Clim. 2012, 25, 1711–1721. https://doi.org/10.1175/2011JCLI4225.1

Wise, E. K. (2010), Spatiotemporal variability of the precipitation dipole transition zone in the western United States, Geophys. Res. Lett., 37, L07706, https://doi.org/10.1029/2009GL042193.

Tables:

Table 1

Catchment Characteristics

	Elevation	**Area**	**Aspect**	**Bedrock /Geology**	**Runoff Efficiency (RE) =(Q/P)**		**Annual Mean Air Temperature (T)**			**Annual Cumulative Precipitation (P)**				**Annual Total normalized* Discharge (Q)**				**Mean Winter normalized* Baseflow (WBF)**			
Catchment Name	Min-Max (m)	(km^2)	%(N+E) %(S+W)		Mean	Range	Mean (°C)	SD	Range	Mean (mm/yr)	SD	Range	CV: (SD/ Mean)	Mean (mm/yr)	SD	Range	CV	Mean (mm/day)	SD	Range	CV
Chalk Creek (W CC)	1725-2477	643	52:48	Sedimentary (carbonate and clastic)	0.17	0.04-0.34	4.8	*0.8*	2-7	558	*108*	291-841	0.2	94	*53*	12-274	0.6	0.08	0.03	0.03-0.19	0.4
Emigration Creek(J EC)	1496 - 2733	41	40:60	Sedimentary (carbonate and clastic)	0.18	0.01-0.54	7	*0.8*	5-10	795	*167*	423-1356	0.2	144	*104*	7-549	0.7	0.12	0.07	0.02-0.37	0.6
Parleys Creek (J PC)	1441 - 2927	135	50:50	Sedimentary (carbonate and clastic)	0.22	0.07-0.50	6.7	*0.8*	4-10	785	*161*	419-1327	0.2	176	*98*	39-523	0.6	0.19	0.07	0.08-0.39	0.4
Red Butte Creek (J RB)	1646 - 2431	19	39:61	Sedimentary (carbonate and clastic)	0.23	0.08-0.55	6.9	*0.8*	5-10	803	*169*	431-1331	0.2	183	*106*	46-600	0.6	0.24	0.08	0.11-0.43	0.3
Mill Creek (J MC)	1539 - 2927	56	51:49	Sedimentary (carbonate and clastic)	0.26	0.13-0.41	5.3	*0.9*	3-8	924	*189*	514-1514	0.2	239	*89*	99-521	0.4	0.37	0.12	0.16-0.67	0.3
Ogden South Fork (W OS)	1582-2567	356	47:53	Sedimentary (carbonate), Metamorphic (quartzite)	0.35	0.16-0.55	5.2	*0.9*	3-8	804	*160*	476-1263	0.2	283	*116*	92-652	0.4	0.28	0.09	0.14-0.63	0.3
City Creek (J CC)	1382 - 2512	46	39:61	Sedimentary (carbonate and clastic)	0.37	0.22-0.68	6.8	*0.8*	5-10	850	*177*	472-1372	0.2	318	*114*	133-781	0.4	0.41	0.08	0.24-0.71	0.2
Big Cottonwood Creek (J BC)	1531 - 3445	127	49:51	Metamorphic (quartzite)	0.48	0.29-0.75	4.3	*0.9*	2-7	1043	*219*	607-1738	0.2	500	*150*	196-919	0.3	0.49	0.14	0.25-1.08	0.3
Weber at Oakley (W O)	2024-3641	420	48:52	Sedimentary (carbonates)/ Igneous (intrusive)	0.48	0.25-0.69	2.6	*0.9*	0-5	946	*182*	544-1485	0.2	458	*143*	165-881	0.3	0.32	0.07	0.19-0.53	0.2
Little Cottonwood Creek (J LC)	1548 – 3510	71	65:35	Igneous (intrusive)	0.62	0.44-0.88	3.4	*0.9*	1-6	1293	*276*	738-2135	0.2	807	*218*	360-1568	0.3	0.51	0.12	0.27-0.91	0.2

Note. Ten snow-dominated catchments in northern Utah range in elevation (min-max), total area size (km), aspect (N-E) (S-W), geology, runoff efficiency (streamflow/precipitation), mean annual temperature, annual cumulative precipitation, annual total discharge, and mean annual winter baseflow. Hydro-metrological variables include mean, standard deviation (SD), range and coefficient of variation (CV=SD/Mean).

*normalized to catchment area, daily streamflow in cfs converted to mm/day

Table 2

Antecedent Hydro-climactic Variables Included in Multiple Linear Regression Model to Predict Δ Winter Baseflow.

Catchments	Precipitation					Temperature		Normalized Melt Rate			Normalized Melt Duration			
	wy(Fall)	wy-1	wy-2	wy-3	wy-4	wy-1	wy-4	wy-1	wy-2	wy-3	wy-2	wy-3	Y-int	R^2
(W CC)	+(0.38)	+(0.57)	+(0.24)	+(0.11)	+(0.17)	-(0.24)		+(0.07)	-(0.07)				(0.03)	**0.84**
(J EC)		+(0.14)				-(0.06)		+(0.44)	+(0.02)				(0.06)	**0.29**
(J PC)	+(0.40)	+(0.38)	+(0.23)			-(0.08)	-(0.07)	+(0.12)	+(0.08)				(-0.01)	**0.62**
(J RB)	+(0.28)	+(0.41)	+(0.27)	+(0.09)		-(0.22)		+(0.11)				+(0.18)	(-0.11)	**0.87**
(J MC)	+(0.12)	+(0.39)	+(0.19)		+(0.06)	-(0.14)		+(0.17)	+(0.19)	+(0.06)			(-0.04)	**0.70**
(W OS)	+(0.49)	+(0.41)				-(0.09)		+(0.04)					(0.02)	**0.46**
(J CC)	+(0.14)	+(0.40)	+(0.19)			-(0.24)	-(0.09)	+(0.26)	+(0.03)	+(0.08)	+(0.09)	+(0.15)	(0.04)	**0.67**
(J BC)	+(0.38)	+(0.35)	+(0.13)		+(0.1)	+(0.08)		+(0.21)	+(0.04)				(-0.07)	**0.58**
(W O)	+(0.30)	+(0.47)	+(0.23)	+(0.13)	+ (0.17)			+(0.15)	+(0.06)				(-0.01)	**0.61**
(J LC)	+(0.56)	+(0.36)											(0.01)	**0.47**

Note. MLR equation: Δ *Winter baseflow*= β *Precipitation*$_{(n\text{-}i)}$ + β *Temperature*$_{(n\text{-}i)}$ + β *Melt Rate*$_{(n\text{-}i)}$ + β *Melt Duration*$_{(n\text{-}i)}$ (wy= current water year, i= number of years in the past (eg. n-1= 1 year previous), β= regression coefficient, R^2 = coefficient of determination of observed vs. predicted values, **bold indicates** P-Val <0.005)

Figures:

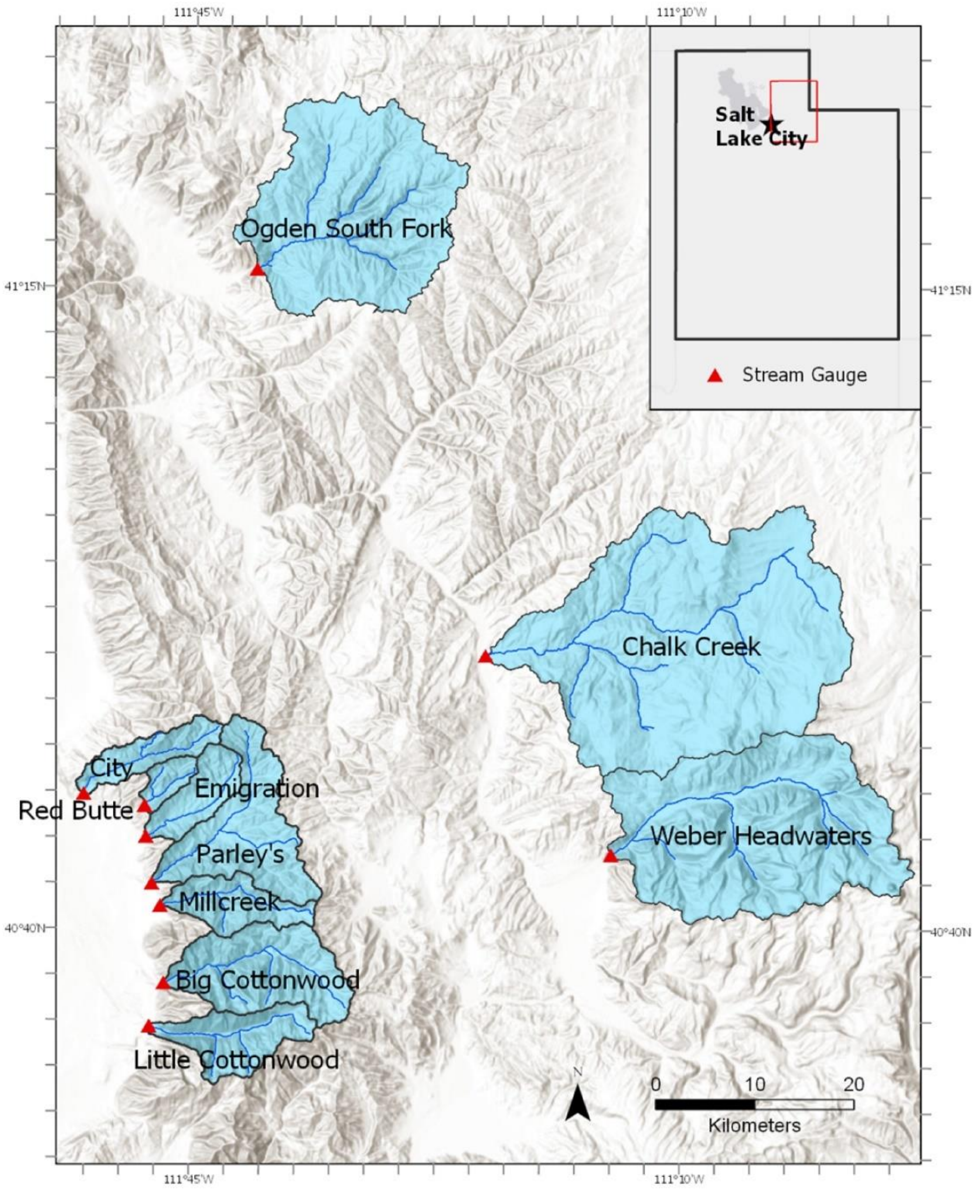

Figure 1: Study area map including the 10 snowmelt-dominated headwater catchments with climate, topography, and geology representing many similar regional catchments throughout the Western US. These catchments are all major water suppliers to the greater Salt Lake City region; each has a continuous gauging station (red triangles) with a record >76 years and feeds the Jordan and Weber Rivers in Northern Utah (state inset map), terminating in Great Salt Lake.

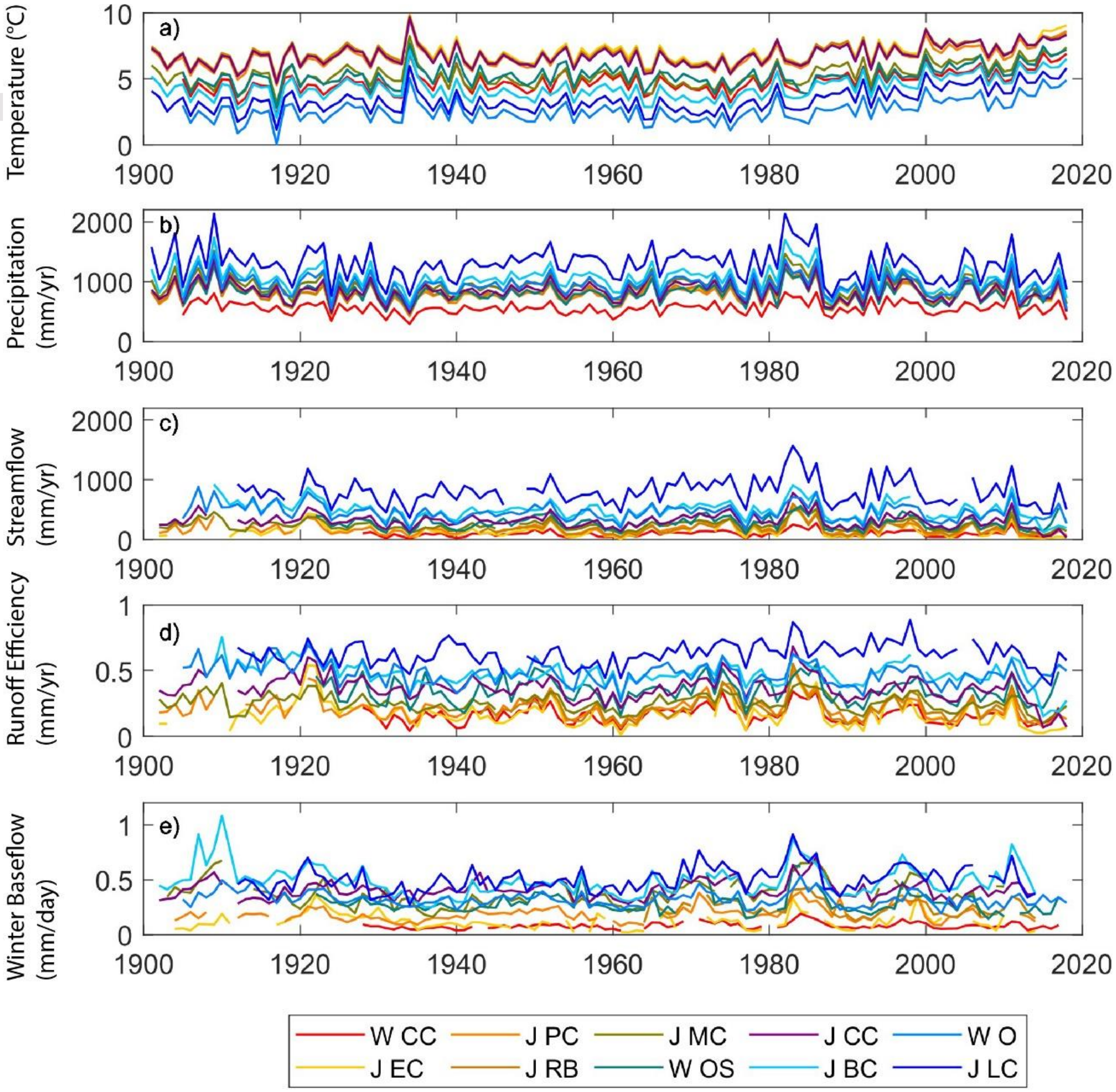

Figure 2: Mean annual (a) temperature (°C), (b) total precipitation (mm/yr), (c) normalized total discharge(mm/yr), (d) runoff efficiency (discharge(mm/yr)/precipitation(mm/yr)) and (e) normalized winter baseflow (mm/day) for 10 Northern Utah headwater catchments from 1902-2018. Mean annual temperature has increased in the last century (slope= (0.027-0.063°C/year)- significantly from 1985-2018 in all catchments SI Table 1); precipitation, discharge, and baseflow exhibit variability from year to year, with no significant +/- trends over the last century (SI Table 1). Each colored line corresponds to a different headwater catchment. Catchments are color-coded from red to dark blue based on mean annual runoff efficiency, with warmer, drier, lower runoff efficiency catchments in red/orange and cooler, wetter, higher runoff efficiency catchments represented by blues.

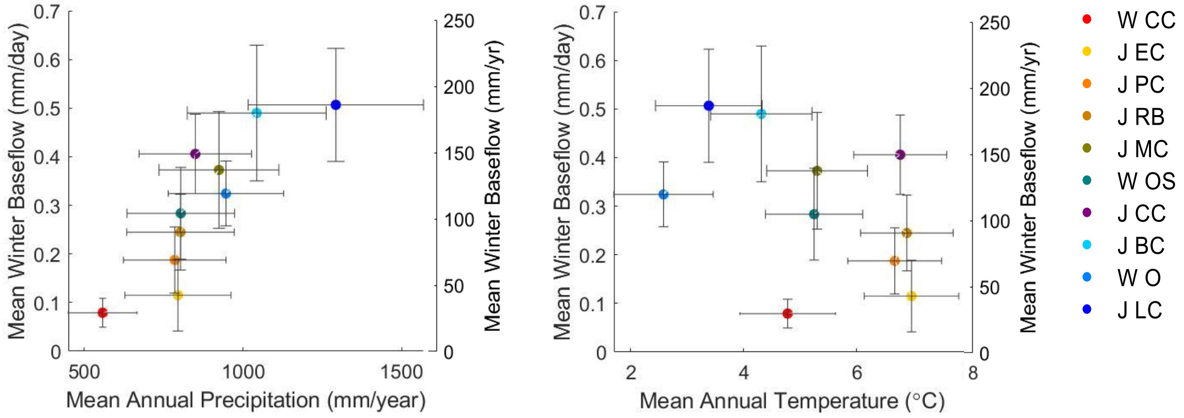

Figure 3: Left Panel: Mean annual precipitation is strongly and significantly ($r^2 = 0.75$; $p<0.001$) related to baseflow (mm/day: left axis, mm/year: right axis) (error bars indicate variability), where wetter catchments have higher baseflow compared to drier catchments (left panel). Right panel: Mean annual temperature is not significantly related to mean catchment baseflow conditions ($r^2= 0.21$; $p = 0.18$).

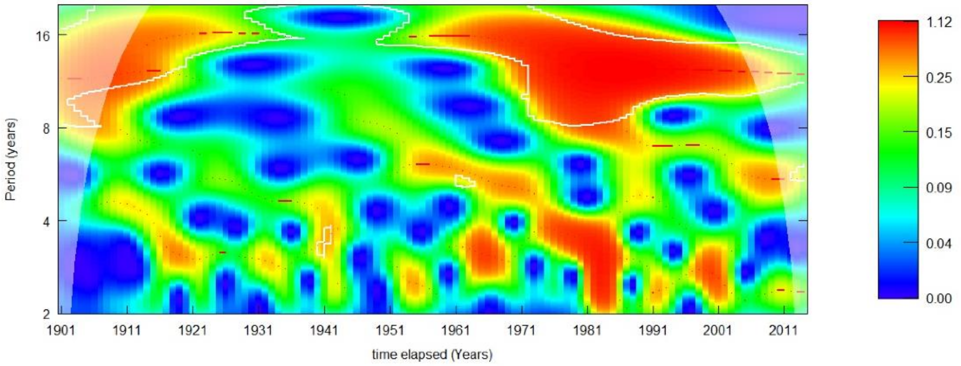

Figure 4: Wavelet transform analysis of winter baseflow (mean across all catchments). Colors indicate the degree of correlation (power level) of the harmonic. White outlines indicate time steps with significant ($p<0.05$) correlations. A century-long 2-5 year periodicity of high correlation/power level (0.23) (red values) ($p<0.10$) and a late-century significant ($p<0.05$) periodicity at a 12-15 year time-scale (power level (0.29)).

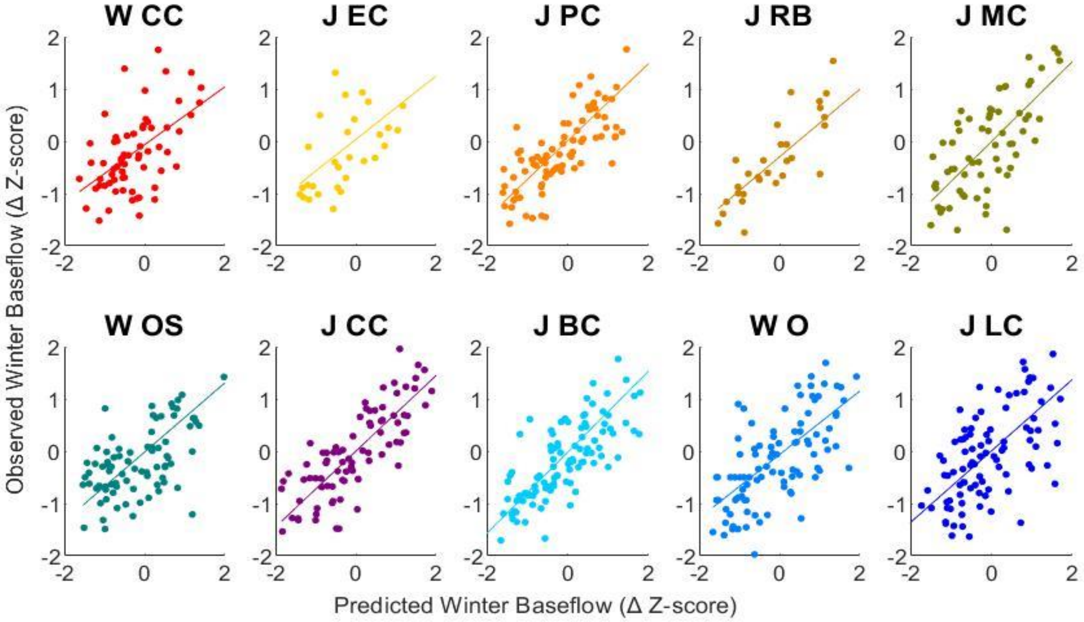

Figure 5: Predicted winter baseflow using antecedent precipitation, temperature, normMR, and normMD, compared to observed winter baseflow (z-scored). On average, the model better predicted winter baseflow in warmer and drier (lower runoff effeciency) catchments R^2>0.7 for W C.C., J P.C., J R.B., J M.C.. The model also reasonably predicts baseflow in cooler and wetter catchments, higher runoff effeciency (R^2> 0.46 (W O.S., J C.C., J B.C., W.O., and J L.C.).