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Recent Upper Colorado River Streamflow Declines Driven by Loss of Spring Precipitation

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Key Points:

- Significant decreases in spring precipitation have been observed since 2000 in headwater basins of the Upper Colorado
- Drier springs have corresponded with greater spring potential evapotranspiration (PET)
- Spring precipitation decreases and PET increases explain much of the variability in observed streamflow deficits in these headwater basins

Supporting Information:

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

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Abstract Colorado River streamflow has decreased 19% since 2000. Spring (March–April–May) weather strongly influences Upper Colorado River streamflow because it controls not only water input but also when snow melts and how much energy is available for evaporation when soils are wettest. Since 2000, spring precipitation decreased by 14% on average across 26 unregulated headwater basins, but this decrease did not fully account for the reduced streamflow. In drier springs, increases in energy from reduced cloud cover, and lowered surface albedo from earlier snow disappearance, coincided with potential evapotranspiration (PET) increases of up to 10%. Combining spring precipitation decreases with PET increases accounted for 67% of the variance in post-2000 streamflow deficits. Streamflow deficits were most substantial in lower elevation basins (<2,950 m), where snowmelt occurred earliest, and precipitation declines were largest. Refining seasonal spring precipitation forecasts is imperative for future water availability predictions in this snow-dominated water resource region.

Plain Language Summary With over 40 million people dependent on the Colorado River, the 19% drop in streamflow since 2000 has been worrying, especially because its cause is not well understood. To explain this drop, we focused on changes to spring weather in snow-dominated basins, which contribute over 80% of the river's water. We found spring precipitation decreases since 2000 not only reduced streamflow but also correlated with higher temperatures and evaporation rates and less cloudiness. These impacts combined to intensify streamflow declines in basins with earlier snowmelt. The importance of spring precipitation to Colorado River streamflow underscores the need to improve seasonal precipitation forecasts. Such improvements would enhance water availability predictions for the one billion people worldwide reliant on snow for water resources.

1. Introduction

The Upper Colorado River Basin (UCRB) (Figure 1a) constitutes approximately 90% of the total flow of the Colorado River, one of the most over-allocated water resource regions in the world (Christensen et al., 2004; Fleck & Udall, 2021; Lukas & Payton, 2020; McCabe & Wolock, 2007; Xiao et al., 2018). Since the onset of the ongoing Millennium drought (“drought”) (2000–present), record streamflow deficits have occurred relative to both the observational record (1906–1999) and the baseline period used in this analysis (1964–1999) (Christensen et al., 2004; Fleck & Udall, 2021; Hoerling et al., 2019; Lukas & Payton, 2020; McCabe & Wolock, 2007; Schmidt et al., 2023; Williams et al., 2022; Xiao et al., 2018). The mountain winter snowpack is the most critical component of UCRB streamflow (Christensen et al., 2004; Heldmyer et al., 2023; Li et al., 2017; Palmer, 1988), but during the drought period, streamflow has frequently been less than anticipated given the amount of winter precipitation (Milly & Dunne, 2020; Udall & Overpeck, 2017; Woodhouse et al., 2016) (Figure 1b). Annual precipitation decreases over the same period also do not fully account for the observed streamflow decline, suggesting there is a certain amount of “missing water” from the UCRB (Figure 1c) (McCabe et al., 2017; Milly & Dunne, 2020; Woodhouse et al., 2016).

To address this conundrum, previous modeling studies explored the sensitivity of streamflow to precipitation and temperature. Streamflow response to decreased precipitation is magnified during drier years (Woodhouse & Pederson, 2018). On the other hand, temperature increases in the UCRB have been linked to streamflow declines through (a) increases in modeled wintertime sublimation and annual evapotranspiration (ET) (Christensen & Lettenmaier, 2006; Ficklin et al., 2013; McCabe et al., 2017; Udall & Overpeck, 2017; Xiao et al., 2018), and (b) earlier snow disappearance, which reduces surface albedo and increases potential evapotranspiration (PET) (Milly & Dunne, 2020). While it is agreed that increased temperature exacerbates UCRB streamflow declines,

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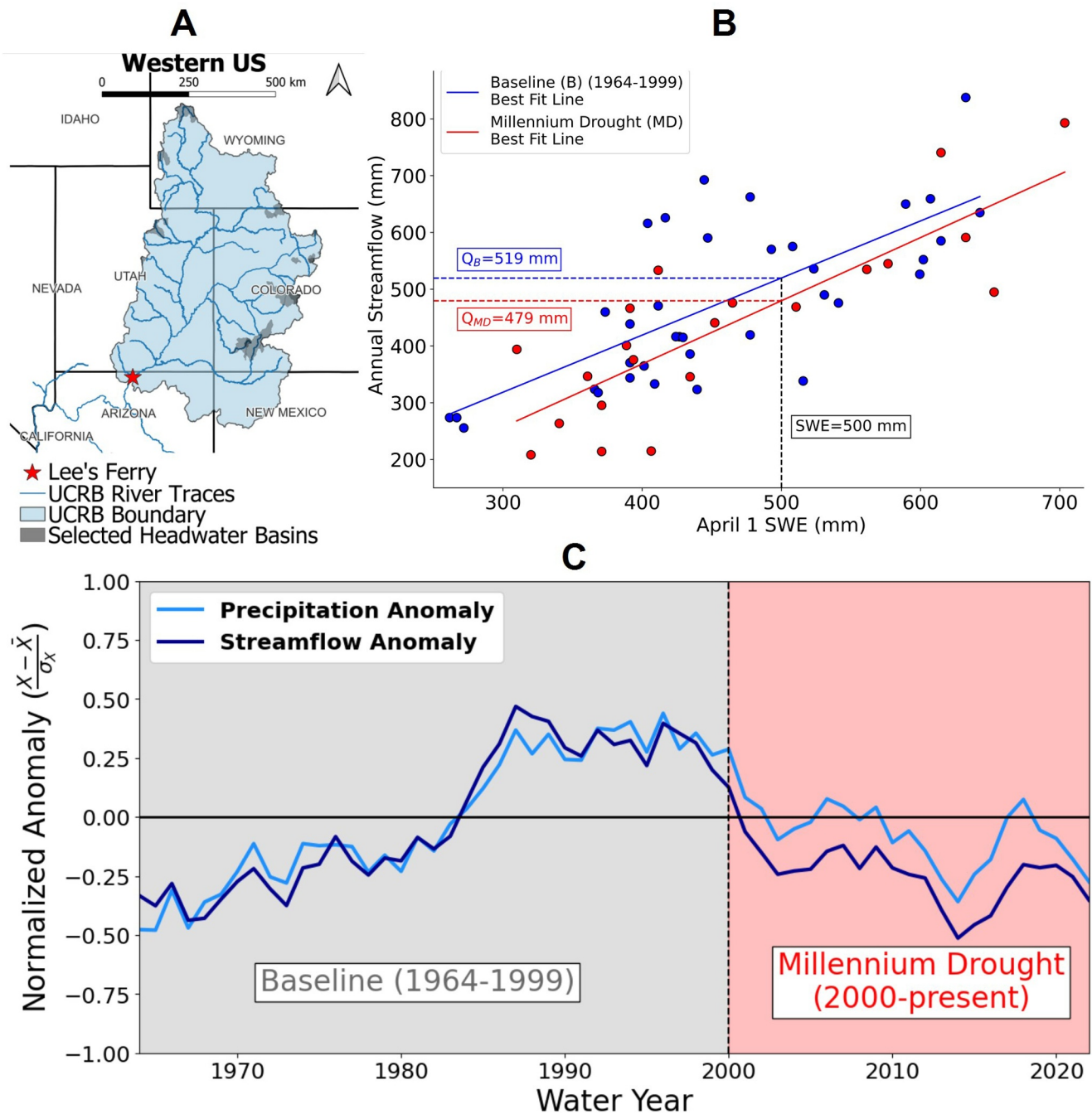


Figure 1. (a) Map of UCRB with the selected headwater basin locations and UCRB outlet at Lee's Ferry (red star). (b) April 1 SWE snow course measurements (1964–2022) in Black Gore Creek basin and area-normalized annual streamflow (USGS gage ID 09066000) in mm for baseline (blue) and Millennium drought (red) years. Using the best fit line, resultant streamflow estimates from 500 mm SWE are displayed in blue (baseline) and red (Millennium drought) boxes. (c) 10-year rolling average of normalized anomalies for UCRB naturalized streamflow as estimated at Lee's Ferry (dark blue line) and UCRB precipitation from PRISM (light blue line).

estimates of this temperature sensitivity vary between studies (Hoerling et al., 2019; McCabe & Wolock, 2007; Milly & Dunne, 2020; Vano et al., 2012; Xiao et al., 2018). The variation is likely due to different model estimations of precipitation and temperature and inherent model differences in how precipitation is allocated to streamflow, which diverge considerably between models (Vano et al., 2012). Thus, the choice of model can significantly influence how streamflow changes are explained (Bennett et al., 2019).

To avoid challenges with model choices, we focus on observed precipitation and streamflow changes, and on estimates of PET as an approximation of non-water stressed ET, within unregulated UCRB headwater basins over 1964–2022. We specifically examine changes by season because seasonality strongly influences the energy available to transpire or evaporate water and the water availability in soil (Carroll et al., 2020, 2024; Foster et al., 2016; Hidalgo et al., 2005; Knowles et al., 2015; Lapides et al., 2022; Meira Neto et al., 2020; Milly & Dunne, 2020; Woodhouse et al., 2016; S. Zhao et al., 2021), and seasonality has recently been linked to unexpected streamflow losses in California (Lapides et al., 2022). In semi-arid basins like the Colorado, PET magnitudes closely match actual ET (AET) observations during non-water stressed conditions (Fisher et al., 2005; Maes et al., 2019), which occur in the spring during and following snowmelt. In winter, AET sometimes matches PET, but with limited energy available, PET remains low. In summer and fall, even with sufficient energy, drier conditions constrain AET.

Spring also marks a rapid transition in snow-dominated headwater regions. As snow melts, surface albedo decreases over newly exposed ground, PET rises quickly, and the annual phenological cycle begins. About 30% of total UCRB precipitation occurs during this dynamic season (Zhao et al., 2023). Observations indicate a decreasing trend in spring precipitation in the UCRB over the last century, and future projections forecast these decreases to continue (Kalra & Ahmad, 2011; McAfee & Russell, 2008; Yin, 2005). Additionally, drier springs correlate with warmer temperatures throughout the western US, even after removing the effects of climate change-driven temperature increases (Koster et al., 2009; Trenberth & Shea, 2005).

Drier and warmer springs shift the timing of plant growth earlier, while decreases in precipitation (and its associated cloud cover) increase mean temperature and surface radiative input, both crucial contributors to PET (Betts et al., 2014; Cayan et al., 2001; Fischer et al., 2009; Hidalgo et al., 2005; Schwartz & Reiter, 2000; Sumargo & Cayan, 2018; W. Zhao & Khalil, 1993). Thus, we expect years with lower spring precipitation to correspond with higher spring PET.

Additionally, basin elevation has been identified as a primary driver for how a basin responds to temperature, precipitation, and land cover change (Biederman et al., 2022; Carroll et al., 2019; Foster et al., 2016; Mayer & Naman, 2011; Tennant et al., 2015) (see Supporting Information S1). Therefore, we hypothesize that reduced spring precipitation and higher spring PET do not impact all basins equally during drier springs. Snow in lower elevation headwater basins melts out earlier (Fassnacht et al., 2003; Lundquist et al., 2004). Earlier snowmelt impacts spring PET over these lower, but not higher, elevation basins because surface albedo decreases earlier, increasing the radiative input into the surface, and plant-driven ET starts earlier with the exposure of plants to sunlight and available water from snowmelt (Milly & Dunne, 2020; Nehemy et al., 2021).

This study uniquely explores how the relationship between spring precipitation and PET affects streamflow throughout the UCRB headwaters. The combined effects from this relationship have not been previously linked to observed streamflow deficits in the UCRB. To confront this research gap, we primarily use observation-based data to (a) establish the significance of spring precipitation and streamflow decreases since 2000, (b) determine the relationship between spring precipitation decrease and PET, and (c) evaluate the role this relationship has in explaining streamflow declines in headwater basins at different elevations.

2. Data and Methods

2.1. Study Basins

Twenty-six UCRB headwater basins (Figure 1a) were selected from the USGS Hydro-Climatic Data Network (HCDN), which identifies natural streams minimally influenced by humans (Slack, Lumb, & Landwehr, 1994). Prior work has shown that 80% of UCRB streamflow originates from only 15% of its area (Christensen & Lettenmaier, 2006). Similarly, the selected basins account for 25% of the average UCRB streamflow but cover only 4% of its land area. These basins span the geographic extent of the UCRB (Figure 2a) and have comparable elevation range (2,290–4,200 m) and forest cover (28%) to the entire headwater region's elevation range (2,270–4,300 m) and forest cover (25%).

2.2. Seasonal Precipitation Change

Gridded UCRB precipitation data were collected from the Parameter-elevation Regressions on Independent Slopes Model, PRISM (PRISM Climate Group, 2014), for the 1964–2022 period. The monthly precipitation

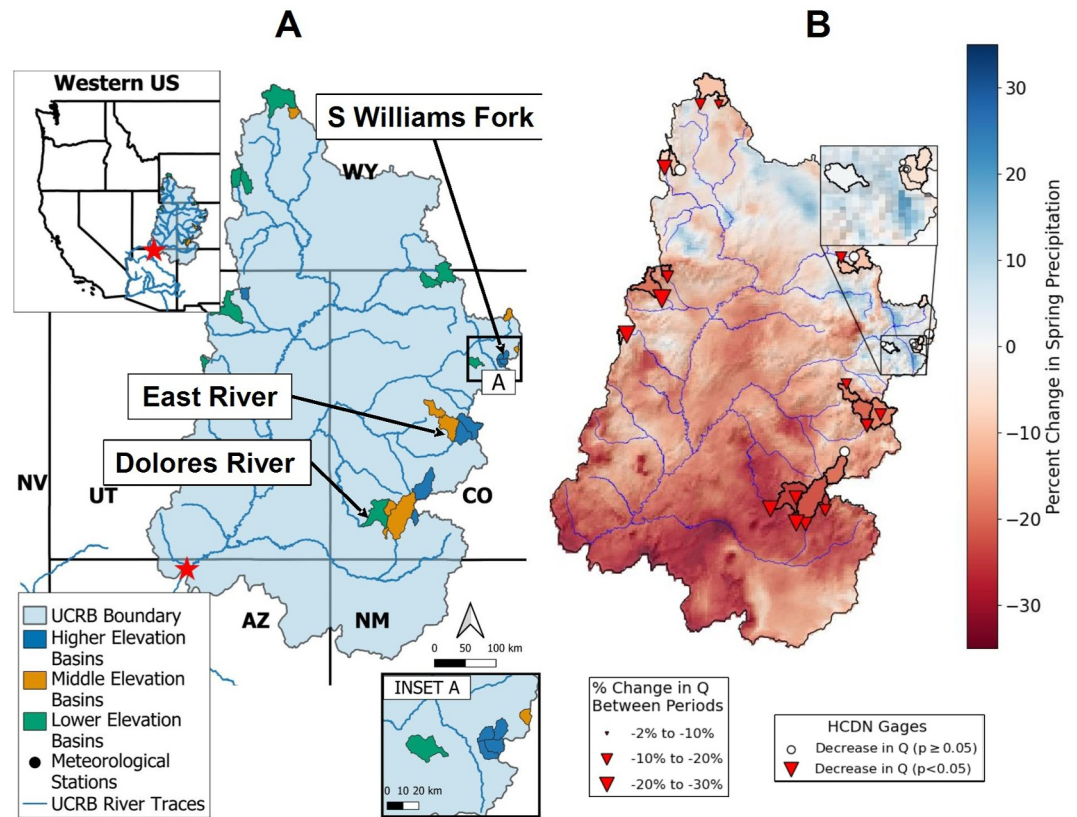


Figure 2. (a) UCRB boundary with higher, middle, and lower elevation basin groupings. Arrows point to basins used in Figure 4. (b) Spring precipitation percent change (shading) and annual streamflow volume difference (symbols) between baseline and drought. Symbols represent significant (red triangles) and insignificant (white circles) streamflow volume (Q) decreases from study basins. Symbol size represents the Q percentage change.

product was spatially averaged over each selected basin. Seasonal and annual aggregates of precipitation were created for each basin for each water year in the data record (see Text S2 in Supporting Information S1). We evaluated annual and seasonal precipitation changes in each basin by comparing mean precipitation totals between the baseline (1964–1999) and drought (2000–2022) periods.

To verify results from PRISM, we compared monthly PRISM estimates against two other commonly used gridded precipitation data sets (NClimgrid and ERA5-Land reanalysis, see Text S2 in Supporting Information S1). We observed consistent trends and strong agreement between products, especially during winter, spring, and fall seasons.

2.3. Basin Streamflow Changes Between Periods With Elevation

Area-normalized water year (October–September) streamflow was calculated from daily mean observations (U.S. Geological Survey, 2016). For the entire UCRB, we utilized the Bureau of Reclamation naturalized streamflow record at Lee's Ferry, AZ. These data have been used in several model evaluation and water balance studies in the UCRB (Hoerling et al., 2019; Vano et al., 2012; Woodhouse et al., 2016; Xiao et al., 2018).

We separated headwater basins into higher ($>3,250$ m), middle (2,950–3,250 m), and lower ($<2,950$ m) elevation groupings based on their area-normalized mean elevation (Figure 2a, Text S2 in Supporting Information S1). Like our evaluation of precipitation change, we compared streamflow volume changes for the UCRB and headwater gages by comparing mean annual streamflow totals between periods.

2.4. Spring Precipitation and PET Relationship

To estimate monthly PET, we used an offline “energy-only” PET (PET-EO) method (Maes et al., 2019; Milly & Dunne, 2016, 2017) derived from ERA5-Land reanalysis net radiation estimates (Muñoz-Sabater et al., 2021). Maes et al. (2019) found the PET-EO method better matched in-situ measurements of non-water stressed ET than the commonly used Penman-Monteith and Priestley-Taylor PET methods. While magnitudes of PET vary, the relationship between spring precipitation and PET is consistent across all methods examined (Text S2 in Supporting Information S1).

Net radiation during spring over non-snow-covered terrain is primarily controlled by changes in cloud cover, which impacts incoming solar radiation (Hidalgo et al., 2005); however, snow albedo also strongly influences the surface energy balance by controlling outgoing shortwave radiation when snow is present (Milly & Dunne, 2020). While the ERA5-Land radiation variables that drive the PET-EO method do account for modeled surface albedo changes over the year (Hersbach et al., 2020), the ERA5-Land albedo in the UCRB headwater regions was generally insensitive to snow cover and did not match satellite albedo observations during snow-covered periods (Figure S11 in Supporting Information S1). Modeled cloud cover from ERA5 correlated well with observations from meteorological stations distributed throughout the UCRB (United States. National Oceanic and Atmospheric Administration, 1998) from 1997 to 2022 (Text S2 in Supporting Information S1).

Based on these analyses, the unadjusted ERA5-Land radiation components represent cloud-related processes well, but not the albedo of snow-covered terrain. Thus, we used the net longwave and shortwave radiation values to estimate the impact that changes to cloud cover have on PET (PET-EO-cloud). We examined PET-EO-cloud estimates against modeled ERA5 cloud cover and PRISM precipitation to illustrate the relationship between spring PET, cloud cover, and precipitation over the entire 1964–2022 period.

To better account for the impact of snow cover on PET changes, our second method (PET-EO-snow) adjusted the surface albedo over snow using MODIS observations of fractional snow-covered area, fSCA, on April 15 (the midpoint of March–April–May) from 2001 to 2017 (A. P. Tran et al., 2019). Here, we assume snow covered grid-cells ($fSCA = 1$) have a surface albedo of 0.8, while snow-free grid-cells ($fSCA = 0$) have an albedo equal to the ERA5-Land modeled snow-free albedo value which varies by land cover, but is generally about 0.2. For fSCA values between 0 and 1, albedo was calculated by combining the snow-covered and snow-free albedo in proportion to fSCA. For further details, see Text S2 in Supporting Information S1. Using these fSCA and PET estimates, we grouped average spring values by 100-m elevation bins over the UCRB to explore how spring snow cover and PET changed with elevation during dry versus wet springs between 2001 and 2017. We classified springs as dry (wet) if their precipitation was more than one standard deviation below (above) the seasonal average.

3. Results

3.1. How Much Have Spring Precipitation and Streamflow Decreased Since 2000?

Annual precipitation decreases were significant ($p < 0.05$) across the UCRB, with a 9% reduction between the baseline and drought periods. In the headwater basins, 17 of 26 basins had significant annual precipitation decreases, of which 13 were lower and middle elevation basins. Seasonally, spring precipitation decreases were largest, averaging 14% across the study basins (Figure 2b). Most headwater basins, except one, showed spring precipitation decreases up to 29% between periods, with significant decreases in 16 of the 26 basins. Lower and middle elevation headwater basins were particularly affected, as 12 of 17 basins showed significant decreases. Basin-specific results for annual and seasonal precipitation changes are detailed in Table S2 of Supporting Information S1.

At both the headwater basin and UCRB scales, spring precipitation reductions accounted for 40%–65% of the annual precipitation decreases between periods (Figure S15 in Supporting Information S1). Fall and winter showed limited change, although some basins had significant summer precipitation decreases. However, unlike spring, these summertime decreases did not correlate with observed streamflow, and only accounted for 15% of the average annual precipitation decreases (Text S2 and Figure S9 in Supporting Information S1).

Annual streamflow reductions occurred at all headwater basin gages and in the UCRB naturalized streamflow record. Significant decreases occurred in four of the nine higher elevation basins, ranging from –15% to –19%.

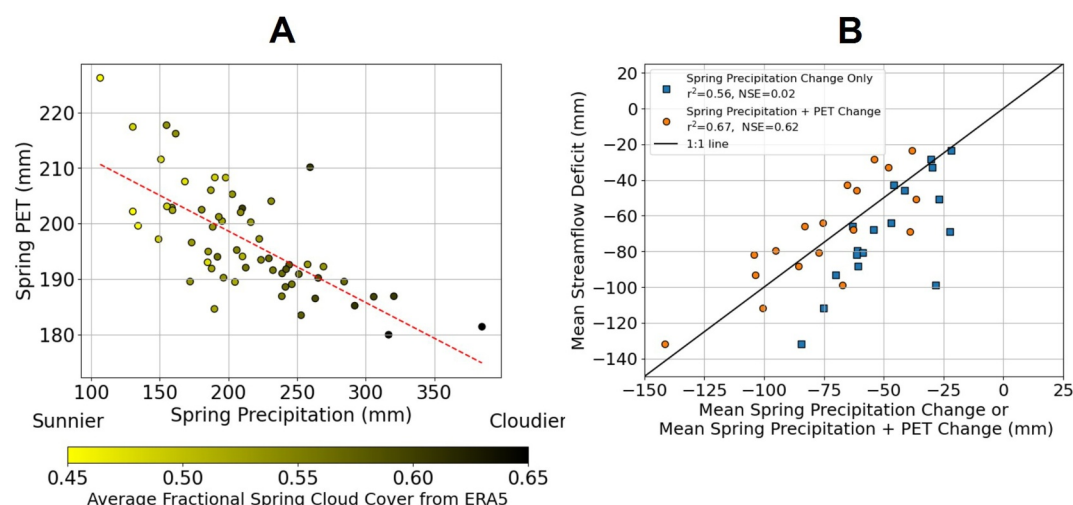


Figure 3. (a) Spring potential evapotranspiration versus spring precipitation, color-coded by ERA5 cloud cover. Values represent spatial average across analyzed headwater basins for 1964–2022 derived from the PET-EO-cloud estimates. (b) Mean spring precipitation changes (blue squares) and mean spring precipitation plus PET-EO-cloud changes (orange circles) plotted against mean streamflow deficits between baseline and drought periods for all headwater basins with significant streamflow declines between periods.

Thirteen of the 17 middle and lower elevation basins showed significant annual streamflow decreases (–8% to –36%). Most basins with significant annual streamflow reductions also had significant spring precipitation decreases (Figure 2b, Table S3 in Supporting Information S1), with the largest relative streamflow declines concentrated in the lower elevation basins (Figures 2b and 4b).

3.2. How Much Can the Spring Precipitation-PET Relationship Explain Streamflow Deficits Since 2000?

Across the headwater basins analyzed, we found drier springs had less cloud cover and greater PET (Figure 3a). Spring was the only season where we found PET to be consistently sensitive to precipitation, with a 10% precipitation reduction corresponding to a 1%–3% PET increase (Figure S13E in Supporting Information S1). Aligning with this sensitivity, we found spring PET increased between 2% and 10% since 2000 across the headwater basins.

In basins with significant streamflow decreases since 2000, spring precipitation decreases alone fall short of explaining observed streamflow deficits (Figure 3b), particularly in basins with the largest streamflow changes. Regressing spring precipitation changes against streamflow declines accounted for 56% of the variance (as quantified by R^2). However, by including the sum of water losses (spring PET-EO-cloud and precipitation changes), the variance explained increased to 67%, and the Nash-Sutcliffe efficiency increased from 0.02 to 0.62 as observed points moved closer to the 1-to-1 line (Figure 3b).

3.3. Are Spring Precipitation and PET Impacts on Streamflow Elevation-Dependent?

Throughout the UCRB, we found earlier snowmelt timing, lower fSCA, and greater spring PET in lower elevation basins (Figure 4a) compared to higher basins (Figure 4d). April 15 fSCA also differed with elevation when comparing wet and dry springs, with the fSCA difference (Δ SCA) expanding to a maximum of 0.25 in the lower headwater elevation band (2,400–3,000 m) before decreasing again at the lowest elevations of the UCRB (Figure 4a). During years with low spring precipitation, we observed an amplified area-normalized spring PET response across all elevations compared to years with high spring precipitation in both the PET-EO-cloud and PET-EO-snow estimates (Figure 4b).

In the headwater regions above 2,400 m, differences in spring PET between wet and dry springs also increased with decreasing elevation. The mean differences in PET between wet and dry springs for the higher (Δ H), middle (Δ M), and lower (Δ L) headwater basin elevation bands were 25, 37, and 50 mm, respectively, for the PET-EO-cloud estimates, and 28, 56, and 78 mm, respectively, for the PET-EO-snow estimates (Figure 4b). Considering

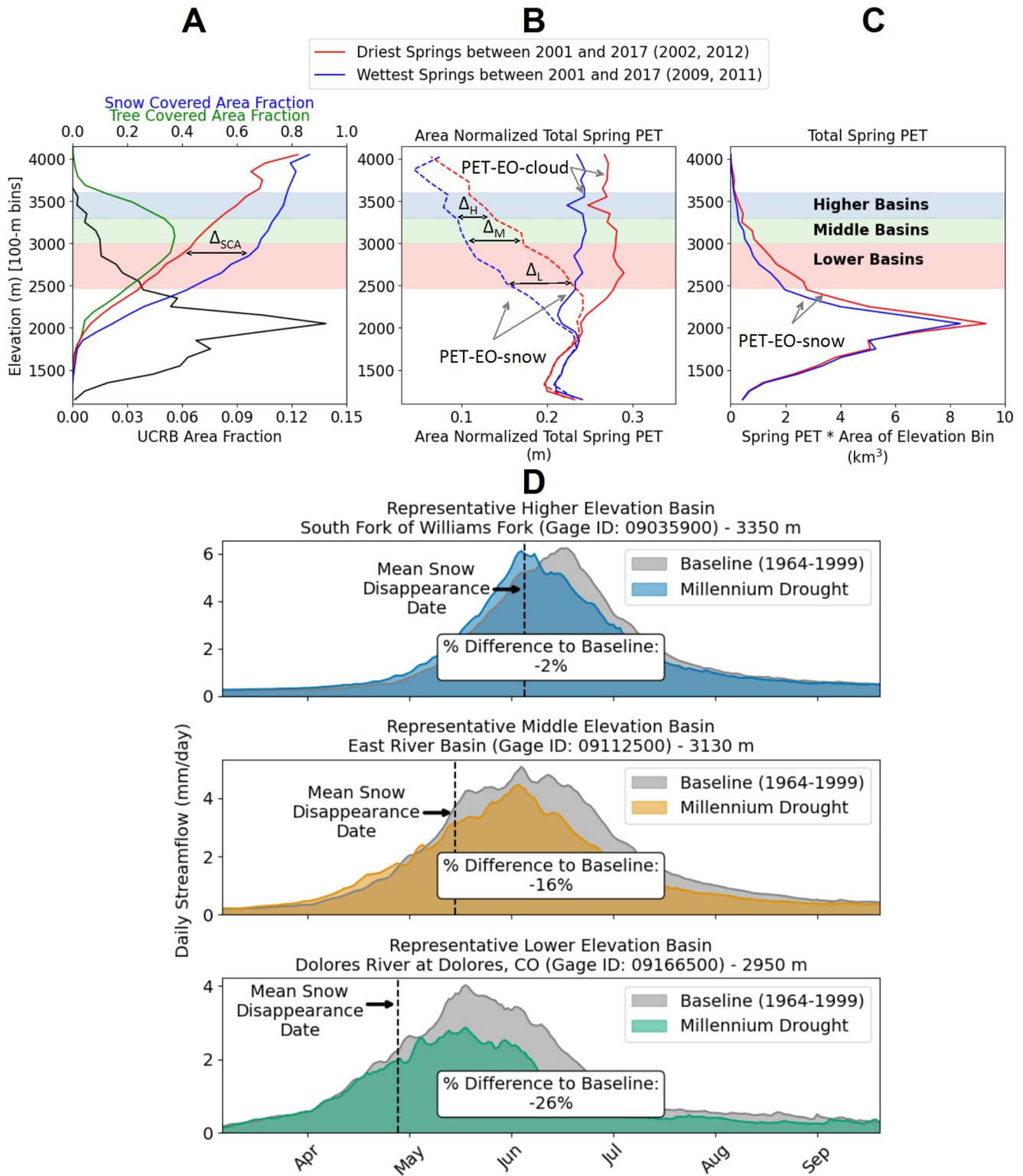


Figure 4.

that a larger proportion of the UCRB's area is contained within the lower elevation headwater regions, more basin total spring PET occurred at these lower elevations during dry springs compared to wet springs (Figure 4c).

4. Discussion

4.1. Consequences of Spring Precipitation and PET Changes on Streamflow

Springtime precipitation decreases since 2000 reduced water input across the selected UCRB headwater regions and the greater basin area (Figure 2b). Nevertheless, precipitation decreases alone did not fully explain the observed streamflow deficits (blue squares, Figure 3b). To account for the remaining “missing water,” we showed that drier springs have greater PET due to feedback from reduced cloud cover and earlier snowmelt timing that increased net radiation (Figures 3a and 4b). Combining spring PET increases with observed precipitation decreases provides a better explanation for UCRB streamflow deficits during the ongoing drought (orange circles, Figure 3b).

Reduced cloud cover allows greater incident solar radiation to reach the surface, leading to warmer temperatures and greater net radiation. Over snow-free terrain, this cloud-radiative feedback drives PET increases (Figures 3a and 4b), in agreement with observations from California (Hidalgo et al., 2005). Over snow-covered terrain, greater incoming radiation during drier springs accelerates snowmelt, reducing snow cover earlier at all elevations to varying extents (Figure 4a). This reduction in snow coverage leads to a decrease in outgoing radiation resulting from the lowered surface albedo, consequentially increasing net radiation and PET. This earlier ground exposure and increased energy allows plants to respond over a longer spring period when ET remains energy-limited.

While prior work has investigated long-term trends toward earlier snowmelt timing in the western US (Clow, 2010; Fritze et al., 2011), the feedback-driven changes to snow-covered area and net radiation presented here are related to inter-annual variability in spring weather patterns (wetter/drier). Given uncertain climate projections of spring precipitation, it is unclear whether the springtime reductions observed since 2000 will persist. Further research is needed to better understand the relationship between long-term climate signals and spring weather patterns in the UCRB. If climate change directly impacts spring precipitation, streamflow losses would be expected to amplify.

4.2. Explaining Spring Precipitation and PET Impacts at Different Elevations

Just as the headwater regions (elevations above 2,300 m) receive the most precipitation in the basin, they also had the greatest net radiation and PET differences between wet and dry springs (Figures 4b and 4c), while the lowest elevations exhibited a minimal signal of basin-wide changes since 2000 (Figures 4c and Text S2 in Supporting Information S1). The highest elevation basins (elevations above 3,300 m) experienced more modest reductions in annual streamflow volume caused by the smaller percentage-wise spring precipitation changes since 2000 and smaller fSCA and PET shifts during drier springs (Figure 4b, Table S2 in Supporting Information S1). These basins are less vulnerable to these shifts due to their comparatively deeper snowpacks and later snowmelt timing (Figure 4d), which limits PET during spring and buffers against the spring precipitation-PET relationship's influence on streamflow.

Spring precipitation percent declines and PET increases were largest within the lower elevation headwater zones (between 2,300 and 2,900 m) of the UCRB. At these elevations, drier springs also exhibited a larger fSCA reduction and greater spring PET increase (Figures 4a and 4b). Without extensive or long-lasting snow cover, the combined effects of spring precipitation decrease and PET increase impacted streamflow the most in lower elevation headwater zones (Figure 4d). This result corroborates findings from Knowles et al. (2015), which

Figure 4. (a) Hypsometric plot of UCRB area fraction (black), tree-covered area (green), and fSCA for wet (blue) and dry (red) spring conditions. Difference between wet and dry years is symbolized as Δ_{SCA} . (b) Hypsometric plot showing area-normalized spring potential evapotranspiration (PET) using the PET-EO-cloud (solid) and PET-EO-snow (dashed) methods for wet (blue) and dry (red) spring conditions. Difference between wet and dry years is symbolized as Δ_{H} , Δ_{M} , Δ_{L} for higher, middle, and lower elevation basins, respectively. (c) Hypsometric plot of total spring PET, accounting for area, using the PET-EO-snow method for wet (blue) and dry (red) spring conditions. Lower, middle, and higher elevation basin bands highlighted in red, green, and blue, respectively. (d) Basin-normalized average daily streamflow during baseline (gray) and drought (colored) periods, in mm/day, for representative higher, middle, and lower elevation basins. Locations marked in Figure 2a. Text boxes show percentage change in streamflow volume relative to baseline. Mean snow disappearance date from MODIS snow-covered area data (2000–2018) indicates when 50% of each basin's snow-covered area disappeared (O'Leary et al., 2020). Note the earlier timing at lower elevations. Further details in the Text S2 in Supporting Information S1.

showed that dry years preserved ET at the expense of streamflow in a lower elevation region of the UCRB headwaters. However, focusing solely on spring changes, we demonstrate that spring PET and precipitation changes closely matched annual streamflow deficits in all basins during the ongoing drought (Figure 3b, Figure S17 in Supporting Information S1), further supporting that spring PET is a good indicator of AET. Thus, energy availability during spring is likely the primary control on AET variability in the UCRB headwaters. Ignoring other water balance losses, our results indicate that drier, warmer springs contributed to more total AET from a streamflow perspective. The data set compiled herein, which tries to avoid modeling, may help with assessing which hydrologic models are appropriately sensitive to springtime precipitation and snowmelt influences on ET.

4.3. Importance of Accurate Seasonal Precipitation Forecasts

Drier springs in the UCRB correlate significantly to warmer spring temperatures (Figure S16 in Supporting Information S1). Since 2000, we observed a significant shift toward drier spring conditions, with a north-south-oriented precipitation gradient (Figure 2b) that could signal the predicted climate change-driven northward shift in storm tracks (Harvey et al., 2020). Our findings corroborate model results from Heldmyer et al. (2023), which showed when warm and dry conditions occur together, a greater loss in UCRB streamflow can be expected. Nonetheless, our research emphasizes the critical role of spring precipitation in driving UCRB streamflow, underscoring the need for further investigation into the underlying causes of these precipitation reductions. Recent research has used oceanic teleconnections, specifically North Pacific sea surface temperature, to predict spring precipitation and streamflow in the UCRB with encouraging results (Zhao et al., 2021, 2023). A better forecast of spring precipitation would benefit water managers in the UCRB region (Lehner et al., 2017; Zhao et al., 2023).

5. Conclusion

Since the onset of the ongoing Millennium drought in the UCRB (2000–present), annual precipitation and April 1 SWE have provided less streamflow than historically observed. We focused on changes during the spring season to explain the observed inconsistency between precipitation and annual streamflow declines in select UCRB headwater basins during the drought. Our analysis revealed significant spring precipitation decreases in these basins between the baseline (1964–1999) and drought periods, which notably outweighed decreases during other seasons. We found years with less spring precipitation and cloud cover corresponded with warmer temperatures and greater spring PET. Including both spring precipitation reductions and spring PET increases better accounted for annual streamflow deficits in these headwater basins compared to precipitation decreases alone. By combining these water losses, we explained 67% of the variance in annual streamflow deficits within these headwater basins since 2000. The compounding impacts of these changes reached a maximum in the lower elevation headwater basins, where the largest relative reductions in annual streamflow volumes were observed.

With continued projections of increasing temperature during spring, it will be paramount to highlight the importance of springtime conditions throughout the UCRB and to better resolve our estimates of seasonal spring precipitation when forecasting water availability. Further work should focus on understanding regional precipitation changes during spring and the interplay between precipitation and other hydrologic fluxes during this dynamic season.

Data Availability Statement

Basin elevations were calculated from the 30 m 3DEP digital elevation model downloaded from the National Map (U.S. Geological Survey, 2019). Fractional tree covered area estimates were derived from the National Land Cover Database (Dewitz & U.S. Geological Survey, 2021). UCRB headwater basin daily streamflow data from NWIS (U.S. Geological Survey, 2016) were downloaded using the dataretrieval Python package (<https://pypi.org/project/dataretrieval/0.1/>). The USBR naturalized streamflow record was obtained from <https://www.usbr.gov/lc/region/g4000/NaturalFlow/provisional.html>. Headwater basin geometry and basin information were obtained from the GAGES II data set (Falcone, 2011). Climatological normal and monthly estimates for precipitation and temperature were downloaded from PRISM (PRISM Climate Group, 2014). NClimGrid monthly estimates for precipitation were downloaded from the links provided in Vose et al. (2015). ERA5-Land monthly reanalysis data were from the links provided in Muñoz-Sabater et al. (2021). Monthly ERA5 Reanalysis cloud cover data were from the links provided in Hersbach et al. (2020). Monthly PET and cloud cover data from CRU-TS4 were from

the links provided in Harris et al. (2020). Hourly cloud cover observations from 1997 to 2022 were obtained from the United States National Oceanographic and Atmospheric Association (1998) from <https://mesonet.agron.iastate.edu/request/download.phtml>. Snow course and snow pillow SWE measurements described in Fleming et al. (2023) were acquired from the USDA Natural Resources Conservation Service (2023) using the Metloom python package (<https://metloom.readthedocs.io/en/latest/readme.html>). Snowmelt timing maps derived from MODIS were downloaded from O'Leary et al. (2020). Daily snow-covered area maps from MODIS were downloaded from H. Tran et al. (2019). Monthly blue-sky albedo climatology from MODIS were archived in Zenodo (Jia et al., 2022). Table S4 in Supporting Information S1 provides a table with direct links and access dates for each of these data sources. These data were processed using Jupyter Notebooks under Python version 3.10.6. All analysis notebooks are available on GitHub via <https://github.com/dlhogan97/Spring-Precipitation-Effect-CO-River>. Processed and compiled data used in this analysis from the references above are available as a downloadable zip file from Zenodo (Hogan & Lundquist, 2024).

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References

- Bennett, A., Nijssen, B., Ou, G., Clark, M., & Nearing, G. (2019). Quantifying process connectivity with transfer entropy in hydrologic models. *Water Resources Research*, 55(6), 4613–4629. <https://doi.org/10.1029/2018WR024555>
- Betts, A. K., Desjardins, R., Worth, D., & Beckage, B. (2014). Climate coupling between temperature, humidity, precipitation, and cloud cover over the Canadian Prairies. *Journal of Geophysical Research: Atmospheres*, 119(23), 13–305. <https://doi.org/10.1002/2014JD022511>
- Biederman, J. A., Robles, M. D., Scott, R. L., & Knowles, J. F. (2022). Streamflow response to wildfire differs with season and elevation in adjacent headwaters of the lower Colorado River Basin. *Water Resources Research*, 58(3), e2021WR030687. <https://doi.org/10.1029/2021WR030687>
- 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>
- Carroll, R. W. H., Gochis, D., & Williams, K. H. (2020). Efficiency of the summer monsoon in generating streamflow within a snow-dominated headwater basin of the Colorado River. *Geophysical Research Letters*, 47(23), e2020GL090856. <https://doi.org/10.1029/2020GL090856>
- Carroll, R. W. H., Niswonger, R. G., Ulrich, C., Varadharajan, C., Siirila-Woodburn, E. R., & Williams, K. H. (2024). Declining groundwater storage expected to amplify mountain streamflow reductions in a warmer world. *Nature Water*, 2(5), 419–433. <https://doi.org/10.1038/s44221-024-00239-0>
- 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), 399–416. [https://doi.org/10.1175/1520-0477\(2001\)082<0399:CIT00S>2.3.CO;2](https://doi.org/10.1175/1520-0477(2001)082<0399:CIT00S>2.3.CO;2)
- Christensen, N., & Lettenmaier, D. P. (2006). 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 Discussions*, 3(6), 3727–3770.
- 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), 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: A response to recent warming. *Journal of Climate*, 23(9), 2293–2306. <https://doi.org/10.1175/2009JCLI2951.1>
- Dewitz & U.S. Geological Survey. (2021). National land cover Database (NLCD) 2019 products (version 2.0) [Dataset]. <https://doi.org/10.5066/P9KZC5M4>
- Falcone, J. A. (2011). GAGES-II: Geospatial attributes of gages for evaluating streamflow [Dataset]. *U.S. Geological Survey*. <https://doi.org/10.3133/70046617>
- Fassnacht, S. R., Dressler, K. A., & Bales, R. C. (2003). Snow water equivalent interpolation for the Colorado River Basin from snow telemetry (SNO^{TEL}) data. *Water Resources Research*, 39(8), 1208. <https://doi.org/10.1029/2002WR001512>
- Fisher, J. B., DeBiase, T. A., Qi, Y., Xu, M., & Goldstein, A. H. (2005). Evapotranspiration models compared on a Sierra Nevada forest ecosystem. *Environmental Modelling & Software*, 20(6), 783–796. <https://doi.org/10.1016/j.envsoft.2004.04.009>
- Ficklin, D. L., Stewart, I. T., & Maurer, E. P. (2013). Climate change impacts on streamflow and subbasin-scale hydrology in the upper Colorado River Basin. *PLoS One*, 8(8), e71297. <https://doi.org/10.1371/journal.pone.0071297>
- Fischer, D. T., Still, C. J., & Williams, A. P. (2009). Significance of summer fog and overcast for drought stress and ecological functioning of coastal California endemic plant species. *Journal of Biogeography*, 36(4), 783–799. <https://doi.org/10.1111/j.1365-2699.2008.02025.x>
- Fleck, J., & Udall, B. (2021). Managing Colorado River risk. *Science (New York, N.Y.)*, 372(6545), 885. <https://doi.org/10.1126/science.abj5498>
- Fleming, S. W., Zukiewicz, L., Strobel, M. L., Hofman, H., & Goodbody, A. G. (2023). SNO^{TEL}, the soil climate analysis Network, and water supply forecasting at the natural resources conservation service: Past, present, and future. *JAWRA Journal of the American Water Resources Association*, 59(4), 585–599. <https://doi.org/10.1111/1752-1688.13104>
- Foster, L. M., Bearup, L. A., Molotch, N. P., Brooks, P. D., & Maxwell, R. M. (2016). Energy budget increases reduce mean streamflow more than snow–rain transitions: Using integrated modeling to isolate climate change impacts on rocky Mountain Hydrology. *Environmental Research Letters*, 11(4), 044015. <https://doi.org/10.1088/1748-9326/11/4/044015>
- Fritze, H., Stewart, I. T., & Pebesma, E. (2011). Shifts in western North American snowmelt runoff regimes for the recent warm decades. *Journal of Hydrometeorology*, 12(5), 989–1006. <https://doi.org/10.1175/2011JHM1360.1>
- Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset [Dataset]. *Nature Publishing Group*, 7(1) 109. <https://doi.org/10.1038/s41597-020-0453-3>
- Harvey, B. J., Cook, P., Shaffrey, L. C., & Schiemann, R. (2020). The response of the Northern Hemisphere storm tracks and jet streams to climate change in the CMIP3, CMIP5, and CMIP6 climate models. *Journal of Geophysical Research: Atmospheres*, 125(23), e2020JD032701. <https://doi.org/10.1029/2020JD032701>
- Heldmyer, A. J., Bjarke, N. R., & Livneh, B. (2023). A 21st-Century perspective on snow drought in the upper Colorado River Basin. *JAWRA Journal of the American Water Resources Association*, 59(2), 396–415. <https://doi.org/10.1111/1752-1688.13095>

- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Hidalgo, H. G., Cayan, D. R., & Dettinger, M. D. (2005). Sources of variability of evapotranspiration in California. *Journal of Hydrometeorology*, 6(1), 3–19. <https://doi.org/10.1175/JHM-398.1>
- Hoerling, M., Barsugli, J., Livneh, B., Eischeid, J., Quan, X., & Badger, A. (2019). Causes for the century-long decline in Colorado River flow. *Journal of Climate*, 32(23), 8181–8203. <https://doi.org/10.1175/JCLI-D-19-0207.1>
- Hogan, D., & Lundquist, J. (2024). Recent upper Colorado River streamflow declines driven by loss of spring precipitation (version 2) [Dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.11043101>
- Jia, A., Wang, D., Liang, S., Peng, J., & Yu, Y. (2022). Global daily surface blue-sky albedo climatology and land cover climatology dataset from 20-year MODIS products (500m) (version V02) [Dataset]. *Zenodo*. <https://doi.org/10.5281/zenodo.6359686>
- Kalra, A., & Ahmad, S. (2011). Evaluating changes and estimating seasonal precipitation for the Colorado River Basin using a stochastic nonparametric disaggregation technique. *Water Resources Research*, 47(5), W05555. <https://doi.org/10.1029/2010WR009118>
- Knowles, J. F., Harpold, A. A., Cowie, R., Zeff, M., Barnard, H. R., Burns, S. P., et al. (2015). The relative contributions of alpine and subalpine ecosystems to the water balance of a mountainous, headwater catchment. *Hydrological Processes*, 29(22), 4794–4808. <https://doi.org/10.1002/hyp.10526>
- Koster, R. D., Schubert, S. D., & Suarez, M. J. (2009). Analyzing the concurrence of meteorological droughts and warm periods, with implications for the determination of evaporative regime. *Journal of Climate*, 22(12), 3331–3341. <https://doi.org/10.1175/2008JCLI2718.1>
- Lapides, D. A., Hahm, W. J., Rempe, D. M., Whiting, J., & Dralle, D. N. (2022). Causes of missing snowmelt following drought. *Geophysical Research Letters*, 49(19), e2022GL100505. <https://doi.org/10.1029/2022GL100505>
- Lehner, F., Wood, A. W., Llewellyn, D., Blatchford, D. B., Goodbody, A. G., & Pappenberger, F. (2017). Mitigating the impacts of climate nonstationarity on seasonal streamflow predictability in the U.S. Southwest. *Geophysical Research Letters*, 44(24), 12–208. <https://doi.org/10.1002/2017GL076043>
- Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the Western United States, and how will that change in the future? *Geophysical Research Letters*, 44(12), 6163–6172. <https://doi.org/10.1002/2017GL073551>
- Lukas, J., & Payton, E. (2020). Colorado River Basin climate and Hydrology: State of the science. <https://doi.org/10.25810/3HCV-W477>
- Lundquist, J. D., Cayan, D. R., & Dettinger, M. D. (2004). Spring onset in the Sierra Nevada: When is snowmelt independent of elevation? *Journal of Hydrometeorology*, 5(2), 327–342. [https://doi.org/10.1175/1525-7541\(2004\)005<0327:SOITSN>2.0.CO;2](https://doi.org/10.1175/1525-7541(2004)005<0327:SOITSN>2.0.CO;2)
- Maes, W. H., Gentile, P., Verhoest, N. E. C., & Miralles, D. G. (2019). Potential evaporation at eddy-covariance sites across the globe. *Hydrology and Earth System Sciences*, 23(2), 925–948. <https://doi.org/10.5194/hess-23-925-2019>
- Mayer, T. D., & Naman, S. W. (2011). Streamflow response to climate as influenced by geology and elevation 1. *JAWRA Journal of the American Water Resources Association*, 47(4), 724–738. <https://doi.org/10.1111/j.1752-1688.2011.00537.x>
- McAfee, S. A., & Russell, J. L. (2008). Northern annular mode impact on spring climate in the Western United States. *Geophysical Research Letters*, 35(17), L17701. <https://doi.org/10.1029/2008GL034828>
- McCabe, G. J., & Wolock, D. M. (2007). Warming may create substantial water supply shortages in the Colorado River Basin. *Geophysical Research Letters*, 34(22), L22708. <https://doi.org/10.1029/2007GL031764>
- McCabe, G. J., Wolock, D. M., Pederson, G. T., Woodhouse, C. A., & McAfee, S. (2017). Evidence that recent warming is reducing upper Colorado River flows. *Earth Interactions*, 21(10), 1–14. <https://doi.org/10.1175/EI-D-17-0007.1>
- Meira Neto, A. A., Niu, G.-Y., Roy, T., Tyler, S., & Troch, P. A. (2020). Interactions between snow cover and evaporation lead to higher sensitivity of streamflow to temperature. *Communications Earth & Environment*, 1(1), 1–7. <https://doi.org/10.1038/s43247-020-00056-9>
- Milly, P. C. D., & Dunne, K. A. (2016). Potential evapotranspiration and continental drying. *Nature Climate Change*, 6(10), 946–949. <https://doi.org/10.1038/nclimate3046>
- Milly, P. C. D., & Dunne, K. A. (2017). A hydrologic drying bias in water-resource impact analyses of anthropogenic climate change. *JAWRA Journal of the American Water Resources Association*, 53(4), 822–838. <https://doi.org/10.1111/1752-1688.12538>
- Milly, P. C. D., & Dunne, K. A. (2020). Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation. *Science*, 367(6483), 1252–1255. <https://doi.org/10.1126/science.aay9187>
- Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., et al. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13(9), 4349–4383. <https://doi.org/10.5194/essd-13-4349-2021>
- Nehemy, M. F., Benettin, P., Asadollahi, M., Pratt, D., Rinaldo, A., & McDonnell, J. J. (2021). Tree water deficit and dynamic source water partitioning. *Hydrological Processes*, 35(1), e14004. <https://doi.org/10.1002/hyp.14004>
- O'Leary, D., Hall, D. K., Medler, M., Matthews, R., & Flower, A. (2020). Snowmelt timing maps derived from MODIS for North America, version 2, 2001–2018 [Dataset]. <https://doi.org/10.3334/ORNLDAAAC/1712>
- Palmer, P. L. (1988). The SCS snow survey water supply forecasting program: Current operations and future directions. *Western Snow Conf.*, (pp. 33–51).
- PRISM Climate Group, O. S. U. (2014). PRISM climate data [Dataset]. <https://prism.oregonstate.edu>
- Schmidt, J. C., Yackulic, C. B., & Kuhn, E. (2023). The Colorado River water crisis: Its origin and the future. *WIREs Water*, 10(6), e1672. <https://doi.org/10.1002/wat2.1672>
- Schwartz, M. D., & Reiter, B. E. (2000). Changes in North American spring. *International Journal of Climatology*, 20(8), 929–932. [https://doi.org/10.1002/1097-0088\(20000630\)20:8<929::AID-JOC557>3.0.CO;2-5](https://doi.org/10.1002/1097-0088(20000630)20:8<929::AID-JOC557>3.0.CO;2-5)
- Slack, J. R., Lumb, A. M., & Landwehr, J. M. (1994). *Hydro-climatic data Network (HCDN) -- A USGS streamflow data set for the U.S. For the study of climate fluctuations*. U.S. Geological Survey. Retrieved from <https://water.usgs.gov/GIS/metadata/usgswrd/XML/hcdn.xml>
- Sumargo, E., & Cayan, D. R. (2018). The influence of cloudiness on hydrologic fluctuations in the mountains of the western United States. *Water Resources Research*, 54(10), 8478–8499. <https://doi.org/10.1029/2018WR022687>
- Tennant, C. J., Crosby, B. T., & Godsey, S. E. (2015). Elevation-dependent responses of streamflow to climate warming. *Hydrological Processes*, 29(6), 991–1001. <https://doi.org/10.1002/hyp.10203>
- Tran, A. P., Runge, J., Faybishenko, B., Dafflon, B., & Hubbard, S. S. (2019). Assessment of spatiotemporal variability of evapotranspiration and its governing factors in a mountainous watershed. *Water*, 11(2), 243. <https://doi.org/10.3390/w11020243>
- Tran, H., Nguyen, P., Ombadi, M., Hsu, K., Sorooshian, S., & Qing, X. (2019). A cloud-free MODIS snow cover dataset for the contiguous United States from 2000 to 2017 [Dataset]. *Nature Publishing Group*. <https://doi.org/10.1038/sdata.2018.300>
- Trenberth, K. E., & Shea, D. J. (2005). Relationships between precipitation and surface temperature. *Geophysical Research Letters*, 32(14), L14703. <https://doi.org/10.1029/2005GL022760>
- 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>

- United States. National Oceanic and Atmospheric Administration. (1998). Automated surface observing system: ASOS user's guide [Dataset]. <http://purl.access.gpo.gov/GPO/LPS41312>
- U.S. Geological Survey. (2016). National water information system [Dataset]. *USGS Water Data for the Nation*. Retrieved from <https://waterdata.usgs.gov/nwis>
- U.S. Geological Survey. (2019). USGS 3D elevation program digital elevation model [Dataset]. <https://elevation.nationalmap.gov/arcgis/rest/services/3DElevation/ImageServer>
- Vano, J. A., Das, T., & Lettenmaier, D. P. (2012). Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature. *Journal of Hydrometeorology*, 13(3), 932–949. <https://doi.org/10.1175/JHM-D-11-069.1>
- Vose, R. S., Applequist, S., Squires, M., Durre, I., Menne, M. J., Williams, C. N., et al. (2015). Gridded 5km GHCN-daily temperature and precipitation dataset [Dataset]. [Object Object]. <https://doi.org/10.7289/V5SX6B56>
- 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>
- Woodhouse, C. A., & Pederson, G. T. (2018). Investigating runoff efficiency in upper Colorado River streamflow over past centuries. *Water Resources Research*, 54(1), 286–300. <https://doi.org/10.1002/2017WR021663>
- 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>
- Xiao, M., Udall, B., & Lettenmaier, D. P. (2018). On the causes of declining Colorado River streamflows. *Water Resources Research*, 54(9), 6739–6756. <https://doi.org/10.1029/2018WR023153>
- Yin, J. H. (2005). A consistent poleward shift of the storm tracks in simulations of 21st century climate. *Geophysical Research Letters*, 32(18), L18701. <https://doi.org/10.1029/2005GL023684>
- Zhao, S., Fu, R., Anderson, M. L., Chakraborty, S., Jiang, J. H., Su, H., & Gu, Y. (2023). Extended seasonal prediction of spring precipitation over the Upper Colorado River Basin. *Climate Dynamics*, 60(5), 1815–1829. <https://doi.org/10.1007/s00382-022-06422-x>
- Zhao, S., Fu, R., Zhuang, Y., & Wang, G. (2021). Long-Lead seasonal prediction of streamflow over the upper Colorado River Basin: The role of the Pacific Sea Surface temperature and beyond. *Journal of Climate*, 34(16), 6855–6873. <https://doi.org/10.1175/JCLI-D-20-0824.1>
- Zhao, W., & Khalil, M. a. K. (1993). The relationship between precipitation and temperature over the contiguous United States. *Journal of Climate*, 6(6), 1232–1236. [https://doi.org/10.1175/1520-0442\(1993\)006<1232:TRBPAT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<1232:TRBPAT>2.0.CO;2)

References From the Supporting Information

- Allan, R., Pereira, L., & Smith, M. (1998). Crop evapotranspiration-guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, 300(9), D05109.
- Arias, P. A., Fu, R., & Mo, K. C. (2012). Decadal variation of rainfall seasonality in the North American monsoon region and its potential causes. *Journal of Climate*, 25(12), 4258–4274. <https://doi.org/10.1175/JCLI-D-11-00140.1>
- Barik, M. G., Hogue, T. S., Franz, K. J., & Kinoshita, A. M. (2016). Assessing satellite and ground-based potential evapotranspiration for hydrologic applications in the Colorado River Basin. *JAWRA Journal of the American Water Resources Association*, 52(1), 48–66. <https://doi.org/10.1111/1752-1688.12370>
- 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>
- Bass, B., Goldenson, N., Rahimi, S., & Hall, A. (2023). Aridification of Colorado River Basin's snowpack regions has driven water losses despite ameliorating effects of vegetation. *Water Resources Research*, 59(7), e2022WR033454. <https://doi.org/10.1029/2022WR033454>
- Bohr, G. S., & Aguado, E. (2001). Use of April 1 SWE measurements as estimates of peak seasonal snowpack and total cold-season precipitation. *Water Resources Research*, 37(1), 51–60. <https://doi.org/10.1029/2000WR900256>
- Brooks, P. D., Gelderloos, A., Wolf, M. A., Jamison, L. R., Strong, C., Solomon, D. K., et al. (2021). Groundwater-mediated memory of past climate controls water yield in snowmelt-dominated catchments. *Water Resources Research*, 57(10), e2021WR030605. <https://doi.org/10.1029/2021WR030605>
- Carroll, R. W. H., Bearup, L. A., Brown, W., Dong, W., Bill, M., & Williams, K. H. (2018). Factors controlling seasonal groundwater and solute flux from snow-dominated basins. *Hydrological Processes*, 32(14), 2187–2202. <https://doi.org/10.1002/hyp.13151>
- Castle, S. L., Thomas, B. F., Reager, J. T., Rodell, M., Swenson, S. C., & Famiglietti, J. S. (2014). Groundwater depletion during drought threatens future water security of the Colorado River Basin. *Geophysical Research Letters*, 41(16), 5904–5911. <https://doi.org/10.1002/2014GL061055>
- Cook, B. I., & Seager, R. (2013). The response of the North American Monsoon to increased greenhouse gas forcing. *Journal of Geophysical Research: Atmospheres*, 118(4), 1690–1699. <https://doi.org/10.1002/jgrd.50111>
- Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., et al. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, 28(15), 2031–2064. <https://doi.org/10.1002/joc.1688>
- Fatichi, S., Ivanov, V. Y., & Caporali, E. (2012). Investigating interannual variability of precipitation at the global scale: Is there a connection with seasonality? *Journal of Climate*, 25(16), 5512–5523. <https://doi.org/10.1175/JCLI-D-11-00356.1>
- Gangopadhyay, S., Woodhouse, C. A., McCabe, G. J., Routson, C. C., & Meko, D. M. (2022). Tree rings reveal unmatched 2nd century drought in the Colorado River Basin. *Geophysical Research Letters*, 49(11), e2022GL098781. <https://doi.org/10.1029/2022GL098781>
- Gray, S. T., Lukas, J. J., & Woodhouse, C. A. (2011). Millennial-length records of streamflow from three major upper Colorado River Tributaries. *JAWRA Journal of the American Water Resources Association*, 47(4), 702–712. <https://doi.org/10.1111/j.1752-1688.2011.00535.x>
- Hamlet, A. F., & Lettenmaier, D. P. (2005). Production of temporally consistent gridded precipitation and temperature fields for the continental United States. *Journal of Hydrometeorology*, 6(3), 330–336. <https://doi.org/10.1175/JHM420.1>
- Harpold, A. A., Sutcliffe, K., Clayton, J., Goodbody, A., & Vazquez, S. (2017). Does including soil moisture observations improve operational streamflow forecasts in snow-dominated watersheds? *JAWRA Journal of the American Water Resources Association*, 53(1), 179–196. <https://doi.org/10.1111/1752-1688.12490>
- Henn, B., Newman, A. J., Livneh, B., Daly, C., & Lundquist, J. D. (2018). An assessment of differences in gridded precipitation datasets in complex terrain. *Journal of Hydrology*, 556, 1205–1219. <https://doi.org/10.1016/j.jhydrol.2017.03.008>
- Jia, A., Wang, D., Liang, S., Peng, J., & Yu, Y. (2022). Global daily actual and snow-free blue-sky land surface albedo climatology from 20-year MODIS products. *Journal of Geophysical Research: Atmospheres*, 127(8), e2021JD035987. <https://doi.org/10.1029/2021JD035987>
- Knowles, N., & Cayan, D. R. (2004). Elevational dependence of projected hydrologic changes in the San Francisco estuary and watershed. *Climatic Change*, 62(1), 319–336. <https://doi.org/10.1023/B:CLIM.0000013696.14308.b9>

- Kouki, K., Luojus, K., & Riihelä, A. (2023). Evaluation of snow cover properties in ERA5 and ERA5-Land with several satellite-based datasets in the Northern Hemisphere in spring 1982–2018. *The Cryosphere*, 17(12), 5007–5026. <https://doi.org/10.5194/tc-17-5007-2023>
- Lundquist, J. D., Hughes, M., Henn, B., Gutmann, E. D., Livneh, B., Dozier, J., & Neiman, P. (2015). High-elevation precipitation patterns: Using snow measurements to assess daily gridded datasets across the Sierra Nevada, California. *Journal of Hydrometeorology*, 16(4), 1773–1792. <https://doi.org/10.1175/JHM-D-15-0019.1>
- Mahanama, S., Livneh, B., Koster, R., Lettenmaier, D., & Reichle, R. (2012). Soil moisture, snow, and seasonal streamflow forecasts in the United States. *Journal of Hydrometeorology*, 13(1), 189–203. <https://doi.org/10.1175/JHM-D-11-046.1>
- McCabe, G. J., & Clark, M. P. (2005). Trends and variability in snowmelt runoff in the western United States. *Journal of Hydrometeorology*, 6(4), 476–482. <https://doi.org/10.1175/JHM428.1>
- McCabe, G. J., & Wolock, D. M. (2011). Independent effects of temperature and precipitation on modeled runoff in the conterminous United States. *Water Resources Research*, 47(11). <https://doi.org/10.1029/2011WR010630>
- Miller, M. P. (2012). The influence of reservoirs, climate, land use and hydrologic conditions on loads and chemical quality of dissolved organic carbon in the Colorado River. *Water Resources Research*, 48(12). <https://doi.org/10.1029/2012WR012312>
- Miller, M. P., Buto, S. G., Susong, D. D., & Rumsey, C. A. (2016). The importance of base flow in sustaining surface water flow in the Upper Colorado River Basin. *Water Resources Research*, 52(5), 3547–3562. <https://doi.org/10.1002/2015WR017963>
- Modi, P. A., Small, E. E., Kasprzyk, J., & Livneh, B. (2022). Investigating the role of snow water equivalent on streamflow predictability during drought. *Journal of Hydrometeorology*, 23(10), 1607–1625. <https://doi.org/10.1175/JHM-D-21-0229.1>
- Moore, C. (2012). *A climatological study of snow covered areas in the western United States*. [M.S., Colorado State University]. Retrieved from <https://www.proquest.com/docview/1020419036/abstract/B5141253E392497DPQ/1>
- 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>
- Nowak, K., Hoerling, M., Rajagopalan, B., & Zagona, E. (2012). Colorado River Basin hydroclimatic variability. *Journal of Climate*, 25(12), 4389–4403. <https://doi.org/10.1175/JCLI-D-11-00406.1>
- O'Leary, D., Hall, D., Medler, M., & Flower, A. (2018). Quantifying the early snowmelt event of 2015 in the Cascade Mountains, USA by developing and validating MODIS-based snowmelt timing maps. *Frontiers of Earth Science*, 12(4), 693–710. <https://doi.org/10.1007/s11707-018-0719-7>
- Pascale, S., Boos, W. R., Bordoni, S., Delworth, T. L., Kapnick, S. B., Murakami, H., et al. (2017). Weakening of the North American monsoon with global warming. *Nature Climate Change*, 7(11), 806–812. <https://doi.org/10.1038/nclimate3412>
- Pribulick, C. E., Foster, L. M., Bearup, L. A., Navarre-Sitchler, A. K., Williams, K. H., Carroll, R. W. H., & Maxwell, R. M. (2016). Contrasting the hydrologic response due to land cover and climate change in a mountain headwaters system: Contrasting hydrologic response from land cover and climate change. *Ecology*, 97(8), 1431–1438. <https://doi.org/10.1002/eco.1779>
- Priestley, C. H. B., & Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, 100(2), 81–92. [https://doi.org/10.1175/1520-0493\(1972\)100<0081:OTAOSH>2.3.CO;2](https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2)
- Raleigh, M. S., & Lundquist, J. D. (2012). Comparing and combining SWE estimates from the SNOW-17 model using PRISM and SWE reconstruction. *Water Resources Research*, 48(1). <https://doi.org/10.1029/2011WR010542>
- Ryken, A. E. C., Gochis, D., & Maxwell, R. (2020). Unraveling groundwater contributions to evapotranspiration in a mountain headwaters: Using eddy covariance to constrain water and energy fluxes in the East River Watershed. *Authorea Preprints*. <https://doi.org/10.22541/au.159559979.93668749>
- Salehabadi, H., Tarboton, D. G., Udall, B., Wheeler, K. G., & Schmidt, J. C. (2022). An assessment of potential severe droughts in the Colorado River Basin. *JAWRA Journal of the American Water Resources Association*, 58(6), 1053–1075. <https://doi.org/10.1111/1752-1688.13061>
- Singer, M. B., Asfaw, D. T., Rosolem, R., Cuthbert, M. O., Miralles, D. G., MacLeod, D., et al. (2021). Hourly potential evapotranspiration at 0.1° resolution for the global land surface from 1981-present. *Scientific Data*, 8(1), 224. <https://doi.org/10.1038/s41597-021-01003-9>
- Sprenger, M., Carroll, R. W. H., Dennedy-Frank, J., Siirila-Woodburn, E. R., Newcomer, M. E., Brown, W., et al. (2022). Variability of snow and rainfall partitioning into evapotranspiration and summer runoff across nine mountainous catchments. *Geophysical Research Letters*, 49(13), e2022GL099324. <https://doi.org/10.1029/2022GL099324>
- Stewart, I. T., Cayan, D. R., & 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>
- Van Kirk, R. W., & Naman, S. W. (2008). Relative effects of climate and water use on base-flow trends in the Lower Klamath Basin. *JAWRA Journal of the American Water Resources Association*, 44(4), 1035–1052. <https://doi.org/10.1111/j.1752-1688.2008.00212.x>
- Vano, J. A., & Lettenmaier, D. P. (2014). A sensitivity-based approach to evaluating future changes in Colorado River discharge. *Climatic Change*, 122(4), 621–634. <https://doi.org/10.1007/s10584-013-1023-x>
- Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., et al. (2014). Understanding uncertainties in future Colorado River Streamflow. *Bulletin of the American Meteorological Society*, 95(1), 59–78. <https://doi.org/10.1175/BAMS-D-12-00228.1>
- Vose, R. S., Applequist, S., Squires, M., Durre, I., Menne, M. J., Williams, C. N., et al. (2014). Improved historical temperature and precipitation time series for U.S. Climate divisions. *Journal of Applied Meteorology and Climatology*, 53(5), 1232–1251. <https://doi.org/10.1175/JAMC-D-13-0248.1>
- Weiß, M., & Menzel, L. (2008). A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments. *Advances in Geosciences*, 18, 15–23. <https://doi.org/10.5194/adgeo-18-15-2008>
- Xu, C., Wang, W., Hu, Y., & Liu, Y. (2024). Evaluation of ERA5, ERA5-Land, GLDAS-2.1, and GLEAM potential evapotranspiration data over mainland China. *Journal of Hydrology: Regional Studies*, 51, 101651. <https://doi.org/10.1016/j.ejrh.2023.101651>