How Will Baseflow Respond to Climate Change in the Upper Colorado River Basin?

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Abstract  Baseflow is critical to sustaining streamflow in the Upper Colorado River Basin. Therefore, effective water resources management requires estimates of baseflow response to climatic changes. This study provides the first estimates of projected baseflow changes from historical (1984–2012) to thirty-year periods centered around 2030, 2050, and 2080 under warm/wet, median, and hot/dry climatic conditions using a hybrid statistical-deterministic baseflow model. Total baseflow supplied to the Lower Colorado River Basin may decline by up to 33%, although this value may increase in the near future by 6% under warm/wet conditions. The percentage of baseflow lost during in-stream transport is projected to increase by 1%–5% relative to historical conditions. Results highlight that climate-driven changes in high-elevation hydrology have impacts on basinwide water availability. Study results have implications for human and ecological water availability in one of the most heavily managed watersheds in the world.

Plain Language Summary  Baseflow (groundwater flowing to streams) is estimated to contribute over 50% of the total streamflow in the Upper Colorado River Basin and is thus crucial for sustaining ecological and human water needs in this highly managed area. Baseflow may be sensitive to changing climate, but the sensitivity is not well constrained. To estimate baseflow response to climate change, we tested how warm/wet, median, and hot/dry future climate scenarios affect baseflow in the basin using a hydrologic model. Results show that the largest declines in baseflow may occur in the headwater streams, and the total baseflow delivered to the Lower Colorado River Basin may decline by up to 33%, although delivery may increase in the near future by 6% under a warm/wet climate. We hypothesize that basinwide baseflow declines because of greater increases in evapotranspiration relative to precipitation in the future. Baseflow loss during in-stream transport is projected to increase by 1%–5%. The changes in baseflow may affect both human and ecological water users in an area where water supply does not always meet demand.

1. Introduction

The southwestern United States has substantially changed since 1900, with warming temperatures, diminishing precipitation and streamflows, worsening drought, and growth in population, irrigated agricultural land, and water withdrawals (MacDonald, 2010). The region is currently experiencing its worst drought in recorded history, with the period from 2000 to 2018 being the driest 19-year period since the late 1500s and the second driest since 800 Common Era (Williams et al., 2020). Despite little change in precipitation in the Upper Colorado River Basin (UCRB) between 1896 and 2019, temperatures have risen (Tillman et al., 2020) and water supplies in the basin have suffered (Udall & Overpeck, 2017). This recent drought has strained water resources and led to Congress passing the Colorado River Basin Drought Contingency Plan (DCP) Authorization Act in 2019. The DCP outlines agreements for Colorado River Basin (CRB) stakeholders to collaborate to reduce the risk that large Colorado River reservoirs (Lake Powell and Lake Mead) decline to critically low elevations. Despite these efforts, both reservoirs reached historic low elevations in 2021 (Bureau of Reclamation, 2021a, 2021b).
Future climate change is expected to increase temperatures and change precipitation in the UCRB and may exacerbate drought (Lukas & Payton, 2020). The potential effects of climate change on basinwide hydrology has led to concern about future regional water availability. Water shortages may affect the ecosystems, the 40 million people, at least 29 federally recognized Tribes, and Mexico that rely on the Colorado River for municipal, agricultural, recreational, spiritual, and hydropower generation use (Bureau of Reclamation, 2012, 2018). Information on the range of hydrologic conditions that we might expect under a changing climate helps water managers plan to avoid the negative consequences of water shortages.

Approximately 85%–90% of the total water year runoff in the CRB starts in the UCRB (McCabe & Wolock, 2020). On average, over half (56%) of the UCRB (Figure 1) streamflow originates as baseflow, a proxy for groundwater discharge to streams across the full discharge distribution, highlighting the importance of baseflow in sustaining surface water (Miller et al., 2016). Baseflow also influences stream water quality in the basin (Rumsey et al., 2017). While many studies have predicted surface runoff (total streamflow including baseflow) response to climate change and anthropogenic activities in the UCRB (Bureau of Reclamation, 2012, 2021c; Christensen & Lettenmaier, 2007; Christensen et al., 2004; McCabe & Wolock, 2007; Milly & Dunne, 2020; Miller et al., 2021; Udall & Overpeck, 2017; Vano et al., 2014), less is known about baseflow response to climate change and it is also not widely considered in water management planning. Considering baseflow could be useful for water resources and ecosystem management and planning.

Declining baseflow trends across the Southwest (1980–2010) have been linked to increases in potential evapotranspiration (Ficklin et al., 2016). Of the estimated 64.8 cubic kilometers (km³) of the total freshwater lost between 2004 and 2013 in the CRB, groundwater storage losses are estimated at 50.1 km³, indicating

Figure 1. Map showing the Upper Colorado River Basin study area.
greater losses of groundwater than surface water (Castle et al., 2014). Increased demand for groundwater in response to reduced surface water availability and potential recharge changes (Meixner et al., 2016; Tillman et al., 2020) may reduce future groundwater storage (Rahaman et al., 2019). Systems that rely on groundwater (aquifers, streams, and groundwater-dependent ecosystems) face increased pressure from water consumption, irrigation, and climate change (Klove et al., 2014). As surface water supplies dwindle, users may increasingly turn to groundwater; however, increased groundwater use may lead to further declines in baseflow and total streamflow (Swanson et al., 2020).

Given the quantified importance of baseflow in sustaining streamflow, effective water resources management in the basin requires estimates of baseflow response to projected climate change. This is particularly important considering the current severe drought and declining reservoir levels (Castle et al., 2014; Williams et al., 2020). Consideration of baseflow as a primary component of the water supply is critical to integrated water resources management in the UCRB. The goals of this study are to characterize the UCRB baseflow response to warm/wet (WW), median (M), and hot/dry (HD) future climate scenarios and identify where and when changes may occur. To our knowledge, these are the first projections of baseflow response to climate change for the UCRB. We also explore specific mechanisms driving changes and potential ecological implications.

2. Methods

We applied projections of future climate to a calibrated hybrid statistical-deterministic baseflow model (SPARROW) to estimate future baseflow changes in the UCRB (Figure 1) under WW, M, and HD climatic conditions for the thirty-year periods centered around 2030, 2050, and 2080 compared to the 1984–2012 historical period (Figure S1 in Supporting Information S1).

2.1. Climate Data Description and Processing

The UCRB baseflow SPARROW model input includes temperature (T), precipitation (P), and runoff (R). Historical T and P from the Parameter-elevation Regressions On Independent Slopes Model (PRISM, Daly et al., 2008) and R from the monthly water balance model (MWBM, Hostetler & Alder, 2016; Wolock & McCabe, 1999) were used to estimate baseflow for the historical period as in Miller et al. (2016). Projections of T and P were obtained from the National Aeronautics and Space Administration (NASA) Earth Exchange Downscaled Climate Projections (NEX-DCP30) data set, and projections of R and actual evapotranspiration (ET_A) were obtained from MWBM using NEX-DCP30 T and P as input (Hostetler & Alder, 2016; Thrasher et al., 2013).

The NEX-DCP30 data were used because they provide bias-corrected climate change projections at a resolution (800 m, 30-arc seconds, Thrasher et al., 2013), high enough to evaluate impacts on processes that are sensitive to small-scale climate gradients and the effects of local topography, both of which are common in the UCRB. During NEX-DCP30 data set development, the Bias-Correction Spatial Disaggregation (BCSD) downscaling method was applied to translate coarser resolution general circulation model (GCM) output derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to the common high-resolution 800-m PRISM grid (Taylor et al., 2012; Thrasher et al., 2013). The BCSD approach adjusts GCM data to remove bias and better match the historical record. Details regarding downscaling approach and limitations are included in the Supporting Information S1.

Numerous strategies to select climate change scenarios for hydrologic analysis exist and each has benefits and drawbacks (Bureau of Reclamation, 2016). Given our focus on understanding the baseflow response to general climate change scenarios, the long-term average calibration of the SPARROW model, and the uncertainties and biases associated with future climate projections from individual GCMs, we used climate scenario-specific T and P (instead of GCM-specific T and P) to evaluate baseflow response to climate change. Future WW, M, and HD climate scenarios for the 30-year periods centered on the 2030s (2020–2049), 2050s (2040–2069), and 2080s (2070–2099) were selected by evaluating the changes in basin-averaged T and P over the UCRB for each future period relative to the historical period (1984–2012) developed in Miller
et al. (2016). The HD scenario uses the 5 downscaled models closest to the 90th percentile change in $T$ and tenth percentile change in $P$, the M scenario uses those closest to the median change in $T$ and $P$, and the WW scenario uses those closest to the tenth percentile change in $T$ and 90th percentile change in $P$. Specific GCMS and Representative Concentration Pathways (RCPs) used are provided in Table S1 in Supporting Information S1. Climate scenarios use both RCP8.5 and RCP4.5.

Period and scenario-specific perturbations were applied to the historical $T$ and $P$ data to calculate future $T$ and $P$. Perturbations were done on a cell-by-cell basis using the Hybrid Delta Ensemble (HDe) approach, which shifts the historical time series at each percentile in the distribution using cell-specific cumulative distribution functions of monthly values from all years and models in that climate scenario and time period (Hamlet et al., 2010). Future $R$ values were estimated by applying future $T$ and $P$ projections to the MWBM and accumulating and bias-correcting period-averaged mean annual $R$ through the stream network (see Supporting Information S1).

### 2.2. SPARROW Baseflow Model

Baseflow in the UCRB was simulated using the long-term average SPARROW model. SPARROW is a spatially explicit hybrid statistical and process-based model that estimates mean baseflow over the simulation period in streams by linking monitoring data with information on watershed characteristics and baseflow sources, routed through a stream network (Miller et al., 2016). The model uses nonlinear least squares regression with mass balance constraints to characterize the spatial relationship between baseflow estimates, derived using site-specific conductivity mass balance models, and (a) sources of water to streams, (b) controls on delivery of baseflow to streams, and (c) in-stream water loss in a watershed under long-term conditions. Full details on model calibration have been previously described (Miller et al., 2016) and are summarized here. Additional details are provided in the Supporting Information S1.

Mean annual baseflow for 1984–2012 was estimated at 146 calibration sites using conductivity mass balance hydrograph separation (Miller et al., 2016; Rumsey et al., 2015). At the regional scale, precipitation controls the spatial variability in baseflow (Miller et al., 2016). Two explanatory variables represent sources of baseflow in the model: $P$ on crystalline and volcanic rocks (coefficient $\beta = 29,000 \text{ m}^3 \text{cm}^{-1}$) and $P$ on sedimentary rocks ($\beta = 30,000 \text{ m}^3 \text{cm}^{-1}$). Topographic relief represents baseflow transport to streams ($\beta = 0.06 \text{ m}$). In-stream loss of baseflow is estimated using a discrete functional form where four stream classifications were defined based on discharge and air temperature in each reach. Classes represent low discharge ($Q$) and cooler temperatures ($T = 0.27 \text{ day}^{-1}$), low $Q$ and warmer $T (\beta = 0.70 \text{ day}^{-1}$), intermediate $Q$ and warmer $T (\beta = 0.12 \text{ day}^{-1})$, and high $Q$ and warmer $T (\beta = 0.03 \text{ day}^{-1})$. This description assumes that evaporative losses are greatest under low flow and high-temperature conditions.

Period and scenario-specific mean $T$, $P$, and $R$ were applied to the calibrated SPARROW baseflow model (using historical model coefficients) to predict changes in future baseflow relative to historical estimates. This approach assumes that future groundwater storage and water management are equal to storage and management during the historical period, which are sources of uncertainty in the model. The results are presented as the incremental baseflow, which represents the baseflow generated in each catchment, as well as the total (accumulated) baseflow, which represents the baseflow that would be estimated in a stream at a given location. The SPARROW model also estimates the amount of incremental baseflow in a given catchment that flows to the basin outlet, referred to as the delivered fraction.

### 3. Results

Precipitation is projected to decrease under the HD scenario at all time periods and increase under the WW and M climate scenarios for all time periods (Table S2, Figure S2 in Supporting Information S1). Temperature is projected to increase across all climate scenarios and time periods with the greatest increases occurring in the 2080s under the HD scenario (Table S2, Figure S3 in Supporting Information S1). Projected $P$ changes vary more across the basin than $T$ changes. Precipitation increases in many headwater catchments across all time periods and climate scenarios, although this is less widespread under the HD scenario.
Baseflow changes are projected in response to climate change. Total projected baseflow generation (sum of incremental baseflow over the basin) increases range from 7% to 9% (0.87, 0.99, and 1.22 km³ yr⁻¹ for 2080, 2050, and 2030s WW, respectively; Table S3 in Supporting Information S1) and total baseflow generation range declines from –3 to –16% (–0.39 to –2.16 km³ yr⁻¹ for 2050s M and 2080s HD, respectively; Table S3 in Supporting Information S1). Total baseflow at the UCRB outlet at Lees Ferry is projected to increase by up to 6% (0.20 km³ yr⁻¹ for 2030s WW) and to decline from –3 to –33% (–0.11 to –1.16 km³ yr⁻¹ for 2080s WW and 2080s HD, respectively; Table S3 in Supporting Information S1).

Historically, 27% of the baseflow generated in the UCRB was delivered to the outlet. In-stream loss was largely attributed to evapotranspiration (ET) and irrigation withdrawals (Miller et al., 2016). The percentage of baseflow generated in the UCRB that is projected to be delivered, after in-stream losses, to Lees Ferry decreases under all time periods and climate scenarios between 1% and 5% (Table S3 in Supporting Information S1).

Patterns of baseflow change vary spatially and temporally (Figure 2, Figure S4 in Supporting Information S1). The largest incremental baseflow changes occur in higher elevation headwater catchments with substantial basinwide effects (Figure 2). Across all climate scenarios and time periods, baseflows in high-elevation headwater catchments are projected to change the most. The greatest and most widespread baseflow declines are projected under the HD scenarios, whereas the greatest and most widespread baseflow increases are projected under the WW scenarios. All three climate scenarios project greater and more widespread declines in baseflow generation and delivery to Lees Ferry with time (Figure 2).

Total baseflow changes as incremental baseflow changes. The projected incremental and total baseflow increases generally diminish and the declines generally increase with time (Figure 2, Figures S4 and S5 in Supporting Information S1). Additionally, the HD and M scenarios project growing declines in baseflow generation with time consistent with the projected declines in P and increases in T, while the WW scenario projects diminishing increases in baseflow generation with time as T increases and despite P increases (Figure 2, Figures S2–S5 in Supporting Information S1). Main-stem rivers are projected to have the largest total baseflow declines across all time periods and climate scenarios relative to tributaries (Figure S4 in Supporting Information S1) as they integrate upstream baseflow generation changes and in-stream loss due to processes such as ET, consumptive use, and groundwater recharge. Generally, total baseflow declines are greatest and most widespread under the HD scenario, followed by the M scenario and the WW scenario, which has the most increases (Figures S4 and S5 in Supporting Information S1). The mean percent change in total baseflow declines or stabilizes with time for all climate scenarios (Figure S5 in Supporting Information S1). Despite increased incremental baseflow generation in some areas, particularly under the WW scenario, baseflow at the UCRB outlet declines across all time periods and climate scenarios, except the 2030s WW, where baseflow at the outlet is projected to increase by 6% (Figure 2, Table S3 in Supporting Information S1).

Reductions in the fraction of baseflow leaving a reach that is delivered to Lees Ferry in headwater catchments drive reductions in total delivered baseflow, despite opposing changes in low-elevation catchments (Figure 3). Declines in the fraction of baseflow delivered to the UCRB outlet are greatest in catchments in the Rocky Mountains and headwaters of the Green River. The land area with greater than 50% declines in the delivered baseflow fraction generally increases with time for all time periods and climate scenarios. Increases in delivered baseflow fraction are projected for lower elevation catchments for the WW and M scenarios at all time periods, although they are most widespread under the WW scenarios, and the magnitude and extent decrease with time. Projected increases in delivered baseflow fraction at lower elevation areas do not balance losses upstream, resulting in net declines in the percentage of baseflow generated in the basin that is delivered to Lees Ferry across all time periods and climate scenarios (Figure 3 and Table S3 in Supporting Information S1).

4. Discussion

4.1. Drivers of Change

Declines in water originating as baseflow delivered to Lees Ferry and the substantial declines in incremental baseflow projected for headwater catchments contrast with the projections of increased P in high-elevation areas, with some exceptions where P is projected to decrease (southern/central Rocky Mountains, especially
Figure 2. Maps showing catchment-scale incremental baseflow anomalies with time for the warm/wet, median, and hot/dry climate scenarios in the Upper Colorado River Basin and the change in the sum of incremental anomalies relative to the total change in baseflow at the basin outlet for each time period and climate scenario.
the HD scenario in the 2080s, Figure S4 in Supporting Information S1). Temperature-driven changes to surface water balance through increases in ET may account for projected declines in catchment-scale baseflow generation and baseflow delivery to Lees Ferry (Figure 2). Even under the WW scenario, where P increases across the entire basin, baseflow at the UCRB outlet declines by the 2080s, suggesting that T and ET increases drive baseflow declines. This response indicates that ET may be somewhat represented by in-stream loss coefficients in the baseflow model, which are a function of T. The importance of T and ET is consistent with previous work investigating the climate impacts on streamflow that emphasize the influence of T and ET on streamflow, and snowmelt-driven streamflow in particular, in the UCRB (Milly & Dunne, 2020; Woodhouse et al., 2016; Xiao et al., 2018).

Although we cannot directly evaluate the effects of changing ET on baseflow with the SPARROW baseflow model, a comparison of the spatial patterns of change in P and ET, with changes in incremental baseflow suggests that changes in P and ET may drive observed patterns in baseflow changes (Figure 2, Figures S2 and S6 in Supporting Information S1). Figure 4 compares changes in net water gain or loss as represented by changes in P×T relative to changes in incremental baseflow aggregated to the Hydrologic Unit Code (HUC) eight scale by mean HUC elevation. Incremental baseflow declines when increases in ET exceed changes in P (net water loss to the atmosphere), and incremental baseflow increases when P increases exceed ET changes (net water gain from the atmosphere). The M and HD scenarios project increased losses of water to the atmosphere relative to historical conditions at high-elevation HUCs, which may explain the spatial patterns of baseflow change. High-elevation areas may experience greater projected impacts because the coefficients for in-stream loss are greater for streams with lower discharge, which are more common in headwater areas. These findings agree with the projections of increased ET at high elevations by Calanca et al. (2006) and Condon et al. (2020). Condon et al. (2020) identified greater increases in ET in more humid areas relative to arid regions because groundwater is deeper and more disconnected from the land surface in arid areas. In headwater catchments, groundwater is more likely shallow and connected to the land surface. Consequently, increased ET would have a larger effect on subsurface storage and presumably baseflow. Changes to P and T seasonality, snow processes (timing, phase, and amount), and recharge may also be important controls on baseflow response but we cannot assess these effects with the current model.

4.2. Effects of Change

Taken together, study findings highlight the impacts that climate change in headwater areas have on basin-wide hydrology and water availability. Projected reductions in baseflow may affect future surface water availability, given the reliance of streamflow on baseflow, that may impact a range of water users including human (e.g., agriculture or municipal and industrial systems) and environmental users. The Colorado River Compact apportions 7.5 million acre-feet per year (maf/yr) to both the Upper and Lower CRB, with 2.8, 4.4, and 0.3 maf/yr apportioned among Arizona, California, and Nevada, respectively, in the Boulder Canyon Project Act, 1928, and 1.5 maf/yr apportioned to Mexico under the Mexican Water Treaty of 1944 (Boulder Canyon Project Act, 1928; Colorado River Compact, 1922; Utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande—Treaty between the United States of America and Mexico, 1944). Baseflow declines of 0.11–1.16 km$^3$ yr$^{-1}$ (0.09–0.94 maf/yr) in the 2080s period under the WW and HD scenarios could limit UCRB abilities to meet legal obligations to the Lower CRB, whereas increases of up to 0.20 km$^3$ yr$^{-1}$ (0.16 maf/yr) under the 2030s WW scenario could support meeting legal obligations. Substantial baseflow declines will also drive streamflow declines. Indeed, UCRB streamflow is projected to diminish, and study findings are consistent with spatial and temporal patterns of projected future streamflow change (Miller et al., 2021). Reduced groundwater levels, inferred from decreased baseflow, may also induce
streams to recharge groundwater aquifers (as losing streams) by reversing or creating downward hydraulic gradients (Kløve et al., 2014).

By sustaining surface water during non-runoff periods, baseflow is critical for ecosystem health and function. Reductions in baseflow threaten aquatic, riparian, and terrestrial ecosystems by reducing their water supply and altering thermal regimes (Carlisle et al., 2014), with water stress effects exacerbated during drought. Reduced baseflow and groundwater levels (below root depth) may influence survival, location, and species composition of terrestrial and riparian vegetation as vegetation responds to changing water availability (Candela et al., 2009; Naumburg et al., 2005). Impacts on riparian systems may threaten flora and fauna that depend on these ecosystems for survival. Moreover, the increases in delivered baseflow fraction lower in the basin may not balance impacts on ecological systems or water users higher in the basin.

**Figure 4.** Scatter plots showing the change in fractional incremental baseflow compared to the percent change in precipitation minus the change in actual evapotranspiration ($\Delta P - \Delta ET_A$) at the Hydrologic Unit Code (HUC) eight scale by mean elevation with time for the warm/wet, median, and hot/dry scenarios in the Upper Colorado River Basin. Points at the origin show no change from historical conditions. Points above the 1:1 line suggest that the ratio of baseflow to runoff increases and points below the 1:1 line suggest that the ratio of baseflow to runoff decreases.
Reductions in stream low flows, often supported by cold groundwater discharge to streams, have been related to increases in surface water temperature (Kløve et al., 2014), which could affect the survival of aquatic species such as trout that depend on cold water refugia. Because of the important role the baseflow plays in delivering dissolved solids and other solutes to streams (Gabor et al., 2017; Miller et al., 2017; Rumsey et al., 2017), baseflow changes may alter stream chemistry, with potential ecological effects as well. Our study indicates greater declines in baseflow higher in the basin and lesser declines and increases in baseflow lower in the basin. This pattern suggests that the projected baseflow changes may increase dissolved solids loading to the UCRB because the baseflow declines occur in areas where baseflow contributes lower dissolved solid loads, while the baseflow increases occur in areas where baseflow contributes higher dissolved solid loads (Rumsey et al., 2017). Projected climate-induced baseflow changes could reverse the long-term dissolved solids decline observed in UCRB streams throughout the twentieth century (Rumsey et al., 2021).

4.3. Future Research

The groundwater response to climate change is highly uncertain (Meixner et al., 2016; Smerdon, 2017). Changes to P and T seasonality, snow processes, extreme events, recharge, and groundwater storage may also be important controls on baseflow response, but the SPARROW model does not explicitly represent these processes; future work could consider changes to these key factors at appropriate spatial scales. UCRB hydrology depends on snowmelt, and changes to snow (timing, phase, and amount) would likely impact baseflow through changes to recharge. Our focus on the long-term average conditions, at the expense of considering extreme events that can substantially affect recharge (Masbruch et al., 2016), represents a source of uncertainty. The timing of climate impacts on baseflow will depend on groundwater transit times, which are not included in this work. Additionally, the “wetting” effect induced by quantile mapping as part of BCSD process (Lukas & Payton, 2020) may impart a wet bias to our study results and so the actual baseflow losses could be greater. A temporally dynamic integrated streamflow, groundwater flow, and baseflow model that also considers water quality and use would support a more complete evaluation of the effects of climate change on water availability.

5. Conclusions

Water shortages threaten the wide range of human and ecological uses supported by the Colorado River. Because baseflow sustains a substantial portion of surface flows in the UCRB, there is a need to understand baseflow response to future climate. Our study provides the first projections of baseflow response to climate change across the UCRB. The results suggest that despite potential increases in both P and baseflow in some areas, water originating as baseflow supplied to the Lower CRB is projected to decline by up to 33%, although delivery may increase in the near future by 6% under WW conditions. The percentage of baseflow lost during in-stream transport is projected to increase by 1%–5% relative to historical conditions due to processes such as increased ET losses that reduce the fraction of baseflow delivered to the UCRB outlet. Study findings highlight the importance of changes in baseflow generation in high-elevation catchments for basin-scale water availability. The projected baseflow changes are expected to impact both human and ecological users with the greatest declines occurring under the HD scenario. By the end of the 21st century, the projected baseflow increases lower in the basin (particularly under the WW and M scenarios) are neither sufficient to compensate for the declines projected in headwater reaches nor do they compensate for the effects on water users higher in the basin. These effects may be most salient for users such as ecological communities that cannot obtain alternative water supplies. Study findings suggest that ongoing water availability challenges in the CRB may continue and be exacerbated in the future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.
Data Availability Statement

Climate scenarios used were developed from the NEX-DCP30 data set, prepared by the Climate Analytics Group and NASA Ames Research Center using the NASA Earth Exchange and distributed by the NASA Center for Climate Simulation (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-dcp30). Study model input and output data are available from Longley et al. (2021) at https://www.sciencedbase.gov/catalog/item/60e86ce6d34e2a7685d7f1e5. Associated stream network shapefiles are available from Buto et al. (2017) at https://www.sciencedbase.gov/catalog/item/588a4fe4e4b0ba3b075e9798.

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References

Hamlet, A., & Carrasco, P. (2010). Statistical downscaling techniques for global climate model simulations of temperature and precipitation with application to water resources planning studies. In Chapter 4 in final report for the Columbia basin climate change scenarios project (pp. 28). University of Washington, Seattle: Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean.

Hostetler, S. W., & Alder, J. R. (2016). Implementation and evaluation of a monthly water balance model over the US on an 800 m grid. Water Resources Research, 52, 9600–9620. https://doi.org/10.1002/2016WR018665

Klove, B., Ala-Aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kverner, J., et al. (2014). Climate change impacts on groundwater and dependent ecosystems. Journal of Hydrology, 518, 250–266.

Longley, P. C., Miller, O. L., Miller, M. P., Alder, J. R., Bearup, L., Pruitt, T., & McKinney, T. S. (2021). Sparrow model inputs and simulated future baselaw for streams of the upper Colorado River basin. U.S. Geological Survey data release. https://www.sciencedbase.gov/catalog/item/60e86ce6d34e2a7685d7f1e5

Lukas, J., & Payton, E. (2020). Colorado River Basin climate and hydrology: State of the science. Western Assessment, University of Colorado Boulder. https://doi.org/10.25810/3hec-w477

MacDonald, G. M. (2010). Water, climate change, and sustainability in the Southwest. Proceedings of the National Academy of Sciences of the United States of America, 107(50), 21256–21262. https://doi.org/10.1073/pnas.0909651107

Boulder Canyon Project Act (1928). Retrieved from https://www.usbr.gov/lc/region/pao/pdf/files/bcpact.pdf

Hamlet, A., Salathe, E., & Carrasco, P. (2010). Statistical downscaling techniques for global climate model simulations of temperature and precipitation with application to water resources planning studies. In Chapter 4 in final report for the Columbia basin climate change scenarios project (pp. 28). University of Washington, Seattle: Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean.

Hostetler, S. W., & Alder, J. R. (2016). Implementation and evaluation of a monthly water balance model over the US on an 800 m grid. Water Resources Research, 52, 9600–9620. https://doi.org/10.1002/2016WR018665

Klove, B., Ala-Aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kverner, J., et al. (2014). Climate change impacts on groundwater and dependent ecosystems. Journal of Hydrology, 518, 250–266.

Longley, P. C., Miller, O. L., Miller, M. P., Alder, J. R., Bearup, L., Pruitt, T., & McKinney, T. S. (2021). Sparrow model inputs and simulated future baselaw for streams of the upper Colorado River basin. U.S. Geological Survey data release. https://www.sciencedbase.gov/catalog/item/60e86ce6d34e2a7685d7f1e5

Lukas, J., & Payton, E. (2020). Colorado River Basin climate and hydrology: State of the science. Western Assessment, University of Colorado Boulder. https://doi.org/10.25810/3hec-w477

MacDonald, G. M. (2010). Water, climate change, and sustainability in the Southwest. Proceedings of the National Academy of Sciences of the United States of America, 107(50), 21256–21262. https://doi.org/10.1073/pnas.0909651107

Bureau of Reclamation. (2012). Colorado River Basin water supply and demand study: Study report. Retrieved from https://www.usbr.gov/lc/region/programs/crbstudy/finalreport/

Bureau of Reclamation (2021a). Lower Colorado River Operations. Lake Mead at Hoover Dam, end of month elevation (feet). Retrieved from https://www.usbr.gov/lc/region/g4900/hourly/mead-elv.html

Bureau of Reclamation (2021b). Water operations: Historic data, Lake Powell. Retrieved from https://www.usbr.gov/rsvrWater/Historical-App.html

Bureau of Reclamation (2021c). Water Reliability in the West — 2021 SECURE Water Act Report. Denver, Colorado: Prepared for the United States congress. Bureau of Reclamation, Water Resources and Planning Office.

Bureau of Reclamation. (2016). Considerations for selecting climate projections for water resources, planning, and environmental analyses. Bureau of Reclamation West-wide Climate Risk Assessment Implementation Team.

Bureau of Reclamation (2018). Ten Tribes partnership tribal water study. Retrieved from https://www.usbr.gov/lc/region/programs/crbstudy/ws/finalreport.html

References

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Milly, P. C., & 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.aax0194

Naumburg, E., Mata-Gonzalez, R., Hunter, R. G., McLendon, T., & Martin, D. W. (2005). Phreatophytic vegetation and groundwater fluctuations: A review of current research and application of ecosystem response modeling with an emphasis on Great Basin vegetation. Environmental Management, 35(6), 726–740. https://doi.org/10.1007/s00267-004-0194-7

Rahaman, M. M., Thakur, B., Kalra, A., & Ahmad, S. (2019). Modeling of GRACE-derived groundwater information in the Colorado River Basin. Hydrology, 6(1), 19. https://doi.org/10.3390/hydrology6010019

Rumsey, C. A., Miller, M. P., Schwarz, G. E., Hirschl, R. M., & Susong, D. D. (2017). The role of baseflow in dissolved solids delivery to streams in the upper Colorado River Basin. Hydrological Processes, 31(26), 4705–4718. https://doi.org/10.1002/hyp.11390

Rumsey, C. A., Miller, M. P., Susong, D. D., Tillman, F. D., & Anning, D. W. (2015). Regional scale estimates of baseflow and factors influencing baseflow in the upper Colorado River Basin. Journal of Hydrology: Regional Studies, 4, 9–107.

Rumsey, C. A., Miller, G., Hirschl, R. M., Marston, T. M., & Susong, D. D. (2021). Substantial declines in salinity observed across the Upper Colorado River Basin during the 20th century, 1929–2019. Water Resources Research, 57(5), 1–21. https://doi.org/10.1029/2020WR028581

Smerdon, B. D. (2017). A synopsis of climate change effects on groundwater recharge. Journal of Hydrology, 555, 125–128. https://doi.org/10.1016/j.jhydrol.2017.09.047

Swanson, R. K., Springer, A. E., Kreamer, D. K., Tobin, B. W., & Perry, D. M. (2020). Quantifying the base flow of the Colorado River: Its importance in sustaining perennial flow in northern Arizona and southern Utah (USA). Hydrogeology Journal. https://doi.org/10.1007/s10040-020-02660-5

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93, 485–498. https://doi.org/10.1175/BAMS-D-11-00041.1

Thrasher, B., Xiong, J., Wang, W., Melton, F., Michaelis, A., & Nemani, R. (2013). Downscaled climate projections suitable for resource management. Eos, Transactions American Geophysical Union, 94(37), 321–323. https://doi.org/10.1029/2013EO370002

Tillman, F., Gangopadhyay, S., & Pruitt, T. (2020). Trends in recent historical and projected climate data for the Colorado River Basin and potential effects on groundwater availability. U.S. Geological Survey Scientific Investigations Report, 24. https://doi.org/10.3133/sir20205107

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/10.1002/2016WR019468

Utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande — Treaty between the United States of America and Mexico (1944). Retrieved from https://www.usbr.gov/lc/region/pao/pdf/pdfs/mxtrystv.pdf

Van, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., & Lettenmaier, D. P. (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

Williams, A. P., Cook, E. R., Smerdon, J. E., Cook, B. I., Abatzoglou, J. T., Bolles, K., & Livneh, B. (2020). Large contribution from anthropogenic warming to an emerging North American megadrought. Science, 368(6488), 314–318. https://doi.org/10.1126/science.aaz9605

Wolock, D., & McCabe, G. (1999). Explaining spatial variability in mean annual runoff in the conterminous United States. Climate Research, 11(2), 149–159. https://doi.org/10.3354/cr011149

Woodhouse, C. A., Pederson, G. T., Morino, K., McCabe, 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