ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE
10.1029/2024EF004841

Special Collection:
Multi-Sector Dynamics: Advancing Complex Adaptive Human-Earth Systems Science in a World of Interconnected Risks

Key Points:

- We introduce a multi-site two-state Gaussian Hidden Markov model to explore drought impacts in Colorado's West Slope Basins and Lake Powell
- Internal variability in the hydroclimatic system can cause spatially compounding drought impacts exceeding historically extreme events
- Streamflow declines driven by an optimistic climate change scenario can transition the system to a drier regime and increase drought impacts

Supporting Information:

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

Correspondence to:
D. F. Gold,
d.f.gold@uu.nl

Citation:
Gold, D. F., Gupta, R. S., & Reed, P. M. (2024). Exploring the spatially compounding multi-sectoral drought vulnerabilities in Colorado's West Slope River Basins. *Earth's Future*, *12*, e2024EF004841. https://doi.org/10.1029/2024EF004841

Received 25 APR 2024
Accepted 21 OCT 2024

Author Contributions:
Conceptualization: David F. Gold, Rohini S. Gupta, Patrick M. Reed
Data curation: David F. Gold
Formal analysis: David F. Gold, Rohini S. Gupta
Funding acquisition: Patrick M. Reed
Investigation: David F. Gold
Methodology: David F. Gold, Rohini S. Gupta, Patrick M. Reed
Project administration: Patrick M. Reed

Exploring the Spatially Compounding Multi-Sectoral Drought Vulnerabilities in Colorado's West Slope River Basins

David F. Gold[1], Rohini S. Gupta[2], and Patrick M. Reed[2]

[1]Department of Physical Geography, Utrecht University, Utrecht, The Netherlands, [2]Department of Civil and Environmental Engineering, Cornell University, Ithaca, NY, USA

Abstract The state of Colorado's West Slope Basins are critical headwaters of the Colorado River and play a vital role in supporting Colorado's local economy and natural environment. However, balancing the multi-sectoral water demands in the West Slope Basins while maintaining crucial downstream deliveries to Lake Powell is an increasing challenge for water managers. Internal variability of the hydroclimatic system and climate change complicate future vulnerability assessments. This work contributes a detailed accounting of multi-sectoral drought vulnerability in the West Slope Basins and the impacts of drought on downstream deliveries. We first introduce a novel multi-site Hidden Markov Model (HMM)-based synthetic streamflow generator to create an ensemble of streamflows for all West Slope basins that better characterizes the region's drought extremes. We capture the effects of climate change by perturbing the HMM to generate an ensemble of streamflows reflecting plausible changes in climate. We then route both ensembles through StateMod, Colorado's water allocation model, to evaluate spatially compounding drought impacts across the West Slope Basins. Our results illustrate how drought events emerging from the system's stationary internal variability in the absence of climate change can significantly impact local water uses and deliveries to Lake Powell, exceeding extreme conditions in the historical record. Further, we find that even modest climate change can cause a regime shift where historically low downstream delivery volumes and extreme drought impacts become routine. These results can inform future Colorado River planning efforts, and our methodology can be expanded to other snow-dominated regions that face persistent droughts.

Plain Language Summary The state of Colorado's West Slope Basins - six watersheds within the Colorado River Basin on the western side of the continental divide - are essential water sources for the Colorado River and play a vital role in supporting the state of Colorado's local economy and natural environment. Water managers in the region are challenged by competing water demands for uses such as agriculture, environmental flows, and downstream deliveries to Lake Powell, a critical regional reservoir. Evaluating drought vulnerability in the region is complicated by the inherent randomness of streamflows and reduced flows from climate change. This work contributes a new analysis of local drought vulnerability in the West Slope Basins and the consequences for water deliveries to Lake Powell. We introduce a method to generate streamflow scenarios and explore drought impacts in the West Slope Basins. We run the scenarios through a model of the human-natural system to explore local and regional drought vulnerability. Our results reveal elevated drought risks to downstream water users, agriculture, and the environment, even without climate change. Further, we find that even optimistic climate change projections can exacerbate drought risk, leading to unprecedented challenges for local water users and the broader regional system.

1. Introduction

The Colorado River is often referred to as the "lifeline of the American Southwest," supporting a population of over 40 million and supplying more consumptive water use than any other river in the United States (US) (Carlson & Muth, 1989; US Bureau of Reclamation, 2012a). Today, the region faces unprecedented water supply challenges from persistent drought, changing climate, and competing multi-sectoral water demands (Lukas & Payton, 2020; Udall & Overpeck, 2017; Wheeler et al., 2022). The river's alpine headwaters composed of the state of Colorado's West Slope Basins (Figure 1a) exemplify many of these challenges (CWCB, 2023). Since 2020, drought events have caused over $2 billion of damage to the state of Colorado's economy, with widespread impacts on the agriculture and tourism industries within the West Slope Basins (A. B. Smith, 2022;

Resources: David F. Gold, Patrick M. Reed
Software: David F. Gold, Rohini S. Gupta
Validation: David F. Gold
Visualization: David F. Gold
Writing – original draft: David F. Gold
Writing – review & editing: David F. Gold, Rohini S. Gupta, Patrick M. Reed

CWCB, 2023). Droughts also threaten native species of endangered fish found only within the West Slope Basins and their surrounding regions (US FWS, 1999; US FWS, 2009). Since 1988, the US federal government has spent over $209 million on efforts to protect endangered aquatic species in the West Slope Basins, and $142 million of additional funding has been more recently under debate in the US Congress (Hickenlooper et al., 2023).

In addition to their local importance, the West Slope Basins are a vital water source for downstream reservoirs and water users. In an average year, the West Slope Basins contribute nearly 70% of the streamflow deliveries to Lake Powell, the nation's second-largest reservoir (Figure 1b and US Bureau of Reclamation (2020)). In 2021, record low storage in Lake Powell driven by persistent drought conditions prompted the US Bureau of Reclamation (Reclamation) to declare the first-ever water shortage in the Upper Colorado River Basin (UCRB), forcing significant cuts for water users in multiple states (US Bureau of Reclamation, 2021b). As local and federal decision-makers craft policy to determine sustainable long-term management of the Colorado River, a comprehensive understanding of drought vulnerability in Colorado's West Slope Basins is critical.

Drought vulnerability emerges through a combination of the internal variability of the region's hydroclimatic system, ongoing changes in climate, multi-sectoral human demands, and institutionally complex water management systems (AghaKouchak et al., 2021; Mishra & Singh, 2010; Van Loon et al., 2016). Internal variability refers to the irreducible uncertainty that stems from interactions across non-linear processes within the hydroclimate system (Hawkins & Sutton, 2009; Lehner & Deser, 2023). Evidence from paleo streamflow reconstructions indicates that internal variability in the UCRB can produce droughts that exceed the most extreme events that have been observed in the last century of the historical record (Ault et al., 2014; Meko et al., 2007; Woodhouse et al., 2006; Woodhouse & Overpeck, 1998). Changes in temperature and precipitation driven by climate change may increase the magnitude of future streamflow drought events even further (Milly & Dunne, 2020; Salehabadi et al., 2022; Udall & Overpeck, 2017). While precipitation changes in the UCRB are subject to a wide range of uncertainty, most models project local temperature increases (Kao et al., 2023; Lukas & Payton, 2020; Rajagopalan, 2023; Udall & Overpeck, 2017). In the West Slope Basins, warmer temperatures have a strong potential to reduce snowpack, change the timing of annual peak flows, increase evaporation, and lead to overall declines in annual streamflow (Heldmyer et al., 2023; Miller et al., 2021; Milly & Dunne, 2020).

Human water use, land management practices, and infrastructure alter drought events by changing the volume, timing, and distribution of regional water resource availability (Van Loon et al., 2024; Wanders & Wada, 2015). The West Slope Basins are part of the institutionally complex UCRB system, which is governed by the Prior Appropriation doctrine leading to a nested set of rules and regulations dictating water rights, reservoir operations, and environmental flows (CWCB, 2023; US Bureau of Reclamation, 2012a). Each basin contains hundreds of water rights holders that withdraw water for diverse multi-sectoral use, many of which are consumptive (e.g., irrigation and municipal water supply), decreasing streamflows and potentially exacerbating water shortages (CWCB, 2023). Land use supporting multiple sectors, such as agriculture and oil and gas development, has altered the natural hydrologic system of the West Slope Basins, changing the timing and volume of runoff (Copeland et al., 2017). Large reservoirs within West Slope Basins also impact the timing and volume of water availability by storing water and altering peak flows through controlled releases (Schmidt, 2010). Transmountain and transbasin diversions from the West Slope Basins export water to agricultural users and large metropolitan areas outside the Basins' watersheds, further altering streamflows (CWCB, 2023).

Characterizing the drought vulnerability in the West Slope Basins thus necessitates modeling the complex feedbacks within the human-natural system that shape, and are shaped by, extreme events (Reed et al., 2022). Two water resources planning models have been developed to capture the human-natural system within the UCRB: The Colorado River Simulation System (CRSS) and the Colorado Decision Support System (CDSS) (Malers et al., 2000; Wheeler et al., 2019). CRSS is a hydro-policy planning model built in Riverware that serves as the primary long-term planning tool for Reclamation (R. Smith et al., 2022; Wheeler et al., 2019; Zagona et al., 2001). In recent years, CRSS has played a key role in supporting Reclamation decisions and policy-making, helping refine negotiations for the Colorado River Basin 2007 Interim guidelines, and exploring operating policies for Lake Mead and Lake Powell (Gastélum & Cullom, 2013; Lukas & Payton, 2020). However, CRSS has only limited representations of water users in key West Slope Basins, including the main stem of the Upper Colorado River above Glenwood Springs, the Yampa River above Maybell, and the Delores River (Wheeler et al., 2019), reducing its utility for exploring the local user level impacts of drought in Colorado's West Slope Basins.

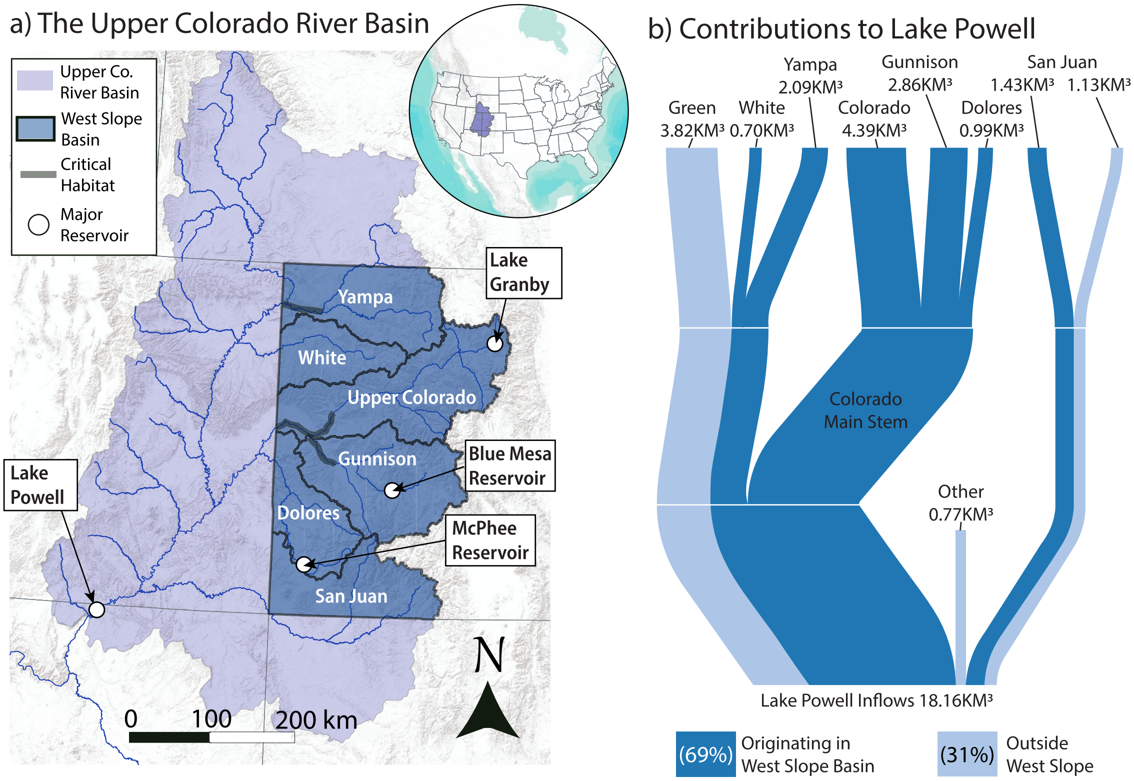

Figure 1. (a) A map of the Upper Colorado River Basin with the five West Slope Basins highlighted in dark blue. (b) Contributions of inflow to Lake Powell (and the Lower Colorado River Basin) by source during an average year. Approximately 69% of the average annual inflow to Lake Powell is generated in West Slope Basins (calculated using average annual natural flow data from 1906 to 2020 (US Bureau of Reclamation, 2020)).

Alternatively, CDSS uses StateMod as the state of Colorado's water planning model, developed by the Colorado Water Conservation Board and Colorado's Division of Water Resources (Malers et al., 2000; Parsons & Bennett, 2006). Unlike CRSS, StateMod was not built to model the entire Colorado River Basin. Instead, the CDSS utilizes several StateMod instances that provide highly detailed representations of the West Slope Basins. The StateMod instances represent the West Slope Basins using a linked network of river nodes that model instream flows, gaging stations, river confluences, diversions, and reservoirs. Each basin instance of StateMod also contains comprehensive representations of water users, water rights, and reservoir operations. Traditionally, the state of Colorado has used historical streamflow data as input to individual basins instances of StateMod to evaluate operational decisions related to local water management and address the impacts of interstate compact obligations (Parsons & Bennett, 2006).

In this paper, we use StateMod to facilitate exploratory modeling of drought vulnerabilities across all six West Slope Basins, including the potential for multi-basin spatially compounding impacts on the region. Exploratory modeling refers to the use of carefully designed computational experiments to systematically explore system behavior and identify key factors that shape future vulnerability (Bankes, 1993; Moallemi et al., 2020). In recent years, exploratory modeling has emerged as a valuable approach for examining human-natural systems in institutionally complex river basins (Biglarbeigi et al., 2018; Culley et al., 2016; Pianosi & Wagener, 2016; Quinn et al., 2018, 2020). For example, Hadjimichael et al. (2020) use an exploratory modeling approach with StateMod to illustrate how uncertainties stemming from climate change, water demand, and institutional and physical infrastructure influence multi-sectoral drought vulnerability within the main branch of the Upper Colorado River, a subbasin within the West Slope. Their results provide a detailed examination of the vulnerability of local agricultural producers, water transfers, and ecosystems within the subbasin. However, their local analysis of the portion of the Upper Colorado River in the state of Colorado does not capture the broader drought impacts across the full suite of West Slope Basins and their potential spatially compounding influences on the inflows to Lake Powell.

The goal of this study is to explore how the internal variability of the hydroclimatic system and plausible changes in climate shape multi-sector drought vulnerability both within each West Slope Basin and across the broader regional system. In our exploratory modeling experiments, we couple StateMod with a novel multi-basin stochastic streamflow generator designed to capture internal variability and preserve the spatial correlation structure within and across basins. Stochastic streamflow generation has a long history supporting planning in the UCRB (Lukas & Payton, 2020). Parametric approaches to streamflow generation utilize hypothesized statistical models of historical streamflow and fit the model parameters to replicate the statistical properties of the historical record. In the UCRB, previous examples of parametric approaches include the entropy copula method introduced by Hao and Singh (2012), the Gaussian Hidden Markov Model (HMM) generator introduced by Bracken et al. (2014), and the Wavelet Autoregressive Modeling approaches introduced by Nowak et al. (2011) and Erkyihun et al. (2016). In contrast, nonparametric approaches such as the Index Sequential Method used by Reclamation (US Bureau of, 1969), the drought scenario generator proposed by Salehabadi et al. (2022) and the maximum entropy bootstrap model introduced by Srivastav and Simonovic (2014) rely on re-sampling from the historical hydrological record rather than making distributional assumptions about the streamflow generation process.

For the exploratory modeling experiments in this work, we build on the two-state Gaussian HMM introduced by Bracken et al. (2014) to develop a parametric synthetic streamflow generator capable of creating multi-site ensembles of synthetic streamflows for the West Slope Basins. We contribute the extended two-state Gaussian HMM for this study because (a) HMMs have demonstrated high performance in capturing distributional statistics of streamflows in the UCRB (Erkyihun et al., 2017), (b) the parameters of two-state Gaussian HMMs can be adjusted to reflect plausible changes to streamflow projected by recent climate models (Quinn et al., 2020), and (c) a two-state HMM can capture persistence that emerges from large-scale climate phenomena that influence streamflows across all six West Slope Bains (Clark et al., 2001; Nowak et al., 2012).

This paper contributes the largest and most comprehensive exploratory modeling analysis of multi-sectoral drought vulnerability in the West Slope Basins to date. Our analysis couples StateMod's highly detailed representation of the region's institutionally complex human-natural system with a parsimonious synthetic streamflow generation framework that is specifically scalable to the hundreds of StateMod streamflow nodes necessary to capture the local user-level water shortages across Colorado's West Slope Basins. We first introduce the new multi-site two-state Gaussian HMM and use it to generate a "baseline" ensemble of streamflow time series that preserves the statistical properties and spatial correlation structure of the historical record and captures the stationary internal variability of the hydroclimatic system. Next, we develop a "climate-adjusted" streamflow ensemble by perturbing the parameters of the multi-site HMM to reflect a 7% decline in average annual West Slope streamflows, representing recent downscaled middle-of-the-road climate projections for the basins (Hegewisch et al., 2023; Rajagopalan, 2023) (for further details, see Section 3.3.1 and Section S2 in supporting information S1). Our climate-adjusted ensemble represents a plausible and arguably optimistic representation of a climate change scenario that combines stationary internal variability with a modest decrease in streamflows. This scenario is intended to serve as a "what-if" exercise that explores how current institutional structures and water management policies in the West Slope Basins perform under warmer and drier conditions. We run the "baseline" and "climate-adjusted" ensembles through StateMod and use the output to evaluate multi-sectoral drought vulnerability across multiple measures of impact, including deliveries to Lake Powell, agricultural shortage, reservoir storage, and environmental flows.

The remainder of this paper is organized as follows: Section 2 presents a detailed description of the West Slope Basins, Section 3 details our methodology and experimental design, Section 4 presents the results of our analysis, and Section 5 presents a brief discussion contextualizing our results in the broader Colorado River Basin system, and Section 6 presents conclusions and future work.

2. Study Area: Colorado's West Slope Basins

The West Slope Basins—Upper Colorado, Gunnison, Yampa, White, San Juan, and Dolores—are subbasins of the UCRB that lie on the western slope of the continental divide in the state of Colorado, as shown in Figure 1a. The West Slope Basins are sparsely populated, encompassing a total area of 92,356 sq km (35,659 sq mi) and supporting a population of 562,000. Approximately 80% of the state of Colorado's precipitation falls in the West Slope Basins, 70% of which is in the form of snowfall. Precipitation and topography are highly variable between and within the West Slope Basins. For example, the headwaters of the Yampa River reach elevations over 3,000 m

10.1029/2024EF004841

(10,000 ft) above sea level and receive an annual average of 152 cm (60 inches) of precipitation, while the elevation of the Yampa at the Utah state line is near 1,524 m (5,000 ft) above sea level, and the average annual precipitation is 25.4 cm (10 inches) (CWCB, 2023).

The West Slope Basins are a critical water source for the Lower Colorado River Basin and play a vital role in supporting the economy and natural environment of the state of Colorado. Collectively, the West Slope Basins contribute nearly 70% of inflows to Lake Powell in an average year, as illustrated in Figure 1b (CWCB, 2023; US Bureau of Reclamation, 2020). West Slope Basins contain 3,715 km^2 (1,434 mi^2) of irrigated farmland and support an agricultural industry estimated to contribute \$1.4 billion annually to the state of Colorado's economy (U.S. Department of Agriculture, 2017). Recreational activities that depend on water resources, including fishing and boating, are estimated to contribute over \$5 billion annually to the state's economy (Business for Water Stewardship, 2020). The West Slope Basins are also home to vulnerable and endangered species of fish not found outside of the Colorado River Basin, including the humpback chub, the Colorado pikeminnow, the bonytail, and the razorback sucker (NatureServe, 2014a, 2014b, 2014c). The U.S. Fish and Wildlife Service has identified several areas critical to the recovery of these fish species and made recommendations on flow levels needed to support sustainable populations that are highlighted in Figure 1a (American Whitewater et al., 2012; The Nature Conservancy, 2012; US FWS, 1999; US FWS, 2009). In addition to these local uses of water, the West Slope Basins are the source of an average of 567 $\frac{million \quad m^3}{year}$ (460,000 $\frac{acre-feet}{year}$) of water that supplies major urban areas in Colorado's Front Range (CWCB, 2023), and the San Juan-Chama project, which sends an average of 135 $\frac{million \quad m^3}{year}$ (110,000 $\frac{acre-feet}{year}$) to the Rio Grande Basin, used to support agricultural and municipal use in New Mexico (Glaser, 1998).

Water rights in the West Slope are governed by the doctrine of "prior appropriation," which allocates water to users based on water right seniority within the larger hierarchical network of the Colorado River Basin (Meyers, 1966). The West Slope Basins contain thousands of diversions drawing from the major rivers and their tributaries to supply irrigated land to water rights holders. River flows are also altered by a network of reservoir systems. Two of the state's largest reservoirs in the West Slope, Blue Mesa (part of the Wayne N. Aspinall Storage Unit on the Gunnison River) and McPhee Reservoir (Dolores River), are owned and operated by the U.S. Bureau of Reclamation (US Bureau of Reclamation, 2012b). Lake Granby (Upper Colorado River), a third large reservoir in the West Slope, is operated by the Northern Colorado Water Conservancy District and plays a vital role as a source for transfers across the Continental Divide through the Colorado-Big Thompson Project. Across the basins, each reservoir is operated with rules designed to balance flood control, recreation, fish and wildlife, irrigation, hydropower, and municipal and industrial uses.

Drought represents a major threat to water users in the West Slope Basins and throughout the Colorado River Basin. The 2000–2023 "Millennium Drought" has led to unprecedented challenges in the region (Schmidt et al., 2023; Wheeler et al., 2022). Storage in Lake Powell dropped sharply at the onset of the drought and has never recovered, reaching an all-time low elevation of 768.69 m (2521.95 ft) in February 2023 ("full pool" elevation is 1,128 m) (US Bureau of Reclamation, 2023). In 2021, the U.S. Bureau of Reclamation ordered a water transfer from the Blue Mesa reservoir to supplement Lake Powell. The transfer dropped the elevation of Blue Mesa 2.4 m (8 ft), causing closures to local marinas and damaging the local economy (Sakas, 2021). Increased temperatures, reductions in snowpack, and changes in snowmelt timing (which impacts peak runoff timing) caused by climate change are expected to intensify future droughts (Heldmyer et al., 2023; Miller et al., 2021; Milly & Dunne, 2020; Salehabadi et al., 2022). Recent studies estimate that climate change is responsible for over 50% of water reductions (Bass et al., 2023; Xiao et al., 2018). As U.S. state and federal officials work to craft new policies to govern the Colorado River, policymakers need improved tools to assess multi-sectoral drought vulnerabilities appropriately.

3. Methodology

This study contributes a new methodology that uses a multi-basin two-state Gaussian HMM and StateMod, the state of Colorado's water planning model (Malers et al., 2000; Parsons & Bennett, 2006), to evaluate current and future drought vulnerability of the West Slope basins. We first use the HMM to develop a "baseline ensemble" of streamflows for all West Slope Basins that explores the system's stationary internal variability by generating ensemble streamflow records that capture the spatial and temporal characteristics of the available historical

10.1029/2024EF004841

record. This stationary HMM-generated ensemble of streamflows aid in overcoming the observation record's limits in capturing extreme droughts and better characterize the full space of plausible water scarcity vulnerabilities. Next, we develop a "climate-adjusted" ensemble of streamflows created by perturbing a subset of the HMM parameters to reflect dryer plausible changes to the region's climate. These changes are derived from downscaled projections within the Coupled Model Intercomparison Project Phases 5 and 6 (CMIP5 and CMIP6) (Cook et al., 2020; O'Neill et al., 2016; Taylor et al., 2012). We then use the two HMM-generated ensembles of synthetic streamflows as inputs to StateMod to evaluate multi-sectoral drought impacts by exploring deliveries to the Lower Colorado River Basin, local water shortage, reservoir levels, and environmental flows. This section first provides an overview of our multi-basin HMM, then introduces the StateMod water planning model, and finally details our experimental design.

3.1. Multi-Basin Hidden Markov Model Streamflow Generator

We develop a multi-basin two-state Gaussian HMM to create synthetic streamflow for the West Slope Basins that better captures the internal variability within the hydrologic system while preserving the spatial and temporal correlation structures within and between basins. The model is fit to the naturalized log-annual flow at the outlet of each West Slope basin and consists of two "hidden" climate states, representing wet and dry hydrologic conditions respectively. We use a two-state model to capture the persistence that emerges from large-scale climate phenomena such as the Pacific Decadal Oscillation and the El Nino-Southern Oscillation, which cause wet and dry conditions to cluster in the historical record (Clark et al., 2001; Nowak et al., 2012). Two-state HMMs have been shown to accurately capture hydrologic extremes and persistence in sub-basins within the Upper Colorado River (Bracken et al., 2014; Quinn et al., 2020) but have not been extended to the broader West Slope context.

The historical streamflows at the five outlet nodes of the West Slope basins are highly correlated at an annual scale (for details, see Figure S3 in Supporting Information S1), which suggests that a unified model that preserves this spatial correlation is preferred over developing independent models for each basin. Thus, we model streamflow in all five basins using a single common wet or dry state in any given year, and a single 2×2 transition matrix dictates the likelihood of persisting and transitioning between a wet and dry state. Once a total annual streamflow value is generated for each outlet node, we subsequently implement a disaggregation technique that allows us to generate flows at hundreds of nodes in each subbasin. Figures S3 and S4 in Supporting Information S1 demonstrate that historical spatial correlation is preserved. We use the Viterbi algorithm to classify each year in the historical record as part of the wet or dry state. The Viterbi algorithm employs dynamic programming to classify the annual flow from each basin in each year of the historical record. Classified states for the historical record of the Gunnison River basin are shown in Figure 2a (for more details on the Viterbi algorithm, see Section S1 in Supporting Information S1).

The multi-basin model is also defined by separate Gaussian multivariate distributions for the naturalized log streamflows at five basin outlet sites. The wet and dry state distributions have respective mean vectors of length five and covariance matrices of size 5×5 that capture the joint variability across the sites. A two-dimensional projection of these distributions is shown in Figure 2b for the Gunnison and Southwest Basins. We estimate the vector of means and the covariance matrix for each distribution and the probability of transitioning between the two states across the period from 1938 to 2013 using the Expectation-Maximization algorithm in the Return levels of hydrologic Python library (Lebedev, 2015). We chose to use the period from 1938 to 2013 to capture recent conditions and avoid including the early 20th-century pluvial. Parameter estimates for each distribution, and each basin can be found in Tables S1–S4 in Supporting Information S1. The goodness of fit assessments for the multi-basin HMM and analysis of autocorrelation and partial autocorrelation to confirm the Markov property can be found in Section S1 in Supporting Information S1.

Formally, the two-state Gaussian HMM is represented in Equations 1 and 2.

$$f(Y_t|X_t = 0) \sim N(\mu_d, \Sigma_d) \tag{1}$$

$$f(Y_t|X_t = 1) \sim N(\mu_w, \Sigma_w) \tag{2}$$

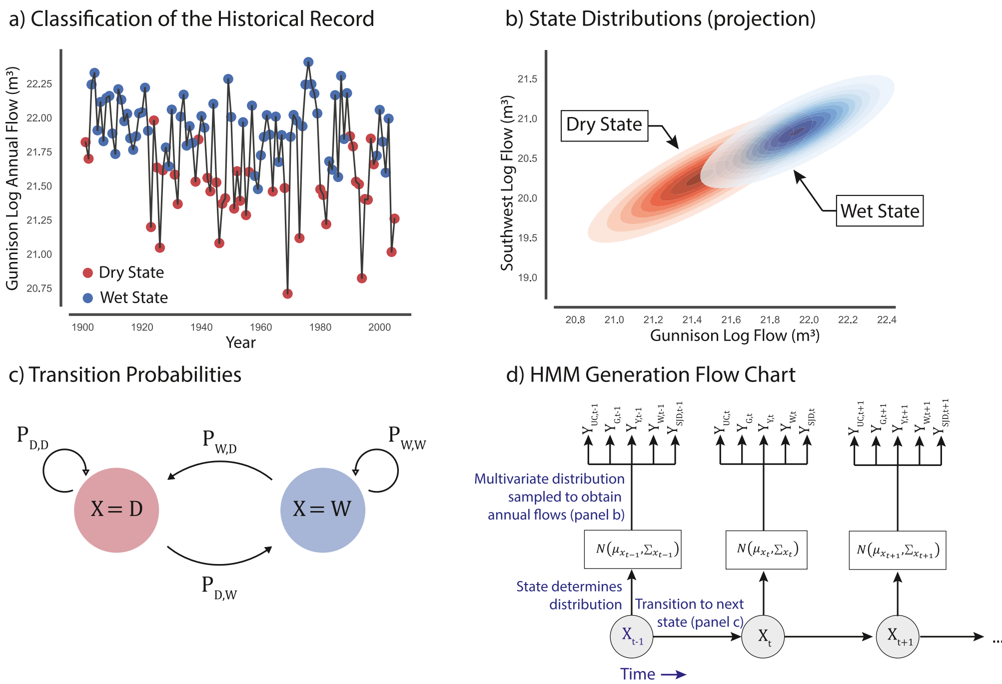

Figure 2. (a) Classified states of the historical record in the Gunnison River basin. (b) Projections of the dry- and wet-state distributions of streamflows of the Gunnison and Southwest Basins. These distributions are 2-dimensional projections of the 5-dimensional Gaussian distributions with means μ_d and μ_w and variances Σ_d and Σ_w used to model all five West Slope Basins. (c) A schematic of transition probabilities from each state. (d) An overview of how the multi-basin Hidden Markov Model is used to develop synthetic streamflow records for the West Slope Basins.

Where Y_t is the vector of annual outflow from all basins at year t, μ_d is the vector of length 5 containing dry state means, μ_w is the vector of length 5 containing wet-state means, Σ_d is the covariance matrix for dry states, and Σ_w is the covariance matrix for wet states.

The state at month, t, of the simulation, X_t, is dependent on the state at the previous timestep, X_{t-1}. The probability of switching between states is represented by a 2×2 state transition matrix, P. Each element of P, p_{ij}, represents the probability of transitioning from state i in month t to state j in month $t + 1$ as shown in Equation 3, and represented in Figure 2c.

$$p_{i,j} = P(X_{t+1} = j | X_t = i) \tag{3}$$

Figure 2d details the process of generating a synthetic record of streamflows from the using the HMM generator. For each month, t, of the synthetic record, the state, X_t is determined by X_{t-1} and P. We initialize the probability of being in a state using the stationary distribution, π, a 1×2 vector with π_i representing the probability of being in state i during the historical record, as shown in Equation 4.

$$\pi_i = P(X_t = i) \tag{4}$$

Each element of π is calculated using Equation 5.

$$\pi_i = \frac{e_{i,1}}{\sum_j^n e_{j,1}} \tag{5}$$

Where $e_{i,1}$ is the $i - th$ element of the eigenvector of P^T corresponding to an eigenvalue of 1.

After the state has been determined, we sample from the appropriate state distribution to get annual outflows at the final node of each basin. We then disaggregate these flows across all nodes in each basin and from annual flows to monthly using a modified version of Nowak et al. (2010)'s method following the methodology used by Quinn et al. (2020). Further details on spatial and temporal disaggregation can be found in Section S1 in Supporting Information S1.

3.2. StateMod

StateMod is the state of Colorado's water planning model, developed by the Colorado Water Conservation Board and Colorado's Division of Water Resources as part of Colorado's Decision Support Systems (CDSS) (Malers et al., 2000; Parsons & Bennett, 2006). Since the late 1980s, Colorado has used StateMod to evaluate operational decisions related to water management and address the impacts of interstate compact obligations (Parsons & Bennett, 2006). To model Colorado's West Slope Basins, StateMod instances have been developed for the Upper Colorado River, Gunnison, Yampa and White basins. The San Juan and Dolores basins are modeled together as the "Southwest" basin. Each basin instance of StateMod contains a linked network consisting of river notes that represent instream flows, gaging stations, river confluences, diversions, and reservoirs.

In each basin, the standard implementations of the StateMod instances simulate the historical water years 1909–2013 while representing the current infrastructure and institutional water rights context. In all West Slope basins, this period contains instances of persistent wet and dry flows, resulting in both periods of drought and high runoff. To model the historical period, StateMod first develops a representation of naturalized flows by superimposing historical diversions data, monthly reservoir storage, and return flows on historical streamflow observations from USGS gauges. StateMod models ungauged segments by using proration factors to distribute water in proportion to the drainage area of ungauged segments. StateMod then applies water demands and reservoir operations using a detailed accounting of water rights and reservoir policies within each basin. Each water right is associated with its location on the stream and an administration number representing the decreed water it is allowed to divert the seniority of its allocation. Each month, StateMod resolves all diversions and other water transfer operations in order of seniority and then estimates the remaining stream flow. StateMod models reservoir operations using minimum and maximum reservoir storage targets. For further information on StateMod modeling procedures, see the user manuals developed and maintained by CDSS (CWCB & CDWR, 2016).

3.3. Experimental Design

3.3.1. Capturing Internal Variability and Plausible Climate Change

In this study, we explore the current and future drought vulnerability of West Slope Basins by running ensembles of synthetically generated streamflows created with the multi-basin HMM through StateMod. To evaluate current drought vulnerability, we develop a "baseline" ensemble of 1,000 synthetically generated 105-year-long streamflow records fit to the historical record. The purpose of this ensemble is to capture a range of flow conditions that emerge from sampling the stationary internal variability of the historical record. We chose an ensemble size of 1,000 streamflows based on the analysis by Quinn et al. (2020) that found the variance of StateMod outputs to be stable with 1,000 ensemble members. Figure 3 shows the range of monthly streamflows from the 1,000 baseline ensemble and the 105 years of the historical record for each basin, illustrating how the baseline ensemble envelopes and expands streamflows in the historical record.

One advantage of using an HMM to generate synthetic streamflows is that its parameters can be modified to reflect changing climate conditions (Bracken et al., 2014; Quinn et al., 2020). In this study, we examine the impacts of a warmer future with less streamflow by modifying the log-space means of the dry- and wet-state distributions within the HMM and shifting the annual peak flows to account for changes in snowpack. We use the adjusted HMM to generate a "climate-adjusted" ensemble of 1,000,105-year streamflow records. Importantly, this ensemble is not intended to predict how regional climate will change but to serve as an exploratory "what-if" experiment to understand how drought vulnerability may evolve under plausible changes to regional climate (Bankes, 1993).

To develop the climate-adjusted ensemble, we reduce the log-space means of the wet- and dry-state distribution by 0.5% while keeping fixed all other parameters of the baseline HMM, such as the wet-dry state transition matrix. This parameterized level of change was selected to yield streamflow records with mean annual real-space flows that are reduced by an average of 7% compared to a baseline period of streamflow from 1970 to 2000. The representation of internal variability within the climate-adjusted ensemble generates a distribution of annual flow changes that range from declines of 20% to increases of 5% (for details, see Figure S10 in Supporting

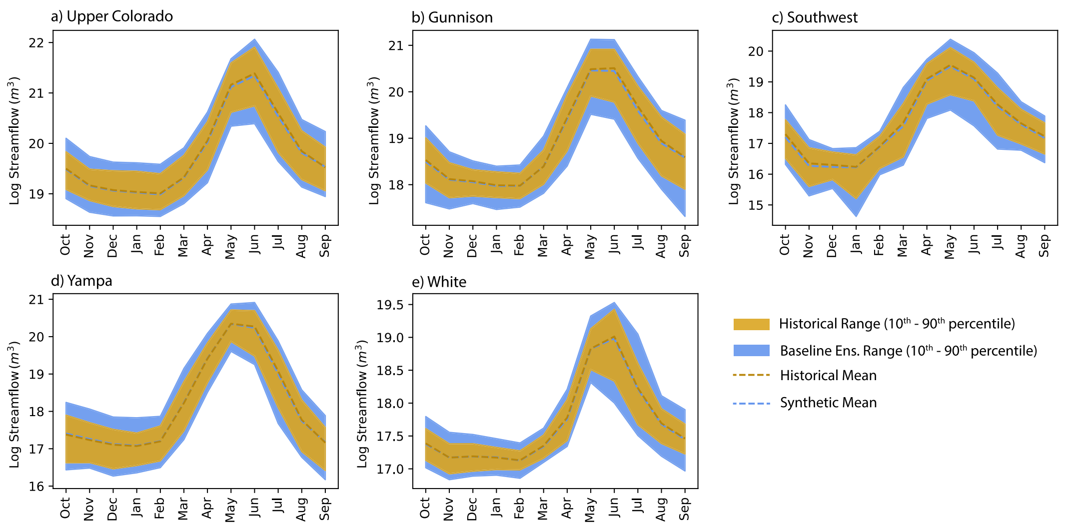

Figure 3. Monthly streamflows at the outlet of each West Slope Basin from the historical record (orange) and baseline Hidden Markov Model ensemble (blue). The mean monthly flows of both sets of records are shown as dashed lines, and the shading shows the 10th–90th percentiles of each set of records.

Information S1). This adjustment aligns with the median mid-century streamflow change at Lee's Ferry generated by 10 GCM models from CMIP5 under RCP 4.5 after they were downscaled and routed through the Variable Infiltration Capacity model (Hegewisch et al., 2023). The synthetic streamflows generated by the climate-adjusted HMM also reflect plausible changes within the limited set of available CMIP6 Colorado River streamflow projections, which yield highly uncertain streamflow changes ranging from −20% to +40% (Kao et al., 2023; Rajagopalan, 2023). The distribution of streamflows within the climate-adjusted ensemble aligns with middle-of-the-road streamflow declines from 220 members of large ensemble simulations generated by Hoerling et al. (2024) (detailed in Figure S11 in Supporting Information S1). Overall, the climate-adjusted HMM provides a view of drought vulnerabilities that explicitly avoids worst-case projections and falls within the middle range of projected climate futures. For more details on how the distribution of streamflows within the climate-adjusted ensemble compares to CMIP 5 and 6 projections, see Section S2 in Supporting Information S1.

In addition to changes to streamflow volume, climate projections also indicate that warmer temperatures may cause earlier snowmelt, shifting peak flows earlier in the year (Hegewisch et al., 2023; Kao et al., 2023). To account for this shift, we adjust the spring peak flows to arrive 30 days earlier, following the methodology used by Hadjimichael et al. (2020). The 30-day shift aligns with projections from both CMIP5 and CMIP6 under multiple forcing scenarios (Hegewisch et al., 2023; Kao et al., 2023). For further details on the snowmelt shifts, see Section S2 in Supporting Information S1.

3.3.2. Exploring Multi-Sectoral Drought Vulnerability

Our first step in evaluating the drought vulnerability of West Slope basins is to explore drought events produced by the baseline and climate-adjusted ensembles of HMM-generated streamflows. For this analysis, we apply a general definition of drought proposed by Tallaksen and Van Lanen (2004) and adopted by Van Loon (2015): "drought is a sustained period of below-normal water availability." We use a moving-window threshold method (Fleig et al., 2006; Prudhomme et al., 2014; Satoh et al., 2022; Van Loon, 2015) to identify droughts as periods when the normalized departure of the n-year rolling mean log annual flow drops 0.5σ below the mean flow in the historical record:

$$drought_t = \begin{cases} True & if \quad \mu_n^t < \mu_{hist} - 0.5\sigma_{hist} \\ False & otherwise \end{cases} \tag{6}$$

where μ_n^t is the n-year running mean streamflow during year t, μ_{hist} is the mean flow of the 105-year historical record, and σ_{hist} is the standard deviation of flow in the 105-year historical record. We select the $\mu_{hist} - 0.5\sigma_{hist}$

10.1029/2024EF004841

threshold following examples in Ault et al. (2014); Ault et al. (2016); Diffenbaugh et al. (2015); Naumann et al. (2018).

Using Equation 6, we explore multiple temporal definitions of drought by varying n from 6 years (multi-year drought) to 25 years (multi-decadal drought). For a given drought event, we define the drought severity using a cumulative deficit (CD) volume measure (Fleig et al., 2006; Hisdal et al., 2004; Stoelzle et al., 2014; Van Loon et al., 2014), calculated as the sum of the normalized difference between the annual flow during each year of the drought period and the mean annual flow of the historical record:

$$Cumulative \quad Deficit = \int_{start}^{end} \frac{\mu_{hist} - Y_t}{\sigma_{hist}} dt \tag{7}$$

where Y_t is the streamflow in year t of a streamflow record (historical or synthetic).

After exploring drought events produced by the HMM-ensembles, we run both the baseline and climate-adjusted ensembles of HMM-generated streamflow records through StateMod to explore current and future drought vulnerability in the institutionally complex West Slope Basins. Our analysis seeks to understand local drought vulnerability (impacts in each basin) and the spatially compounding impacts for the state of Colorado and the Lower Colorado River Basin. To evaluate vulnerability, we post-process StateMod output and focus on four measures of drought vulnerability—cumulative deliveries to Lake Powell, consumptive use water shortage, environmental flows, and reservoir storage. Cumulative delivery to Lake Powell captures the impact of drought on Lake Powell and the Lower Basin states. As the headwaters of the Colorado River (Figure 1b), West Slope Basins have an outsized influence on flows in the Lower Basin. Our analysis explores the frequency and persistence of low flows generated by both the baseline and climate-adjusted ensembles after routing them through StateMod.

Our second measure, consumptive use shortage, captures the shortage from agriculture, municipal, and industrial use. StateMod tracks consumptive use shortage during each month of the 105-year simulation. In the West Slope, most consumptive use is from agriculture (CWCB, 2023). In our analysis, we sum consumptive use shortages within each basin and across all West Slope Basins to understand the magnitude of local agricultural shortage and the spatially compounding impacts of shortage on the State of Colorado. More details on the calculation of consumptive use shortage can be found in Section S3 in Supporting Information S1.

Our third measure, environmental flow hazard, evaluates the fraction of simulated years that fail to meet late summer and fall streamflow recommendations provided by the US Fish and Wildlife Service (US FWS) (US Bureau of Reclamation, 2012b; US FWS, 1999; US FWS, 2009). The US FWS generated Biological Opinions for each basin that highlight areas of critical habitat and recommended flow to support vulnerable and endangered species. Peak flows in the spring are important for building cobble bars and flushing sediment from the substrate used by native species for spawning (US FWS, 1999). However, accurately modeling spring environmental flows is not possible using StateMod with a monthly timestep. Instead, our analysis focuses on low-flow periods in August, September, and October when streamflow depletions from agricultural diversions can endanger native fish populations (Dibble et al., 2023; US FWS, 1999; US FWS, 2009). For more details on environmental flow requirements, see Section S4 in Supporting Information S1.

Our final measure, reservoir storage, focuses on the reservoir levels in the region's three largest reservoirs, Blue Mesa, Lake Granby, and McPhee. We examine the percentiles of each reservoir across both the "baseline" and "climate-adjusted" ensembles and compare elevations to the historical mean and low periods assuming current operating policies. These results can inform policymakers when developing future reservoir operating policies.

4. Results

4.1. Drought Events Produced by the Multi-Basin HMM Ensembles

We begin by comparing the frequency and severity of hydrologic droughts that emerge from the HMM ensembles with drought events observed in the historical record of naturalized streamflow. The impact of drought in the West Slope basins - and the Colorado River basin more broadly—is shaped by the spatial and temporal extent of drought events. Figure 4 compares the spatial and temporal extent of droughts produced by the HMM ensembles

10.1029/2024EF004841

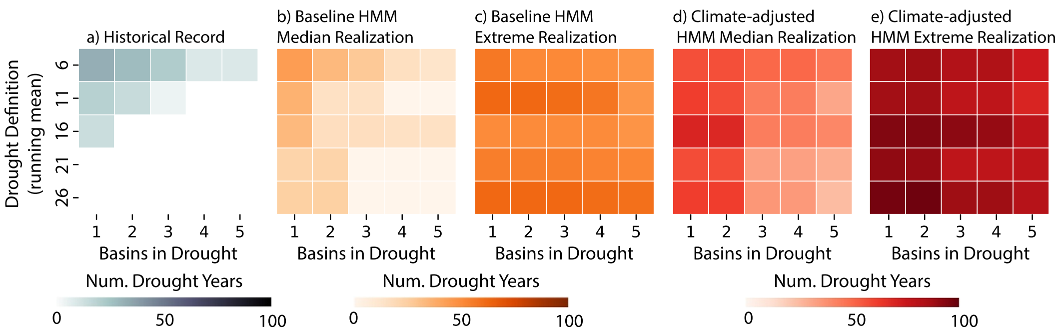

Figure 4. The number of years classified as drought according to the length of the running mean used to define a drought period (n in Equation 6; vertical axis in this figure), and the number of West Slope Basins simultaneously experiencing drought (horizontal axis in this figure). The shading in each cell represents the number of years classified as drought under each definition. (a) Drought events in the historical record. (b) The median realization from the Hidden Markov Model ensemble, measured by the total cumulative deficit (CD) across all droughts and all basins. (c) An extreme realization represented by the 99th percentile total CD from the baseline ensemble. (d) The median realization from the climate-adjusted ensemble. (e) The 99th percentile realization from the climate-adjusted ensemble.

against droughts observed in the historical record. In the panels of Figure 4, each row represents a different temporal definition of drought by applying different lengths of the running mean (values of n) to the drought definition in Equation 6. Each column represents the number of basins that simultaneously experience drought. The shading of each cell represents the number of years within a 105-year record classified as drought according to the spatial and temporal criteria defined by its row and column.

Figure 4a shows the spatial and temporal extents of droughts observed in the historical record. Thirty-five years of the historical record are classified as multi-year ($n = 6$) drought events that occur in a single basin (top left cell of Figure 4a). As the spatial and temporal extents are increased, the number of observed years classified as drought decreases. All five basins experienced a multi-year drought simultaneously in only 11 years of the historical record (top right cell). Two decadal droughts ($n = 11$) are observed in the historical record, one occurred in two basins simultaneously, and a second occurred in three basins simultaneously. Only one basin experienced a drought defined using $n = 16$, and no multi-decadal droughts ($n = 21$ and $n = 26$) are observed in the historical record.

The ensemble generated by the baseline HMM produces a range of drought events across ensemble members. While many ensemble members yield drought events similar to the historical record (for details, see Section S4 in Supporting Information S1), other ensemble members produce drought events that are more persistent and have a broader spatial extent than any drought in the observed historical record. Figure 4b shows the realization within the baseline ensemble with the median total CD—defined as the total CD of all droughts across all basins in a 105-year record. The median ensemble member contains one persistent drought ($n = 16$) that occurs simultaneously across all five basins and one multidecadal drought (defined using either $n = 21$ or $n = 25$) that occurs in two basins simultaneously. The realization shown in Figure 4c represents the 99th percentile of total CD across the baseline ensemble and contains severe drought events that have a broader spatial extent and are more persistent than any event in the historical record. These extreme events are not outliers within the baseline ensemble; 17.5% of realizations within the baseline ensemble contain at least one multi-decadal drought event that spans all five basins. The baseline HMM maintains the historical record's statistical moments and correlation structures, and these extreme events emerge solely from better capturing the systems' internal variability. This finding aligns with recent studies using other statistical techniques and paleo records that show the potential for internal variability to generate persistent and spatially compounding drought in the Colorado River Basin (Ault et al., 2014; Gangopadhyay et al., 2022; Meko et al., 2007; Robeson et al., 2020).

The majority of streamflow records produced by the climate-adjusted HMM contain spatially compounding drought events that are more persistent than any event in the observed historical record. Figure 4d shows the median realization within the climate-adjusted ensemble, defined using total CD. This realization contains one multi-decadal drought event (classified using both $n = 21$ and $n = 26$) that spans all five basins simultaneously and long periods of drought in individual basins. The realization with the 99th percentile total CD in the climate-adjusted ensemble, shown in Figure 4e, contains over 50 years of drought in all five basins simultaneously. The

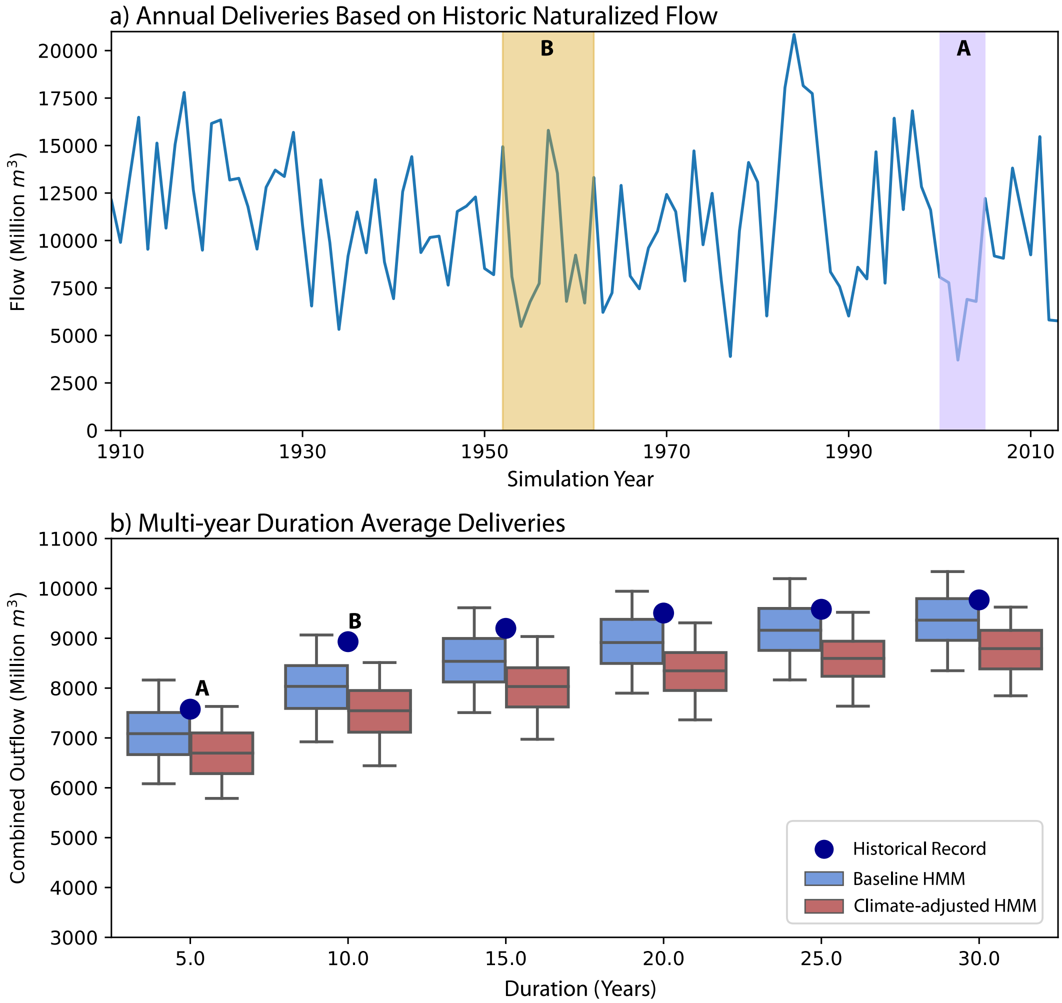

Figure 5. Duration-severity of deliveries to Lake Powell using the visualization procedure introduced by Salehabadi et al. (2022). (a) Cumulative deliveries to Lake Powell from the West Slope basins after routing the historical record of naturalized streamflow through StateMod. Period A, highlighted in light purple, represents the lowest deliveries when averaged over a 5-year period. Period B, highlighted in beige, represents the lowest deliveries when averaged over a 10-year period. (b) Duration-severity of deliveries after the naturalized historical streamflows (blue points), baseline Hidden Markov Model (HMM) records (blue boxplots), and climate-adjusted HMM records (red boxplots) are routed through StateMod. The lines within the boxplot represent the ensemble medians, the boxes represent the interquartile range, and the whiskers represent the 5th and 95th percentiles.

increasing persistence and spatial extent of droughts shown in Figures 4d and 4e provide further evidence that the small adjustments made to the HMM to produce the climate-adjusted ensemble transition the region into a new regime that contains a heightened risk of persistent streamflow deficits relative to the last century.

4.2. Deliveries to Lake Powell and the Lower Basin

To understand the consequences of drought events produced by the HMM ensembles, we examine deliveries to Lake Powell and the Lower Basin after routing the naturalized historical streamflow and HMM ensembles through StateMod. Unlike the naturalized flows, this evaluation contains a detailed accounting of water rights, consumptive use, reservoir storage, and operational policies within the West Slope basins (described in Section 3.2). Figure 5 shows the cumulative deliveries to Lake Powell from all five West Slope basins using a duration-severity plot in the style of Salehabadi et al. (2022). Figure 5a shows the total deliveries to Lake Powell after routing naturalized streamflow from the historical record through StateMod in all five basins. We highlight two periods of persistent low deliveries in Figure 5a. The light purple shaded area, period A, represents the period with the lowest mean annual deliveries when averaged over 5 years. The area shaded in beige, period B, shows the period with the lowest mean annual deliveries averaged over 10 years. The average annual deliveries to Lake Powell from the West Slope basins during periods A and B are plotted as points in Figure 5b. The remaining points in Figure 5b represent the lowest mean annual deliveries in the historical record when averaged across 15, 20, 25, and 30-year durations. The blue boxplots in Figure 5b represent the distribution of the first percentile deliveries for each duration across the 1,000 members of the baseline ensemble. The red boxplots in Figure 5b represent the distribution of first percentile deliveries from the climate-adjusted HMM.

Comparing deliveries from the naturalized historical record (blue points) and the ensemble generated by the baseline HMM (blue boxplots), we observe that the deliveries in the baseline ensemble generally envelope the deliveries resulting from the historical naturalized flow, with historical deliveries near the 75th percentile of the baseline ensemble for most durations. Some realizations contain longer durations with lower delivery volumes than any produced by the naturalized historical record. For example, the 5th percentile of the 10-year average delivery from the baseline HMM is below the lowest average 5-year delivery from the historical record. In other words, some members of the baseline ensemble contain periods when all-time low deliveries from the historical record (i.e., average delivery volume of period A) persist for twice as long (i.e., the duration of period B). Further, the 5th percentile of the 30-year average deliveries in the baseline ensemble is lower than the deliveries during the lowest 10-year period of the historical record (period B), highlighting that after accounting for internal variability, plausible low-deliveries to Lake Powell can persist for decades under the current water management policies represented within StateMod.

Deliveries generated by the climate-adjusted HMM (red boxplots) reflect the impact of the drier regional streamflow regime illustrated in Figure 4. The low deliveries in the historical record for each duration are near the higher 95th percentile of Lake Powell deliveries from the climate-adjusted ensemble, implying that historically unprecedented dry periods are extremely likely under the drier climate regime. The climate-adjusted ensemble also generates low deliveries that persist for longer periods than events that emerge from stationary internal variability within the baseline ensemble. For example, the median 10-year 1st percentile delivery from the baseline ensemble is roughly equal to the median 15-year 1st percentile delivery from the climate-adjusted ensemble, and the median 20-year 1st percentile delivery in the baseline ensemble is near the median 30-year 1st percentile delivery in the climate-adjusted ensemble. Put more simply, extreme events in the climate ensemble take 50% more time to deliver streamflow to Lake Powell when compared to extreme events from the baseline ensemble.

4.3. Reservoir Storage Levels

We next examine the local impacts of droughts within the baseline and climate-adjusted ensembles on the West Slope basins. Figure 6 shows how storage levels of the region's three largest reservoirs vary across the baseline and climate-adjusted HMM ensembles using Tea-cup diagrams, a visualization commonly employed by the US Bureau of Reclamation (US Bureau of Reclamation, 2022). The vertical axis of each panel in Figure 6 shows reservoir storage volume, and the shading represents the average monthly storage percentile across the 1,000-member HMM ensembles of 105-year records. Dark brown shading represents storage levels that are exceeded by 99% of monthly reservoir storage volumes within an ensemble, while dark green shading represents storage volumes exceeded by only 1% of all months. The white-shaded levels show the median storage volume across an ensemble. For comparison with the historical record, we plot mean monthly storage across the full historical record as a blue dashed line and the historic low in 2021 as a pink dotted line. All storage levels shown in Figure 6 are functions of the streamflow ensembles and the reservoir operating policies built into StateMod. For more information on reservoir operating policies within StateMod, see (CWCB & CDWR, 2016).

For Blue Mesa, Colorado's largest reservoir, the baseline ensemble yields a heightened risk of low storage levels compared to the historical record (left column of Figure 6a). While Blue Mesa's median storage level across the baseline ensemble is close to the historical average, the historically unprecedented low storage level of 2021—which caused marina closures and threatened the local tourism industry (Sakas, 2022)—falls within the 20th percentile of the baseline ensemble. The 2021 low levels in Blue Mesa were influenced by a large transfer from Blue Mesa to Lake Powell ordered by the US Bureau of Reclamation (US Bureau of Reclamation, 2021a), which is not modeled in StateMod. Our results suggest that the historical baseline stationary internal variability of the reservoir's inflows can cause extremely low storage levels to manifest under current operating policies, even in the absence of such large transfers.

10.1029/2024EF004841

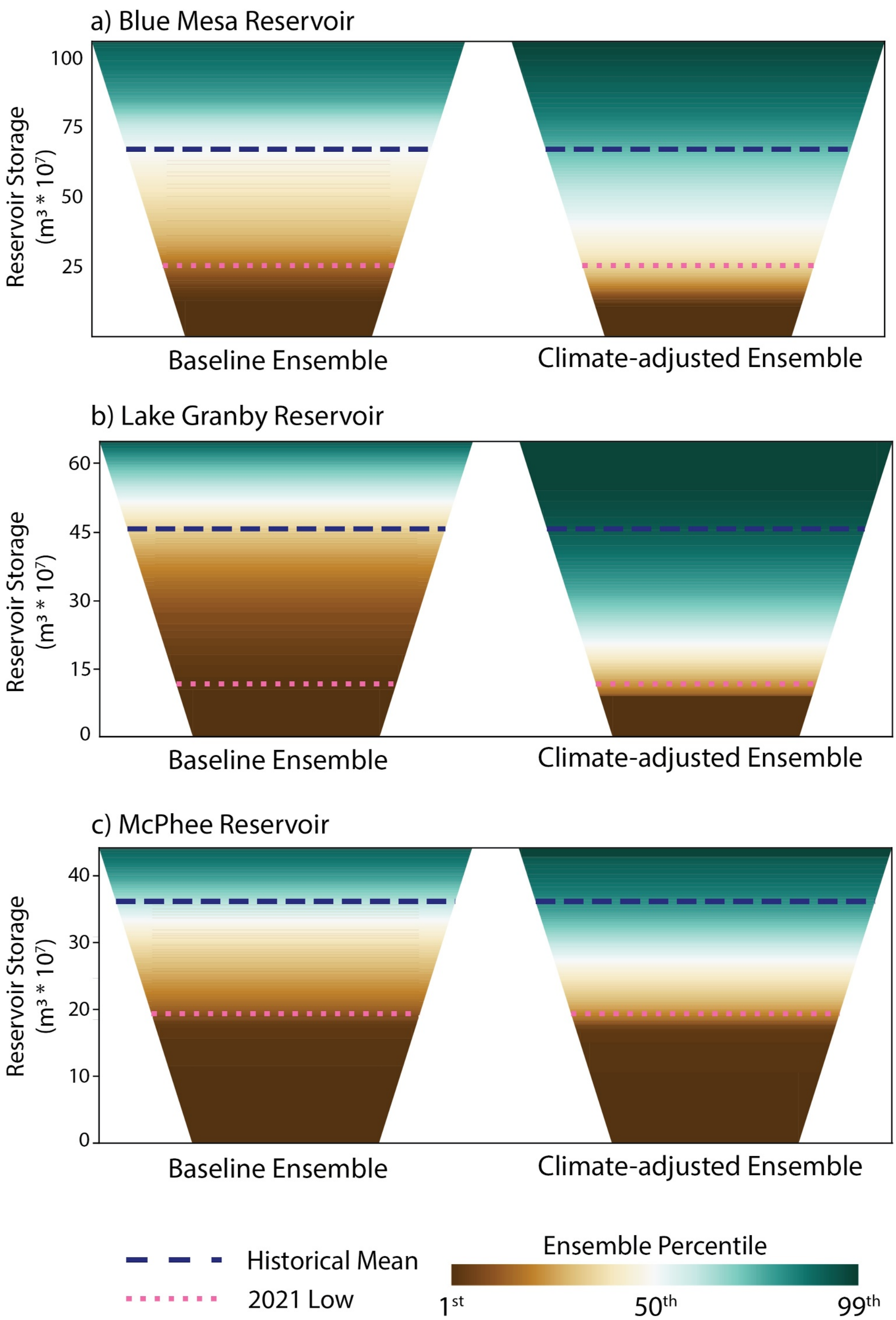

Figure 6. Tea-Cup diagrams showing reservoir storage of the West Slope's three largest reservoirs, Blue Mesa (Gunnison), Lake Granby (Upper Colorado), and McPhee (Southwest). The Tea-Cup diagrams show reservoir storage volume on the vertical axis. The colors represent the percentiles of average monthly storage across the baseline and climate-adjusted ensembles. The historical mean monthly reservoir storage volume and the historical lows from 2021 are shown as blue and pink dashed lines.

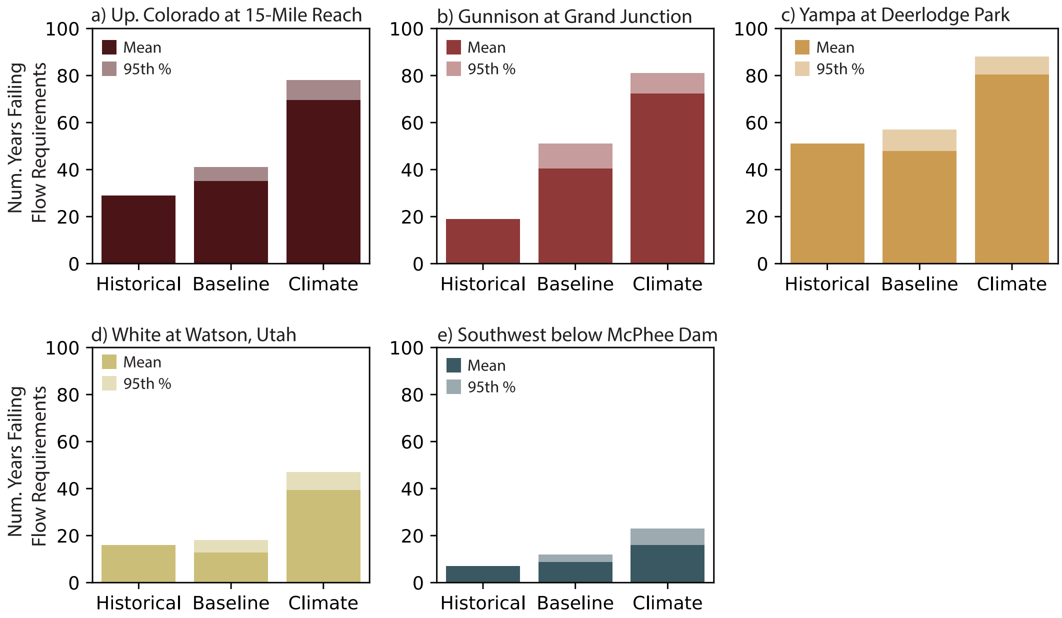

Figure 7. The frequency of late summer and fall environmental violations across West Slope basins under the historical record, baseline ensemble, and climate-adjusted ensemble.

Results from the baseline ensemble do not show a similarly heightened risk for the region's second and third largest reservoirs, Lake Granby and McPhee. The median shortage volumes for both reservoirs under the baseline ensemble fall near the ensemble medians. Lake Granby rarely reaches its 2021 low under the baseline ensemble, and the 2021 low falls near McPhee's 5th percentile of storage level according to its stationary historical baseline. Our results indicate that stationary historical internal variability alone is unlikely to result in unprecedentedly low storage levels under the existing operating policies represented in StateMod. However, the 2021 low levels of McPhee Reservoir caused widespread shortages for agricultural water users and prompted reservoir operators to greatly restrict reservoir releases (Cope, 2021). Our analysis suggests that these challenging conditions are produced approximately once every 20 years under the records generated from the stationary internal variability of the system.

Results from the climate-adjusted ensemble (right column of each panel in Figure 6) indicate that maintaining historical monthly storage volumes in all three reservoirs is not likely under the climate change conditions reflected in the climate-adjusted HMM. Under the climate-adjusted ensemble, the historical average monthly reservoir level falls near the 75th percentile storage in Blue Mesa, the 85th percentile in McPhee, and the 95th percentile in Lake Granby. In all three reservoirs, the median storage level of the climate-adjusted ensemble is greatly reduced relative to the medians in the historical baseline ensemble. This shift in reservoir storage underscores the implications of the regime change illustrated in Figure 4—under the "new normal" conditions of aridity, the region's largest reservoirs cannot maintain historical storage levels without changes in reservoir operating policy. While few other studies have directly modeled West Slope Reservoirs under plausible climate conditions, our results generally agree with a detailed analysis of Blue Mesa by Kopytkovskiy et al. (2015), who found that decreased streamflows and increased temperatures greatly reduce reservoir storage. Our results also align with an analysis commissioned by the City of Cortez, Colorado, which found that plausible changes in temperature and snowpack reduce storage on McPhee Reservoir (Arens et al., 2018).

4.4. Environmental Flows

Figure 7 explores the frequency of not meeting environmental flow goals during the late summer and fall low-flow conditions for the historical record and the HMM ensembles. Extended periods of low flow in August through October threaten the viability of larvae and reduce the connectivity between foraging and spawning areas for subadult and adult fish (Dibble et al., 2023; Osmundson et al., 1995). In each basin, we compare the number of years that fail to meet the US FWS recommended environmental flow requirements under historical streamflows

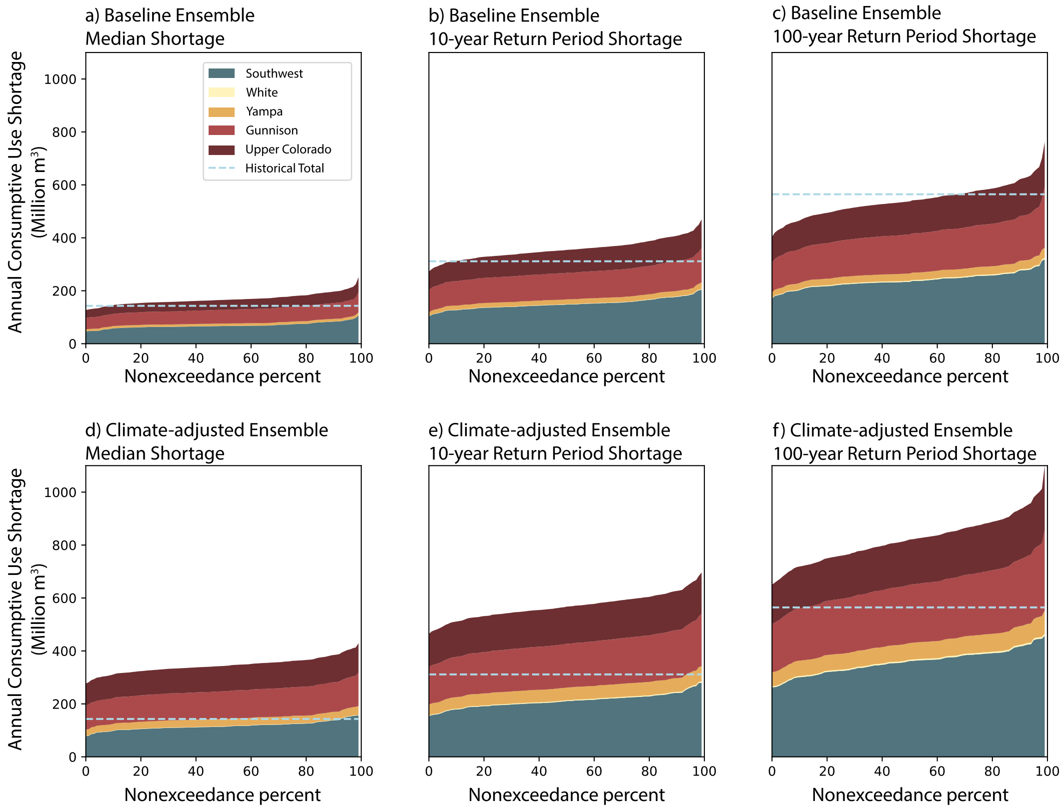

Figure 8. Cumulative consumptive use shortage across West Slope basins. Each panel represents a different percentile of annual shortage experienced during a 105-year record. The filled colors represent shortages in each basin, sorted according to severity across an ensemble. The blue dashed line represents the cumulative regional shortage resulting from the historical streamflow record for each percentile plotted.

with the number of failure years from both HMM ensembles. Violations of recommended flow occur naturally during periods of drought, and local species may tolerate infrequent violations (US FWS, 1999; US FWS, 2009). Figure 7 is intended to highlight the relative differences between historical conditions and the HMM ensembles rather than directly measure ecosystem viability. In recent years, the state of Colorado and the Federal government have adopted augmentation measures, such as upstream reservoir releases and purchasing water rights, to decrease the frequency of violations, which are incorporated into StateMod and reflected in the results shown in Figure 7 (CWCB, 2023; CWCB & CDWR, 2016).

The results in Figure 7 highlight that the drier regime under the climate-adjusted HMM increases the frequency of low-flow conditions not meeting environmental flow targets across all of the West Slope basins. Environmental flows in the Southwest basin experience the smallest increase in violation frequency because the reach evaluated in this study is directly below McPhee reservoir, which is operated to maintain environmental flows (potentially at the expense of reservoir storage as shown in Figure 6). The Upper Colorado, Gunnison, and Yampa basins experience greater increases in environmental flow violations, with violations occurring in roughly 80% of simulated years.

4.5. Agricultural Consumptive Water Use Shortages

Irrigation is the primary consumptive use of streamflow in the West Slope basins (CWCB, 2023). To examine the drought vulnerabilities for the West Slope's agricultural sector, we plot each basin's total consumptive use shortage in Figure 8. Figures 8a–8c show the consumptive use shortage from the Baseline ensemble, and Figures 8d–8f show results for the climate-adjusted ensemble. Figure 8a compares the median annual regional shortage from the 105-year historical record (blue dashed line) with the distribution of median annual shortages from the baseline ensemble of 1,000,105-year records. Each ensemble member of the baseline HMM produces a different median shortage level across 105 years, and these shortage levels are sorted and plotted separately for each basin using the colored fill. The horizontal spread across the panel thus represents the impact of stationary internal variability on the median shortage experienced in each basin. Figure 8b shows how estimates of the 10-year return period shortage event - the shortage that has an exceedance probability of 0.10 within a given 105-year record. Figure 8c shows the 100-year return period shortage event - the shortage that has an exceedance probability of 0.01 in a given 105-year record.

The stationary internal variability of streamflows captured within the baseline ensemble generates a small spread in shortage events, with the cumulative regional shortage similar to the historical record under most realizations (Figures 8a–8c. However, Figure 8d shows a large increase in the median consumptive use shortage across all basins under the climate-adjusted ensemble. The distribution of median shortages from the climate-adjusted ensemble, plotted in Figure 8d, resembles the distribution of the 10-year shortage event in the baseline ensemble, plotted in Figure 8b. In other words, shortages generated by dry conditions under stationary internal variability become routine under the climate change scenario reflected by the climate-adjusted HMM. Dry periods in the historical record have led to increased cattle feed costs and reduced agricultural production, causing tens of millions of dollars of damage to Colorado's agricultural sector (Colorado Division of Homeland Security and Emergency Management et al., 2020). Our results indicate that even middle-of-the-road projections for changes in climate may cause a fundamental shift in the West Slope's capacity for agricultural output.

The impact of the drier climate regime on consumptive use shortage increases when we examine extreme events in Figures 8e and 8f. The 10-year shortage events across the climate-adjusted ensemble (Figure 8e) exceed the 100-year shortage events within the historical record and baseline ensemble shown in Figure 8c. The levels of shortage shown in Figure 8e indicate that prior extreme historic shortage volumes are experienced much more frequently in the drier climate. The 100-year shortage event under the climate-adjusted HMM (Figure 8f) is over twice the total shortage volume of the 100-year event within the observed historical record. This difference represents a volume greater than the total storage of McPhee Reservoir, suggesting that extreme droughts influenced by climate change may have severe and unprecedented impacts on the region's agricultural sector.

5. Discussion

Our exploratory modeling analysis results reveal two surprising insights with consequences for the future management of the Colorado River Basin. First, the baseline ensemble results demonstrate that the cumulative impacts of drought on deliveries to Lake Powell are significantly magnified compared to the local impacts within each basin. While the baseline ensemble yields small increases in drought vulnerability within individual basins relative to historical records, dry periods emerging from the system's stationary internal variability generate unprecedented low delivery volumes to Lake Powell (Figure 5b). Low delivery volumes severely affect Lake Powell and the Lower Colorado River Basin, threatening hydropower generation, water supply, and sensitive ecosystems (Bruckerhoff et al., 2022; Johnson et al., 2016; Wheeler et al., 2022). The differences in drought vulnerability across spatial scales would be difficult to predict without the detailed multi-sectoral modeling conducted in this study. Our findings underscore the importance of supporting drought vulnerability analysis with the multi-basin HMM, which captures spatially and temporally compounding events not observed in the historical record.

Second, results from the climate-adjusted ensemble illustrate that the relatively optimistic 7% mean reduction in streamflows (as compared to the broader range of plausible climate change projections) substantially increases multi-sectoral drought vulnerabilities in the West Slope Basins. Across the West Slope Basins, the middle-of-the-road mid-century decrease in average streamflow represented in the climate-adjusted ensemble increases the tension between downstream deliveries to Lake Powell and upstream reservoirs' storage, environmental flows, as well as local irrigation demands. The declines in long-term water deliveries to Lake Powell (Figure 5b) have significant implications for representatives of the seven Colorado River Basin States and the Federal government as they negotiate future water allocations. Our findings indicate that the 7% middle-of-the-road projected streamflow decline would necessitate substantial changes in reservoir operating policies and reductions in water use within the West Slope basins to maintain deliveries to Lake Powell. However, our analysis of reservoir storage impacts in Section 4.3 demonstrates that the “new normal” dry conditions reflected in the climate-adjusted ensemble cause reduced storage in several key reservoirs under their current operating policies. The increases in environmental flow violations (Section 4.4) and unprecedented levels of agricultural shortage (Section 4.5)

10.1029/2024EF004841

generated by the climate-adjusted ensemble further illustrate the severity of multi-sectoral tensions stemming from climate-driven droughts.

Overall, our findings demonstrate that the West Slope Basins are severely strained by droughts emerging from the baseline stationary internal variability, and the more modest levels of plausible reductions in streamflow caused by climate change could trigger a cascade of multi-sectoral impacts. Our results underscore the urgent need for policymakers to explore innovations in water management paradigms, such as changes in water allocation accounting and infrastructure operations (Wheeler et al., 2021)), and to rapidly adopt proposals currently being debated by the US Senate (Hickenlooper et al., 2023) to mitigate the environmental impacts of increasingly frequent low-flow conditions.

6. Conclusion

The West Slope Basins are a vital water source for the UCRB and the state of Colorado. Drought in the West Slope Basins impacts deliveries to Lake Powell, agricultural production, recreation, and ecosystems. This work presents an exploratory modeling study of the local multi-sector drought impacts in the West Slope Basins and their implications for Lake Powell and the broader Colorado River Basin. We first introduce a multi-basin two-state Gaussian HMM-based synthetic streamflow generator to facilitate exploratory modeling of multi-sector drought vulnerability in the West Slope Basins. We then use the HMM to create a baseline ensemble of streamflows that reflects stationary internal variability and a climate-adjusted ensemble that reflects a middle-of-the-road climate scenario. Finally, we run both streamflow ensembles through StateMod and evaluate local and spatially compounding regional drought impacts.

Results from our baseline HMM ensemble highlight the impacts of internal variability on drought vulnerability in the Colorado River Basin. Drought events emerging from the stationary internal variability exhibit increased severity, persistence, and spatial extent compared with the most extreme events in the observed historical record. Within the West Slope Basins, our results illustrate that the multi-sectoral impacts of the recent millennium drought on reservoir storage, environmental flows, and agriculture are not outliers but stem from events that frequently emerge from the stationary internal variability. Our results further illustrate the spatially compounding drought impacts of drought on delivery volumes to Lake Powell and the Lower Colorado River Basin. Droughts emerging from stationary internal variability cause deliveries to drop below historical lows and increase the duration of low delivery periods. Our findings exemplify how drought vulnerability analyses relying only on the observed historical streamflow record may severely underestimate the magnitude of potential drought events and their spatially compounding impacts.

Results from the climate-adjusted ensemble reveal that even modest streamflow declines from a middle-of-the-road climate change projection strongly increase regional drought risks. The 7% decrease in streamflows captured within the climate-adjusted ensemble causes a regime shift that makes historical drought events routine and generates unprecedented drought events in terms of severity, persistence, and spatial extent. When routed through StateMod, our findings indicate that climate-induced droughts lead to prolonged periods of drastically reduced downstream water deliveries to Lake Powell, jeopardizing the sustainability of a vital component of the Colorado River Basin system. In the West Slope Basins, our analysis shows that current reservoir operating policies for Blue Mesa, Lake Granby, and McPhee Reservoir cannot sustain historical storage volumes under middle-of-the-road climate change projections. Future operational adaptations will need to balance sustainable storage levels with unprecedented regional agricultural shortages and an increased frequency of environmental flow violations. While the effects of climate change on streamflows in the UCRB remain highly uncertain, our results show that the water supplies in the West Slope Basins could be near a tipping point if a dryer future is realized. A relatively modest decrease in streamflow could generate a cascade of multi-sectoral impacts, threatening agricultural output, lowering reservoir levels, and harming sensitive ecosystems.

This work explores the impact of internal variability and a middle-of-the-road climate-change scenario on multi-sectoral drought vulnerability in the West Slope Basins. Future work can extend drought vulnerability analysis in the West Slope Basins by conditioning a similar HMM on paleo-reconstructed streamflow data available for each outlet node, which could expand the range of internal variability captured by the HMM. Paleo-based reconstructions of climate indices like the El Nino Southern Oscillation could also be used to create non-homogeneous HMMs where the transition matrix varies with paleo-based covariates. Future work can also explore additional climate scenarios, including alternative magnitudes of streamflow declines, changes in the persistence of large-scale climate patterns, and alterations in the spatial structure of drought events. Additional future work can explore how uncertainties stemming from human factors such as water demand, physical infrastructure, and institutionally complex water management systems influence drought vulnerability in the West Slope Basins and the broader regional system.

Data Availability Statement

StateMod (Version 15.0) was developed by CDSS and is publicly available from https://cdss.colorado.gov/software/statemod (CWCB & CDWR, 2016). Instructions for replicating the computational experiment, data processing code, and figure generation can be found at https://doi.org/10.5281/zenodo.13827786 (Gold et al., 2024a). All data for this work, including input data, raw output, and final results, can be found at https://doi.org/10.57931/2345933 (Gold et al., 2024b).

Acknowledgments
This research was sponsored by the US Department of Energy's Office of Science as a part of the research in MultiSector Dynamics within the Earth and Environmental System Modeling program. The funding is part of the Integrated Multisector, Multiscale Modeling (IM3) Scientific Focus Area associated with Grant DE-AC05-76RL01830. The authors would like to thank Jennie Rice, Chris Vernon, Travis Thurber, and Antonia Hadjimichael for their insights and discussions of this work. The authors also thank the two anonymous reviewers and the editorial team for helping improve the clarity and contribution of this study.

References

AghaKouchak, A., Mirchi, A., Madani, K., Di Baldassarre, G., Nazemi, A., Alborzi, A., et al. (2021). Anthropogenic drought: Definition, challenges, and opportunities. *Reviews of Geophysics*, *59*(2). https://doi.org/10.1029/2019rg000683

American Whitewater. (2012). Lower Dolores river implementation, monitoring, and evaluation plan for native fish.

Arens, S., Clifford, K., Dilling, L., Ehret, S., & Henderson, J. (2018). *Vulnerability, consequences and adaptation planning scenarios. City of Cortez (Tech. Rep.)*. Western Water Assesssment.

Ault, T. R., Cole, J. E., Overpeck, J. T., Pederson, G. T., & Meko, D. M. (2014). Assessing the risk of persistent drought using climate model simulations and paleoclimate data. *Journal of Climate*, *27*(20), 7529–7549. https://doi.org/10.1175/jcli-d-12-00282.1

Ault, T. R., Mankin, J. S., Cook, B. I., & Smerdon, J. E. (2016). Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American southwest. *Science Advances*, *2*(10), e1600873. https://doi.org/10.1126/sciadv.1600873

Bankes, S. (1993). Exploratory modeling for policy analysis. *Operations Research*, *41*(3), 435–449. https://doi.org/10.1287/opre.41.3.435

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

Biglarbeigi, P., Giuliani, M., & Castelletti, A. (2018). Partitioning the impacts of streamflow and evaporation uncertainty on the operations of multipurpose reservoirs in arid regions. *Journal of Water Resources Planning and Management*, *144*(7), 05018008. https://doi.org/10.1061/(asce)wr.1943-5452.0000945

Bracken, C., Rajagopalan, B., & Zagona, E. (2014). A hidden Markov model combined with climate indices for multidecadal streamflow simulation. *Water Resources Research*, *50*(10), 7836–7846. https://doi.org/10.1002/2014wr015567

Bruckerhoff, L. A., Wheeler, K. G., Dibble, K. L., Mihalevich, B. A., Neilson, B. T., Wang, J., et al. (2022). Water storage decisions and consumptive use may constrain ecosystem management under severe sustained drought. *JAWRA Journal of the American Water Resources Association*, *58*(5), 654–672. https://doi.org/10.1111/1752-1688.13020

Business for Water Stewardship. (2020). Economic contributions of water-related outdoor recreation in Colorado. Retrieved from https://businessforwater.org/wp-content/uploads/2020/06/SA_BWS_Exec_Summary_Digital-1.pdf

Carlson, C. A., & Muth, R. T. (1989). *The Colorado River: Lifeline of the American southwest* (Vol. 106, pp. 220–239). Canadian Special Publication of Fisheries and Aquatic Sciences.

Clark, M. P., Serreze, M. C., & McCabe, G. J. (2001). Historical effects of El Nino and la Nina events on the seasonal evolution of the montane snowpack in the Columbia and Colorado River Basins. *Water Resources Research*, *37*(3), 741–757. https://doi.org/10.1029/2000wr900305

Colorado Division of Homeland Security and Emergency Management, Colorado Water Conservation Board, and Colorado Resiliency office. (2020). The state of Colorado. *Future avoided costs explorer: Colorado hazards (Tech. Rep.)*.

Cook, B. I., Mankin, J. S., Marvel, K., Williams, A. P., Smerdon, J. E., & Anchukaitis, K. J. (2020). Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future*, *8*(6), e2019EF001461. https://doi.org/10.1029/2019ef001461

Cope, A. (2021). As the drought intensifies in the four corners, its impacts are visible on Mcphee reservoir's shores. Retrieved from https://www.ksjd.org/news/2021-06-21/as-the-drought-intensifies-in-the-four-corners-its-impacts-are-visible-on-mcphee-reservoirs-shores

Copeland, S. M., Bradford, J. B., Duniway, M. C., & Schuster, R. M. (2017). Potential impacts of overlapping land-use and climate in a sensitive dryland: A case study of the Colorado plateau, USA. *Ecosphere*, *8*(5), e01823. https://doi.org/10.1002/ecs2.1823

Culley, S., Noble, S., Yates, A., Timbs, M., Westra, S., Maier, H., et al. (2016). A bottom-up approach to identifying the maximum operational adaptive capacity of water resource systems to a changing climate. *Water Resources Research*, *52*(9), 6751–6768. https://doi.org/10.1002/2015wr018253

CWCB. (2023). *The Colorado water plan (Tech. Rep.)*. Colorado Water Conservation Board.

CWCB, and CDWR. (2016). Upper Colorado River Basin water resources planning model user's manual (Tech. Rep.). *Colorado Water Conservation Board and Colorado Division of Water Resources*. Retrieved from https://www.colorado.gov/pacific/cdss/modeling-datasetdocumentation

Dibble, K. L., Yackulic, C. B., Bestgen, K. R., Gido, K., Jones, M. T., McKinstry, M. C., et al. (2023). Assessment of potential recovery viability for Colorado Pikeminnow Ptychocheilus Lucius in the Colorado River in grand canyon. *Journal of Fish and Wildlife Management*, *14*(1), 239–268. https://doi.org/10.3996/jfwm-22-031

Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences* (Vol. 112(13), 3931–3936). https://doi.org/10.1073/pnas.1422385112

Erkyihun, S. T., Rajagopalan, B., Zagona, E., Lall, U., & Nowak, K. (2016). Wavelet-based time series bootstrap model for multidecadal streamflow simulation using climate indicators. *Water Resources Research*, *52*(5), 4061–4077. https://doi.org/10.1002/2016wr018696

Erkyihun, S. T., Zagona, E., & Rajagopalan, B. (2017). Wavelet and hidden Markov-based stochastic simulation methods comparison on Colorado river streamflow. *Journal of Hydrologic Engineering*, *22*(9), 04017033. https://doi.org/10.1061/(asce)he.1943-5584.0001538

Fleig, A. K., Tallaksen, L. M., Hisdal, H., & Demuth, S. (2006). A global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences*, *10*(4), 535–552. https://doi.org/10.5194/hess-10-535-2006

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

Gastélum, J. R., & Cullom, C. (2013). Application of the Colorado River simulation system model to evaluate water shortage conditions in the central Arizona project. *Water Resources Management*, *27*(7), 2369–2389. https://doi.org/10.1007/s11269-013-0292-5

Glaser, L. S. (1998). *The san Juan-Chama project*. Bureau of Reclamation History Program.

Gold, D. F., Gupta, R. S., & Reed, P. M. (2024a). Exploring the spatially compounding multi-sectoral drought vulnerabilities in colorado's west slope river basins (v1.0) [Software]. https://doi.org/10.5281/zenodo.13827786

Gold, D. F., Gupta, R. S., & Reed, P. M. (2024b). Gold-et-al_2024_EarthsFuture (Version v1) [Dataset]. *MSD-LIVE Data Repository*. https://doi.org/10.57931/2345933

Hadjimichael, A., Quinn, J., & Reed, P. (2020). Advancing diagnostic model evaluation to better understand water shortage mechanisms in institutionally complex river basins. *Water Resources Research*, *56*(10), e2020WR028079. https://doi.org/10.1029/2020wr028079

Hadjimichael, A., Reed, P. M., Quinn, J. D., Vernon, C. R., & Thurber, T. (2024). Scenario storyline discovery for planning in multi-actor human-natural systems con-fronting change. *Earth's Future*, *12*(9), e2023EF004252. https://doi.org/10.1029/2023ef004252

Hao, Z., & Singh, V. P. (2012). Entropy-copula method for single-site monthly streamflow simulation. *Water Resources Research*, *48*(6). https://doi.org/10.1029/2011wr011419

Hawkins, E., & Sutton, R. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, *90*(8), 1095–1108. https://doi.org/10.1175/2009bams2607.1

Hegewisch, K., Abatzoglou, J., & Chegwidden, O. (2023). *Future Streamflows (Tech. Rep.)*. UC Merced. Retrieved from https://climatetoolbox.org/

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

Hickenlooper, J. W., Romney, M., Lujan, B. R., Heinrich, M., & Bennet, M. F. (2023). *S.2247 - Upper Colorado and san Juan River basins endangered fish recovery programs reauthorization act of 2023 (Tech. Rep.)*. United States Senate.

Hisdal, H., Tallaksen, L. M., Gauster, T., Bloomfield, J. P., Parry, S., Prudhomme, C., & Wanders, N. (2004). Hydrological drought characteristics. In *Hydrological drought* (pp. 157–231). Elsevier.

Hoerling, M. P., Eischeid, J. K., Diaz, H. F., Rajagopolan, B., & Kuhn, E. (2024). Critical effects of precipitation on future Colorado River flow. *Journal of Climate*, *37*(16), 4079–4093. https://doi.org/10.1175/jcli-d-23-0617.1

Johnson, M., Ratcliff, L., Shively, R., Weiss, L., et al. (2016). Looking upstream: An analysis of low water levels in Lake Powell and the impacts on water supply, hydropower, recreation, and the environment: A companion report to the bathtub ring.

Kao, S.-C., Ghimire, G. R., & Gangrade, S. (2023). *CMIP6-based multi-model streamflow projections over the conterminous us (Tech. Rep.)*. Oak Ridge National Laboratory (ORNL).

Kopytkovskiy, M., Geza, M., & McCray, J. (2015). Climate-change impacts on water resources and hydropower potential in the upper Colorado River Basin. *Journal of Hydrology: Regional Studies*, *3*, 473–493. https://doi.org/10.1016/j.ejrh.2015.02.014

Lebedev, S. (2015). Hmmlearn. Retrieved from https://hmmlearn.readthedocs.io/

Lehner, F., & Deser, C. (2023). Origin, importance, and predictive limits of internal climate variability. *Environmental Research: Climate*, *2*(2), 023001. https://doi.org/10.1088/2752-5295/accf30

Lukas, J. J., & Payton, E. A. (2020). Colorado River Basin climate and hydrology: State of the science. In *Western water assessment*. University of Colorado.

Malers, S. A., Bennett, R. R., & Nutting-Lane, C. (2000). Colorado's decision support systems: Data-centered water resources planning and administration. *Watershed management and operations management*, *2000*, 1–9. https://doi.org/10.1061/40499(2000)153

Meko, D. M., Woodhouse, C. A., Baisan, C. A., Knight, T., Lukas, J. J., Hughes, M. K., & Salzer, M. W. (2007). Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters*, *34*(10). https://doi.org/10.1029/2007gl029988

Meyers, C. J. (1966). The Colorado River. *Stanford Law Review*, *19*, 1–75. https://doi.org/10.2307/1227048

Miller, O. L., Putman, A. L., Alder, J., Miller, M., Jones, D. K., & Wise, D. R. (2021). Changing climate drives future streamflow declines and challenges in meeting water demand across the southwestern United States. *Journal of Hydrology X*, *11*, 100074. https://doi.org/10.1016/j.hydroa.2021.100074

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.aay9187

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, *391*(1–2), 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Moallemi, E. A., Kwakkel, J., de Haan, F. J., & Bryan, B. A. (2020). Exploratory modeling for analyzing coupled human-natural systems under uncertainty. *Global Environmental Change*, *65*, 102186. https://doi.org/10.1016/j.gloenvcha.2020.102186

NatureServe. (2014a). Gila cypha in the IUCN red list of threatened species 2014. https://doi.org/10.2305/IUCN.UK.2014-1.RLTS.T9184A174778456.en

NatureServe. (2014b). Ptychocheilus Lucius in the IUCN red list of threatened species 2013. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T18829A174780793.en

NatureServe. (2014c). Xyrauchen texanus in the IUCN red list of threatened species 2013. https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T23162A174781799.en

Naumann, G., Alfieri, L., Wyser, K., Mentaschi, L., Betts, R. A., Carrao, H., et al. (2018). Global changes in drought conditions under different levels of warming. *Geophysical Research Letters*, *45*(7), 3285–3296. https://doi.org/10.1002/2017gl076521

Nowak, K. C., 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

Nowak, K. C., Prairie, J., Rajagopalan, B., & Lall, U. (2010). A nonparametric stochastic approach for multisite disaggregation of annual to daily streamflow. *Water Resources Research*, *46*(8). https://doi.org/10.1029/2009wr008530

Nowak, K. C., Rajagopalan, B., & Zagona, E. (2011). Wavelet auto-regressive method (WARM) for multi-site streamflow simulation of data with non-stationary spectra. *Journal of Hydrology*, *410*(1–2), 1–12. https://doi.org/10.1016/j.jhydrol.2011.08.051

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The scenario model intercomparison project (scenariomip) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Osmundson, D., Nelson, P., Fenton, K., & Ryden, D. (1995). Relationships between flow and rare fish habitat in the 15-mile reach of the upper Colorado River (Tech. Rep.). *United States Fish and Wildlife Service*.

Parsons, R., & Bennett, R. (2006). Reservoir operations management using a water resources model. In *Operating reservoirs in changing conditions* (pp. 304–311).

Pianosi, F., & Wagener, T. (2016). Understanding the time-varying importance of different uncertainty sources in hydrological modelling using global sensitivity analysis. *Hydrological Processes*, *30*(22), 3991–4003. https://doi.org/10.1002/hyp.10968

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N. W., Dankers, R., et al. (2014). Hydrological droughts in the 21st century, hotspots and uncertainties from a global multimodel ensemble experiment. *Proceedings of the National Academy of Sciences* (Vol. 111(9), 3262–3267). https://doi.org/10.1073/pnas.1222473110

Quinn, J. D., Hadjimichael, A., Reed, P., & Steinschneider, S. (2020). Can exploratory modeling of water scarcity vulnerabilities and robustness be scenario neutral? *Earth's Future*, *8*(11), e2020EF001650. https://doi.org/10.1029/2020ef001650

Quinn, J. D., Reed, P. M., Giuliani, M., Castelletti, A., Oyler, J. W., & Nicholas, R. E. (2018). Exploring how changing monsoonal dynamics and human pressures challenge multireservoir management for flood protection, hydropower production, and agricultural water supply. *Water Resources Research*, *54*(7), 4638–4662. https://doi.org/10.1029/2018wr022743

Rajagopalan, B. (2023). *Critical effects of precipitation on future Colorado River flow (Tech. Rep.)*. HydroShare. Retrieved from http://www.hydroshare.org/resource/52f57fb7e08d46ffbb8ea65073c9eefc

Reed, P. M., Hadjimichael, A., Moss, R. H., Brelsford, C., Burleyson, C. D., Cohen, S., et al. (2022). Multisector dynamics: Advancing the science of complex adaptive human-earth systems. *Earth's Future*, *10*(3), e2021EF002621. https://doi.org/10.1029/2021ef002621

Robeson, S. M., Maxwell, J. T., & Ficklin, D. L. (2020). Bias correction of paleoclimatic reconstructions: A new look at 1,200+ years of upper Colorado River flow. *Geophysical Research Letters*, *47*(1), e2019GL086689. https://doi.org/10.1029/2019gl086689

Sakas, M. E. (2021). *Drought-hit blue mesa reservoir losing 8 feet of water to save Lake Powell. A western slope marina feels the pain*. CPR News.

Sakas, M. E. (2022). The marinas at Colorado's blue mesa reservoir won't open this season as the threat of a water release to lake Powell looms. Retrieved from https://www.cpr.org/2022/05/18/blue-mesa-reservoir-marinas-lake-powell/

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

Satoh, Y., Yoshimura, K., Pokhrel, Y., Kim, H., Shiogama, H., Yokohata, T., et al. (2022). The timing of unprecedented hydrological drought under climate change. *Nature Communications*, *13*(1), 3287. https://doi.org/10.1038/s41467-022-30729-2

Schmidt, J. C. (2010). A watershed perspective of changes in streamflow, sediment supply, and geomorphology of the Colorado River. In *Proceedings of the Colorado river basin science and resource management symposium* (Vol. 5135, pp. 51–75). us geological survey, scientific investigations report.

Schmidt, J. C., Yackulic, C. B., & Kuhn, E. (2023). The Colorado river water crisis: Its origin and the future. *Wiley Interdisciplinary Reviews: Water*, *10*(6), e1672. https://doi.org/10.1002/wat2.1672

Smith, A. B. (2022). Us billion-dollar weather and climate disasters (pp. 1980–present).

Smith, R., Zagona, E., Kasprzyk, J., Bonham, N., Alexander, E., Butler, A., et al. (2022). Decision science can help address the challenges of long-term planning in the Colorado river basin. *JAWRA Journal of the American Water Resources Association*, *58*(5), 735–745. https://doi.org/10.1111/1752-1688.12985

Srivastav, R. K., & Simonovic, S. P. (2014). An analytical procedure for multi-site, multi-season streamflow generation using maximum entropy bootstrapping. *Environmental Modelling and Software*, *59*, 59–75. https://doi.org/10.1016/j.envsoft.2014.05.005

Stoelzle, M., Stahl, K., Morhard, A., & Weiler, M. (2014). Streamflow sensitivity to drought scenarios in catchments with different geology. *Geophysical Research Letters*, *41*(17), 6174–6183. https://doi.org/10.1002/2014gl061344

Tallaksen, L. M., & Van Lanen, H. A. (2004). Hydrological drought: Processes and estimation methods for streamflow and groundwater.

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*(4), 485–498. https://doi.org/10.1175/bams-d-11-00094.1

The Nature Conservancy. (2012). Estimated conditions for flow-dependent ecological systems. *Reclamation Managing Water in the West Technical Report D- System Reliability Metrics*.

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

US Bureau of, R. (1969). *Report of the committee on probabilities and test studies to the task force on operating criteria for the Colorado river (Tech. Rep.)*. US Bureau of Reclamation. Retrieved from http://www.riversimulator.org/Resources/USBR/ProbabilitiesOnOperatingCriteriaColoradoRiverBoR1969opt.pdf

US Bureau of Reclamation. (2012a). Colorado River basin water supply and demand study. Retrieved from https://www.usbr.gov/watersmart/bsp/docs/finalreport/ColoradoRiver/CRBS_Executive_Summary_FINAL.pdf

US Bureau of Reclamation. (2012b). Mcphee reservoir operations. Retrieved from https://www.usbr.gov/uc/wcao/water/rsvrs/mtgs/pdfs/mcphee_ops2012.pdf

US Bureau of Reclamation. (2020). Colorado River basin natural flow and salt data. Retrieved from https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html

US Bureau of Reclamation. (2021a). Reclamation releases updated projections of Colorado River system conditions. Retrieved from https://www.usbr.gov/newsroom/news-release/3994?filterBy=region&region=Upper%20Colorado%20Basin

US Bureau of Reclamation. (2021b). Reclamation's July 24-month study implements contingency operations in the upper Colorado River basin. Retrieved from https://www.usbr.gov/newsroom/news-release/3917?filterBy=region&region=Upper%20Colorado%20Basin

US Bureau of Reclamation. (2022). Upper Colorado region. Retrieved from https://www.usbr.gov/uc/water/basin/

US Bureau of Reclamation. (2023). Blue mesa reservoir storage data. Retrieved from https://data.usbr.gov/time-series/search?v=1

U.S. Department of Agriculture. (2017). Census of agriculture. Retrieved 10/1/2023, from https://www.nass.usda.gov/Publications/AgCensus/2017/

US FWS. (1999). Final programmatic biological opinion for bureau of reclamation's operations and depletions, other depletions, and funding and implementations of recovery program actions in the upper Colorado River, above the confluence with the Gunnison River.

US FWS. (2009). Final Gunnison river basin programmatic biological opinion.

Van Loon, A. F. (2015). Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, *2*(4), 359–392. https://doi.org/10.1002/wat2.1085

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I., Stahl, K., Hannaford, J., et al. (2016). Drought in the Anthropocene. *Nature Geoscience*, *9*(2), 89–91. https://doi.org/10.1038/ngeo2646

Van Loon, A. F., Tijdeman, E., Wanders, N., Van Lanen, H. J., Teuling, A., & Uijlenhoet, R. (2014). How climate seasonality modifies drought duration and deficit. *Journal of Geophysical Research: Atmospheres*, *119*(8), 4640–4656. https://doi.org/10.1002/2013jd020383

Van Loon, A. F., Wanders, N., Bloomfield, J. P., Fendeková, M., Ngongondo, C., & Van Lanen, H. A. (2024). Human influence. In *Hydrological drought* (pp. 479–524). Elsevier.

Wanders, N., & Wada, Y. (2015). Human and climate impacts on the 21st century hydrological drought. *Journal of Hydrology*, *526*, 208–220. https://doi.org/10.1016/j.jhydrol.2014.10.047

Wheeler, K. G., Kuhn, E., Bruckerhoff, L., Udall, B., Wang, J., & Gilbert, L. (2021). *Alternative management paradigms for the future of the Colorado and green rivers*. Center for Colorado River Studies, (Vol. 6, 1–85).

Wheeler, K. G., Rosenberg, D. E., & Schmidt, J. C. (2019). *Water resource modeling of the Colorado River: Present and future strategies*, (Vol. 2).

Wheeler, K. G., Udall, B., Wang, J., Kuhn, E., Salehabadi, H., & Schmidt, J. C. (2022). What will it take to stabilize the Colorado River? *Science*, *377*(6604), 373–375. https://doi.org/10.1126/science.abo4452

Woodhouse, C. A., Gray, S. T., & Meko, D. M. (2006). Updated streamflow reconstructions for the upper Colorado River Basin. *Water Resources Research*, *42*(5). https://doi.org/10.1029/2005wr004455

Woodhouse, C. A., & Overpeck, J. T. (1998). 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society*, *79*(12), 2693–2714. https://doi.org/10.1175/1520-0477(1998)079<2693:yodvit>2.0.co;2

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

Zagona, E. A., Fulp, T. J., Shane, R., Magee, T., & Goranflo, H. M. (2001). Riverware: A generalized tool for complex reservoir system modeling 1. *JAWRA Journal of the American Water Resources Association*, *37*(4), 913–929. https://doi.org/10.1111/j.1752-1688.2001.tb05522.x

References From the Supporting Information

Hadjimichael, A., Reed, P. M., Quinn, J. D., Vernon, C. R., & Thurber, T. (2023). *Multi-actor, multi-impact scenario discovery of consequential narrative storylines for human-natural systems planning*. Authorea Preprints.

Hoylman, Z. H., Bocinsky, R. K., & Jencso, K. G. (2022). Drought assessment has been outpaced by climate change: Empirical arguments for a paradigm shift. *Nature Communications*, *13*(1), 2715. https://doi.org/10.1038/s41467-022-30316-5

Lall, U. (1995). Recent advances in nonparametric function estimation: Hydrologic applications. *Reviews of Geophysics*, *33*(S2), 1093–1102. https://doi.org/10.1029/95rg00343

Mondal, A., & Mujumdar, P. P. (2015). Return levels of hydrologic droughts under climate change. *Advances in Water Resources*, *75*, 67–79. https://doi.org/10.1016/j.advwatres.2014.11.005

Slater, L. J., Anderson, B., Buechel, M., Dadson, S., Han, S., Harrigan, S., et al. (2021). Nonstationary weather and water extremes: A review of methods for their detection, attribution, and management. *Hydrology and Earth System Sciences*, *25*(7), 3897–3935. https://doi.org/10.5194/hess-25-3897-2021