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The Future Hydrology of the Colorado River Basin

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David Rosenberg, Sara Goeking, John C. Schmidt

A summary of current hydrology projections for the basin with perspective on how to incorporate them into CRSS and other planning models

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Executive Summary.

Long-range planning of the water supply provided by the Colorado River requires realistic assessments of the impact of a continuation of the current drought that began in 2000, the impact of potentially extreme future droughts, and the long-term and progressive decline in watershed runoff that is caused by a warming climate. Water-supply managers want to know the maximum plausible stresses to water users so that plans for conservation, reservoir operations, and/or construction of new infrastructure can be properly developed. River managers want to know the implications of various water-supply plans on the flow-regime and water-quality characteristics of the Colorado River and its headwater branches in order to develop natural resource management plans that maintain desired attributes of river ecosystems. Although it is relatively easy to qualitatively describe scenarios of drought or water abundance, it is much harder to quantitatively estimate likely future conditions. In the white paper, we developed methods to make such quantitative estimates, thereby providing an approximate answer to the question, "***How dry might future conditions in the Colorado River watershed become?***" It is difficult to assign a probability to this assessment, and our analysis is guided by the principle that ***what has happened in the past might happen again in the future***.

We evaluated the record of natural runoff at Lees Ferry based on analysis of historic observations and tree-ring streamflow reconstructions. The Lees Ferry record is widely used by water-supply managers to evaluate the supply of water available for allocation among the states of the Colorado River basin, as well as by Mexico. To evaluate the severity of sustained droughts, we advanced a new and powerful analysis methodology based on calculating sequence-average and cumulative depletions relative to the natural flow mean. These analyses show that the current millennium drought that started in 2000 has an average flow far less than the natural flow record starting in 1906 available from the U.S. Bureau of Reclamation. However, ***when viewed from the perspective of past flows reconstructed from tree-rings, or future flows projected from climate models, significantly more severe droughts are not only plausible, but increasingly likely, recognizing that hotter and drier conditions are making matters worse.***

We identified the magnitude and duration of the most severe droughts of the past 600 years. Three past droughts stand out in the record of prior flows. We use the term ***millennium drought*** to refer to the period between 2000 and 2018—***mean flow of 12.44 million acre feet/year (maf/yr) for 19 years; 2.3 maf/yr less than the long term mean of 14.76 maf/yr*** computed from the 1906-2018 natural flow record. The ***mid-20th century drought*** was the period between 1953 and 1977—***mean flow of 12.89 maf/yr for 25 years***; ***1.9 maf/yr less than the long term mean***. Both of these are plausible scenarios of future droughts, because they have occurred in the recent past and indeed may be continuing today. We use the term ***paleo tree-ring drought*** to refer to the period between 1576 and 1600 that is based on tree ring estimates of streamflow—***mean flow of 11.76 maf/yr for 25 years; 3 maf/yr less than the long term mean***.

We implemented an analytical scheme that assumed that years of low runoff that occurred

in the worst of past droughts might occur again in the future but that the sequence in which these years of low runoff occur in the future might differ from what occurred in the past. This method simulates possible future droughts by developing sequences of low runoff years randomly selected from the records of the three severe past droughts described above. Each grouping of randomly-assigned sequences of low-flow years drawn from one of these past droughts is referred to as a ***scenario***. Multiple (100) sequences were simulated for each scenario. These scenarios would severely test the operational rules, and planning and management strategies of the Colorado River system. Each scenario, and each sequence within each scenario, is based on past flows that actually occurred in the 20th or 21st century or has been estimated from tree-ring hydrology. The random ordering of years of low flow is a justifiable approach to estimating possible conditions in the future, because it has been shown that year-to-year correlation of flows in the Colorado basin is small.

Climate change studies show that, with warming, runoff will decline in the future. We show that the random sequences we have produced for each scenario are within the range in severity of the droughts derived from climate projections. In fact, the most severe of future climate projections produced from general circulation models (GCM) that were selected by the best reproduction of historic drought severity, suggest more severe future droughts than those of our study. Thus, future warming of Earth's climate might make matters even worse than we estimate here.

The work in this white paper is novel, because we combined analysis of the most recent Lees Ferry natural flow estimates provided by tree-ring hydrology studies with the drought-scenario-based resampling methodology outlined above. ***Our results demonstrate that planning in which the 1988-2018 period containing the current drought is used as a stress test might not consider drought scenarios that are sufficiently extreme. The future might be far drier than managers currently anticipate.***

An additional aspect of our research is that ***we developed and implemented a scheme for incorporation of our estimates of future drought at Lees Ferry into the Colorado River Simulation System (CRSS).*** This effort required development of a disaggregation method that estimates future drought conditions at every input node of CRSS. These data are available as supplementary data to this white paper (Salehabadi and Tarboton, 2020). Our goal is to provide a rigorous quantitatively derived set of drought scenario inputs that can be used by any stakeholder proficient in CRSS, or any other model of the Colorado system, who wishes to analyze current risks or alternative management paradigms that might be useful in confronting severe sustained long-term drought.

We also provided one example of the stresses that a severe sustained drought would place on the Colorado River system by using the CRSS model and our quantitative estimates of future droughts to evaluate the frequency of Lake Powell elevations declining below a critical threshold if "business as usual" water management were pursued during a severe drought. We ran the April 2020 version of CRSS initialized with the projected January 1, 2021 reservoir conditions, the current interpretation of the Law of the River within CRSS, and the future drought scenarios estimated in this study. We compared our results with predicted conditions based on the hydrology represented using the Index Sequential Method derived from the natural flow estimates calculated by Reclamation. The scenarios we developed indicate that there would be long periods when Lake Powell pool elevations would fall below that which is required to produce hydropower. Thus, new strategies and plans will be necessary to confront the challenge of severe future droughts.

Acknowledgements

We are grateful to the Catena Foundation and the Walton Family Foundation for their generous support of this project. Guidance, advice, feedback and insightful conversation greatly improved the quality of this effort – thanks to Chris Harris, Don Ostler, Sara Larsen, Amy Haas, and Jim Prairie for their thoughtful contributions. The future of the Colorado River team worked hard to refine and direct these ideas: Jian Wang, Bethany Neilson, Christy Leonard, and Bryce Mihalevich. Thanks to Lael Gilbert for editing support.

This is a publication in white paper series from the Future of the Colorado River Project.

White Paper 1: Fill Mead First – A Technical Assessment
Executive Summary, Full Paper

White Paper 2: Water Resource Modeling of the Colorado River: Present and Future Strategies
Full Paper, CRSS Schematic (high resolution)

White Paper 3: Managing the Colorado River for an Uncertain Future
Brief, Full Paper

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The Future Hydrology of the Colorado River Basin

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1. Introduction

The Colorado River is a critical source of water for the southwestern United States and northwestern Mexico. The river's watershed spans parts of seven U.S. states and the Mexican states of Baja California and Sonora (Figure 1). The largest region of irrigated agriculture in the watershed is the Imperial/Coachella/Mexicali Valleys and nearby Yuma that provide produce and livestock feed for both countries, especially in winter. Other important agricultural areas include central Arizona, Palo Verde Valley, Montezuma Valley, Grand Valley, Uncompahgre Valley, and the Uinta Basin. The Colorado River also provides a critical water supply to some of the largest metropolitan areas in the United States, including Los Angeles, Phoenix, San Diego, Denver, Las Vegas, Salt Lake City, Albuquerque, and Tucson, as well as Tijuana and Mexicali in Mexico.

Earth's warming climate is expected to cause a persistent and possibly irreversible decline in watershed runoff to the Colorado River for decades, if not centuries, yet demand already exceeds supply. Kuhn and Fleck (2019) distinguished the Colorado River's "two stories" in their recent book *Science Be Dammed*: "nature's water flowing in and humans taking it out." Development of sustainable water-supply management policies regarding how much water can be taken out of the Colorado River partly depends on anticipating the magnitude and patterns of "nature's water flowing in." Policy development about how the Colorado River will be managed unavoidably takes place with uncertain understanding of what future watershed runoff will be. In their recent white paper *Managing the Colorado River for an Uncertain Future*, Wang, Rosenberg et al. (2020) highlighted the nature of this uncertainty and proposed development of adaptable water-supply-management policies that are sufficiently flexible to accommodate the wide ranging predictions about future hydrologic conditions. Wang, Rosenberg et al. (2020) proposed different policy-planning strategies that might be pursued (1) under circumstances where future conditions can be anticipated with defined probabilities and (2) under circumstances where alternative future scenarios can be described but whose probability of occurrence is unknown. Wang, Rosenberg et al. (2020) termed the former category as Level 2 uncertainty and the latter category as Level 3 uncertainty.

Figure 1. Map showing the watershed, or hydrologic basin, of the Colorado River and areas beyond the watershed that are served by trans-basin diversions (adapted and revised from U.S. Bureau of Reclamation, 2012).

Recent studies, including the *Colorado River Basin Water Supply and Demand Study* (U.S. Bureau of Reclamation, 2012) and *Colorado River Basin Climate and Hydrology: state of the science* (Lukas and Payton, 2020), summarized the current state of knowledge about watershed climate, hydrology, and water resource modeling. Lukas and Payton (2020) comprehensively summarized and synthesized the on-going work of federal and state agencies and universities to continually improve monitoring and prediction of water supply.

The *Future of the Colorado River* project (https://qcnr.usu.edu/coloradoriver/futures) seeks to evaluate alternative management policies that minimize the adverse impacts of a declining water supply, while also developing tools and approaches useful in anticipating and describing the ecological implications of those policies. The project utilizes existing river management modeling tools such as the Colorado River Simulation System (CRSS) and also is developing new modeling tools that help describe the impacts of uncertainties in future hydrology, demand, and ecosystem conditions and operations to better cope with future extreme droughts.

Any model addressing management of the Colorado River is ultimately driven by assumptions about the watershed's future hydrology, even though the precise characteristics of that future are unknown. ***The primary purpose of this white paper is to summarize current understanding of future hydrology from the perspective of how that understanding can be incorporated into CRSS and other river planning models.*** Our goal is to complement the work of Lukas and Payton (2020) by focusing on planning-relevant and policy-relevant scientific and engineering issues that affect characterization of the Colorado River's future hydrology. ***Another purpose of this paper is to provide scenarios that characterize and estimate plausible future drought conditions, based on analysis of estimated 20th and 21st century natural flow and tree ring-estimated natural flow***. These scenarios are based on the record of previous droughts that occurred in the historic past and that are plausible based on tree-ring hydrology. These scenarios are of low probability, and would significantly stress the existing water-supply system. However, implementation of good engineering and good planning methodologies requires evaluation of system behavior under a wide range of possible future conditions. Although the probabilities of some of the scenarios proposed here cannot be statistically evaluated, each scenario described in this report has occurred in the past or can be reconstructed from the past record of streamflow. Thus, each scenario described here is plausible. **If such conditions have**

happened in the past, they might occur in the future, and these scenarios should be considered in future planning. It is our intention that the scenarios described in this report be used to evaluate alternative paradigms for managing the Colorado River, because consideration of the possibility of these dire circumstances will encourage the water management community to consider options for allocation of water supply under the most challenging of drought conditions. The CRSS model is driven by inputs of monthly streamflow at 29 nodes spread across the Colorado River Basin. To use the drought scenarios developed from natural and tree ring estimated streamflow at Lees Ferry, these annual data need to be translated into corresponding monthly flows at each of the CRSS nodes. We used the Water Year Block Disaggregation method to achieve this objective so as to convert our drought scenarios into a format that can be integrated into CRSS for the evaluation of alternative management paradigms.

Readers guide

The audience for this paper is stakeholders, planners, water managers, and management agency staff. This paper first presents an overview of the physiography of the Colorado River Basin. Then we describe how the basin has been partitioned for the purposes of our analysis based on annual streamflow correlation. We then examine trends in hydrologic and climatic variables. This background provides context for the next section which identifies severe droughts that have been recorded, both in observed streamflow as well as paleo reconstructions of streamflow based on tree rings. This section is followed by a section reviewing briefly some of what is known about climate change and projected impacts in this area. Then the paper, in section 7, uses stochastic methods to generate potential future drought scenarios to use in planning, and this part is the substantive contribution of this work. These planning scenarios provide a diverse set of plausible future drought conditions, against which, we suggest, any future operation, contingency planning, or system management paradigms should be tested. We make this suggestion, not because we know these scenarios will occur, but because we know these scenarios could occur. Prudent planning requires consideration of how the Colorado River water supply and river management system would respond to such stresses. Section 8 gives results detailing the potential severity of droughts contained in our planning scenarios, and presents a very preliminary assessment of what the impacts would be on the level of Lake Powell, based on CRSS modeling. We present this brief analysis of implications to Lake Powell in an effort to inspire more comprehensive identification and analyses of management paradigms that might provide favorable conditions for water supply throughout the Colorado River watershed. The paper includes a number of side bars that expand on details and provide supplementary information on key aspects of the hydrology, but that are kept out of the main text so as not to disrupt flow. Sidebar 1 examines historical studies estimating the total flow in the Colorado. Sidebar 2 gives information on the natural flow downstream of Hoover Dam, pointing out differences between early approaches and the current approach to these natural flow estimates. Sidebar 3 defines the concept of natural flows, which are the flows that would have occurred in the river in the absence of human withdrawals and consumptive uses and gives details on how they are estimated by various agencies. Sidebar 4 examines the unusually wet period in the natural flow database, from 1906-1929, referred to as the Early 20th Century Pluvial. Sidebar 5 summarizes some of what is known about how forests in the Colorado River Basin, are changing and what the impacts may be for future streamflow, and sidebar 6 provides a brief comparison of some of the tree ring reconstructions available for the flow at Lees Ferry. One of these reconstructions was used in developing our drought scenarios, but given that there are multiple tree ring reconstructions available, this sidebar provides some rationale for our selection.

2. Physiographic and Hydrologic Overview

Key points

- The Colorado River extends from snow dominated high mountain regions with significant runoff to deserts.
- 85% of the annual average runoff originates from 15% of the watershed in western Colorado, southwestern Wyoming, and northeastern Utah.

The Colorado River and most of its tributaries cross many mountains and high plateaus to reach to the Gulf of California. There is a long history of river-based scientific exploration in the Colorado River Basin. This section aims to briefly describe the physiographic and hydrologic attributes of the river.

The Colorado River's headwaters are in the middle and southern Rocky Mountains (Fig. 2), and the river "… runs from the land of snow to the land of sun" (Powell, 1875). The headwater streams generally drain south and west and eventually join to form the three primary Upper Basin branches of the drainage network. The upper Colorado River (once called the Grand River) and the Green River join to form the main-stem Colorado River in the Canyonlands region of the Colorado Plateau (Figure 2). The other headwater branch, the San Juan River, enters the Colorado River ~140 mi (230 km) further downstream and drains the San Juan Mountains in the southernmost part of the Rockies. Approximately 80 mi (125 km) downstream from this confluence is Lees Ferry, where the Colorado River flows across a 3-mi (5-km) long open valley that is one of the only places where the river banks are easily accessible. Thereafter, the river flows 290 mi (470 km) through Marble and Grand Canyons before entering the broad valleys and isolated mountain ranges of the Basin and Range. The Gila River is the one long tributary whose course is wholly within the Basin and Range. The Gila River's headwaters are in the Mexican Highlands of west-central New Mexico. The Gila crosses the Sonoran Desert and joins the main stem at the head of the Colorado River delta in the Salton Trough.

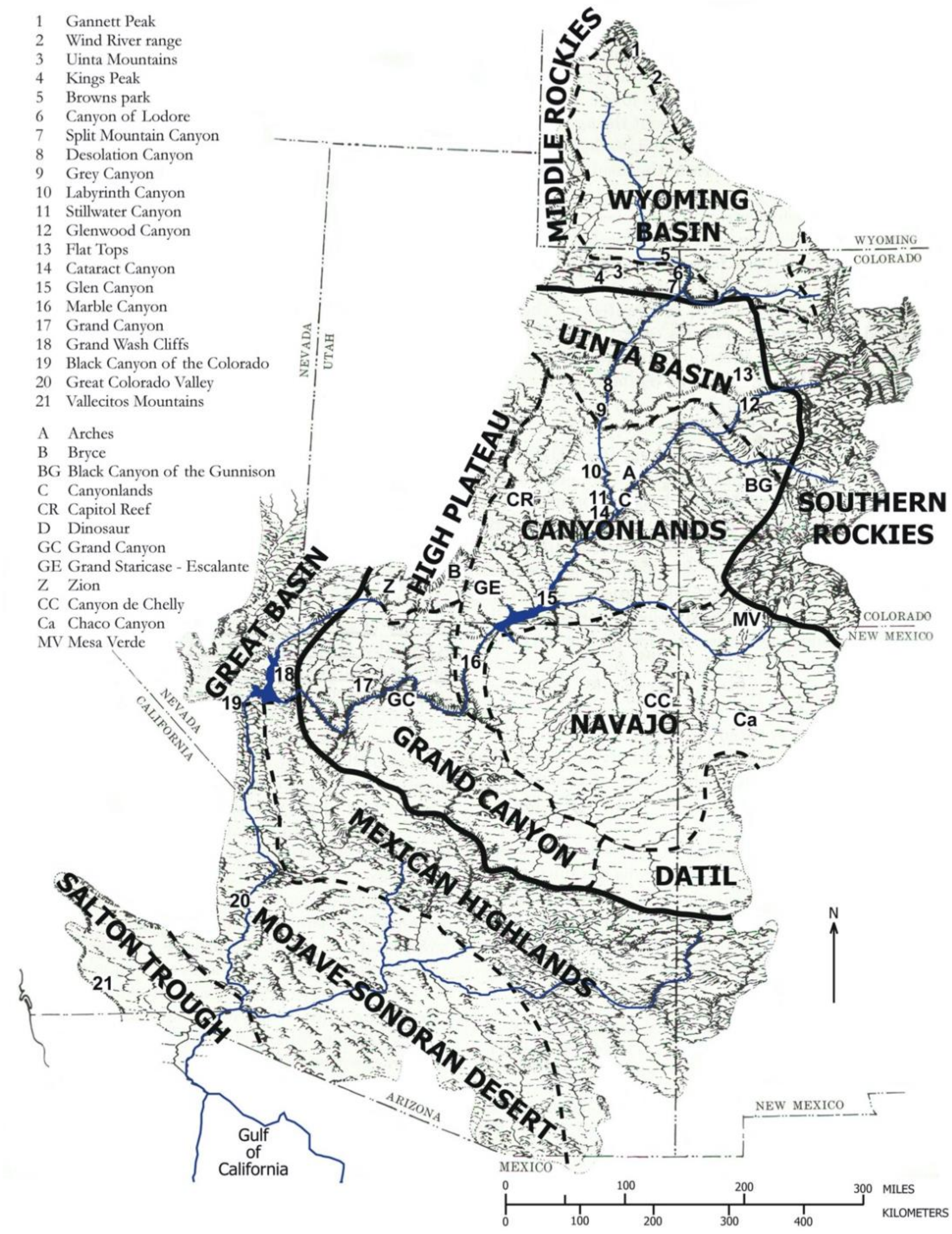


Figure 2. Map showing the subdivisions of the three physiographic provinces of the Colorado River watershed. The Rocky Mountains are in the north and east; the Colorado Plateau is in the center of the watershed, and the Basin and Range is to the south and west. The delta of the Colorado River is in the Salton Trough (adapted from Hunt, 1969; and physiographic divisions are from Graf, 1987)

The Colorado River Basin includes headwater mountain ranges where mean annual temperature is below freezing and annual precipitation is more than 60 inches (1500 mm), and the basin also includes low-elevation deserts of the Basin and Range where annual precipitation is as little as 4 inches (100 mm) and maximum daily temperatures sometimes exceed 120°F (49°C) (Figure 3). Thus, the watershed has tremendous hydroclimatic diversity (Lukas and Harding, 2020). Most of the annual runoff is produced in a small part of the watershed. Christensen and Lettenmaier (2007) estimated that 85% of the average annual runoff comes from 15% of the watershed in western Colorado, southwestern Wyoming, and northeastern Utah. These are also the areas with the highest runoff efficiency, measured as the proportion of total annual precipitation that becomes runoff, and most of this runoff occurs as snowmelt. The disproportionate hydrologic influence of the small and sparsely measured mountains introduces uncertainty in understanding modern hydrological processes and predicting future streamflow of the Colorado River.

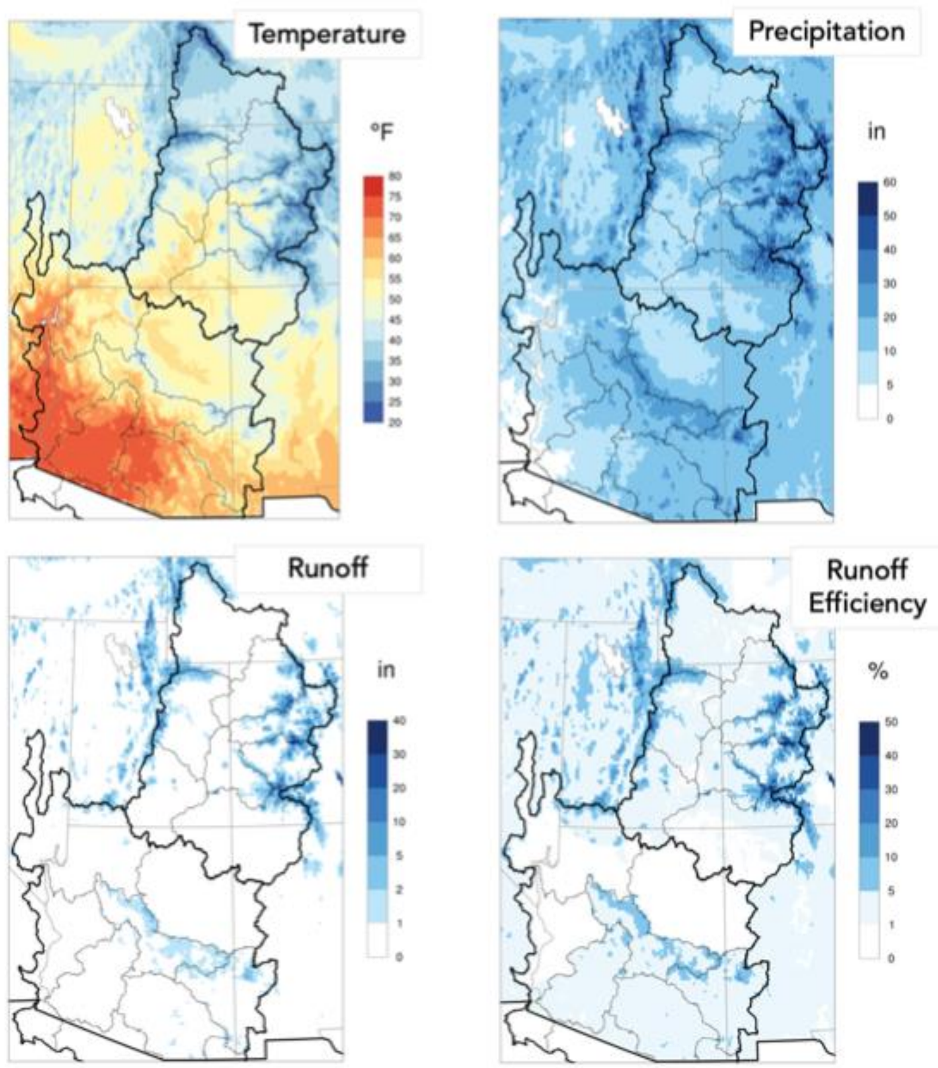


Figure 3. Average hydroclimatic conditions of the Colorado River watershed between 1981 and 2010: observed average annual temperature (upper left), observed average annual precipitation (upper right), modeled average annual runoff (lower left), and modeled average runoff efficiency (lower right). (from Lukas and Harding, 2020, fig. 2.1).

LaRue (1916) estimated the total annual flow of the Colorado River and the proportion of the mainstem flow that came from each of the three headwater branches (Sidebar 1). His report, *The Colorado River and Its Utilization*, primarily focused on identification and analysis of potential dam sites that might reduce the flood risk near Yuma and create storage of a sufficient proportion of the annual snowmelt flood that would allow expansion of irrigated agriculture. On the basis of measurements made between 1895 and 1914, LaRue (1916) estimated the average annual flow of the Colorado River at Laguna Dam, just upstream from the Gila River confluence, and demonstrated that the vast majority of water flowing past Yuma had come from the Upper Basin. In response to these findings, much of the focus of modern stream-flow measurements and analysis of the effects of climate change has been concentrated on the Upper Basin that is the source of most of the streamflow.

Scores of gages were established throughout the Upper Basin to more precisely characterize the sources and amounts of streamflow (Figure 4). Iorns et al. (1965) comprehensively summarized these data at the time that the dams and irrigation projects of the Colorado River Storage Project were being completed. Iorns et al. (1965) estimated that the annual natural flow at Lees Ferry in the first half of the 20th century was ~7% less than that estimated by LaRue (1916) for the early 20th century (Sidebar 1).

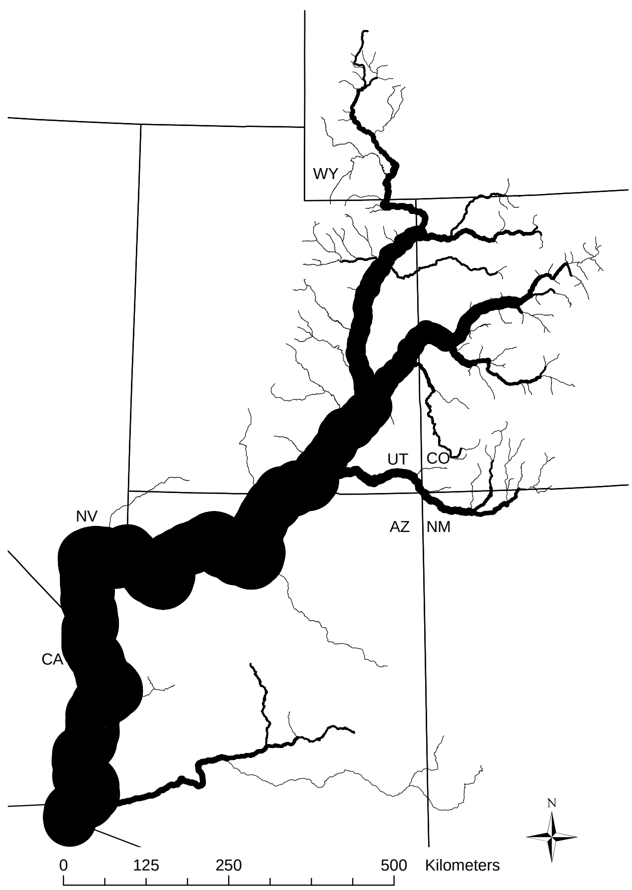


Figure 4. Map showing relative amount of streamflow between 1917 and 1957, estimated by Iorns et al (1964; 1965) for all river segments upstream from Lees Ferry and gaging records in the Lower Basin. Note the abundance of tributary branches in the Upper Basin that reflects the number of gaging stations established after LaRue's (1916) report.

Scientists and engineers have struggled to quantify the magnitude of losses in the ~ 500 mi (800 km) of the lower Colorado River between the Grand Wash Cliffs, where the Colorado River leaves the Colorado Plateau, and the Gulf of California. The river crosses different isolated ranges in nine short canyons, and 85% of the lower Colorado River's length is distributed in four intervening long valley segments. LaRue (1925) described the challenge in comparing stream-flow data at Lees Ferry, or elsewhere in the canyons of the Colorado Plateau, and data collected near Yuma:

> The chief difficulty in applying … [the Yuma] record to the canyon section lies in the fact that there is a large and variable loss of water by evaporation from the stream channel, especially from the overflowed lands in the valleys between Yuma and Pierces Ferry. These lands are submerged and saturated by the annual summer floods. The area thus flooded varies from year to year, and the considerable amount of water passing into the dry, heated desert air by evaporation and transpiration from the rank growth of vegetation also varies. It is impossible to estimate accurately the amount of water thus lost.

LaRue (1916) estimated that 92.5% of the total flow at Laguna Dam came from the Upper Basin and flowed past Lees Ferry, and Reclamation's modern natural flow data suggest a similar percentage of flow coming from the Upper Basin. Other efforts to compare flow at Lees Ferry and Yuma suggested channel and floodplain losses were less (Sidebar 2). The different estimates of lower Colorado River losses are an important source of discrepancy concerning the natural flow of the river at Yuma.

3. Partitioning into Hydrologic Regions

Key points

- The Upper Colorado River Basin can be separated into four hydrologically similar parts based on the statistical similarity (correlation) of water year natural flow originating in each CRSS subwatershed.
- The Green River carries streamflow from middle Rocky Mountains and the southern Rocky Mountains.
- The greatest runoff comes from the southern Rockies that supply the upper Colorado and San Juan Rivers, as well as part of the Green River streamflow.

To get an understanding of climate and where natural flow originates in the Colorado River Basin, whether there are trends in these quantities and whether these trends are different for different areas within the basin, we subdivided the basin into regions for trend analysis. Although the headwater branches of the Colorado River are traditionally distinguished by their physiographic watersheds, we chose to use an alternative approach that grouped those parts of the basin that have similar hydrologic characteristics based on correlation. We identified regions of hydrologic similarity based on tributary inflows and estimated intervening flows in Reclamation's Natural Flow Database that gives data for each of the 29 CRSS nodes.

3.1. 29 CRSS Local Watersheds

The CRSS is a water-resources planning model developed by Reclamation for long-term planning studies and policy evaluation (Zagona et al., 2001; U.S. Bureau of Reclamation, 2012). This model incorporates key components of the Colorado River's channel network such as the river's main stem, major tributaries, intervening flows between gages, diversions, and reservoirs, along with the operational rules presently implemented as the Law of the River. The CRSS does not represent the watershed with equal spatial resolution, but we focused on the network as presently described in CRSS (Wheeler et al., 2019). The model identifies 20 inflow nodes in the Upper Basin where natural flow is considered to enter the drainage network. There are 4 nodes on tributaries that enter the Colorado River downstream from Lees Ferry for which natural flows are not estimated, and there are 5 nodes on the Lower Colorado River whose reported natural flows are a mixture of estimated natural flows from upstream and actual tributary inflow. Estimated intervening flows for river segments that include major reservoirs represent inflow estimated that are corrected for estimated reservoir evaporation. Collectively, these nodes divide the Colorado River Basin into 29 different local watersheds defined as the area that drains directly to each node excluding area that drains to a node further upstream (Figure 5).

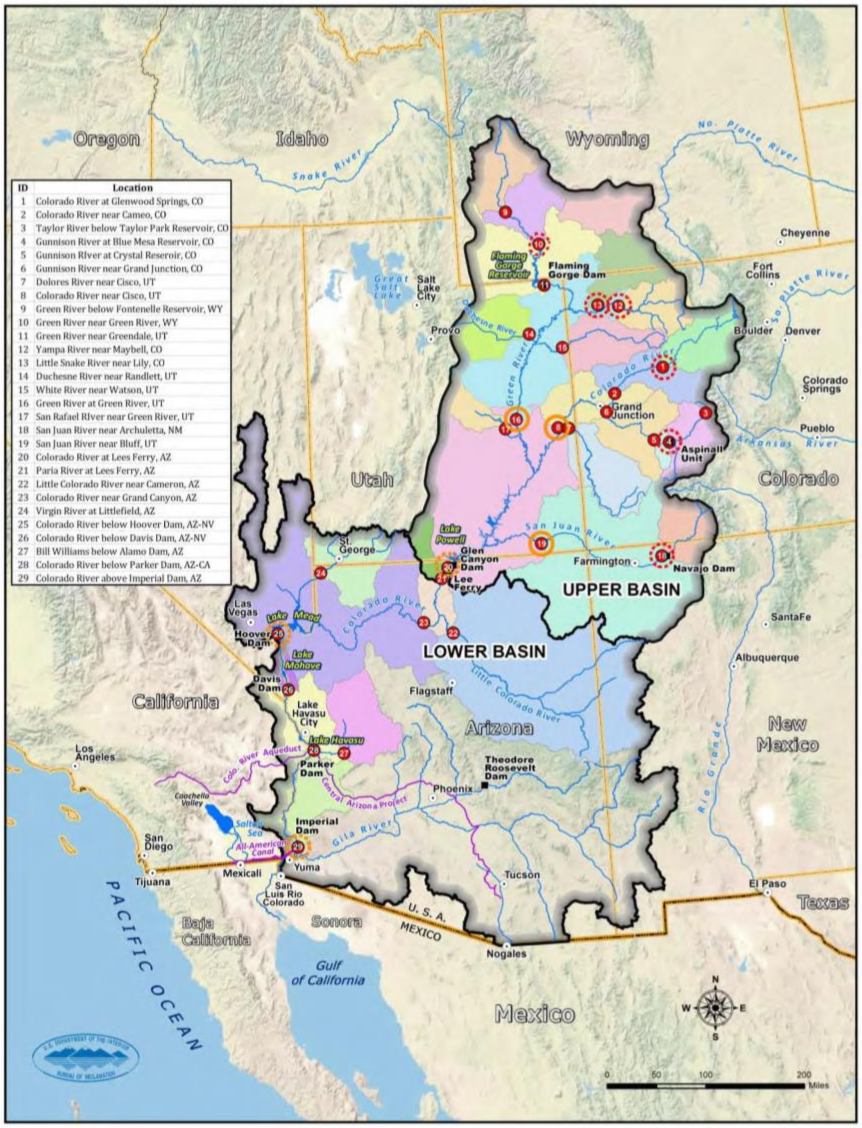


Figure 5. Map showing the Colorado River Basin in the United States and the 29 inflow nodes used in the CRSS model and showing the local-watersheds of each node. Note that the local-watershed of each node only includes the area downstream from any node further upstream.

Reclamation (2020) estimates the natural flow at each node. These data are published and updated as the *Colorado River Basin Natural Flow and Salt Data* (https://www.usbr.gov/lc/region/g4000/NaturalFlow/), and this database includes the estimated natural flow originating within each local-watershed (referred to as intervening flow in the Reclamation data) as well as the flow coming from further upstream. These data are regularly revised due to source data updates, and the most recent update was in January 2020. Natural flow is the flow that would have occurred in the absence of human activities such as trans-basin diversions, irrigated agriculture, municipal and industrial uses, and reservoir evaporation (Sidebar 3). Lukas et al. (2020b) described the methods used to arrive at these estimates, and discussed some of the limitations, including uncertainty in estimates of consumptive water use by evapotranspiration from irrigated agriculture. These limitations are important to bear in mind, because tree-ring hydrology studies that extend estimates of natural flows more than a millennium begin with cross-correlation of tree ring widths with the natural flow data base and any updating or changing of natural flow estimates has ramifications for the results from tree-ring hydrology.

3.2. Correlation Based Regions

We calculated the cross-correlation between the annual local-watershed inflow to each node and every other node and examined sites where there were strong cross correlations (Figure 6). The pattern observed in the Upper Basin suggested a grouping of sites into the following regions: middle Rocky Mountains (MRM) (sites 9, 10, 11, 14, 15 and 17), southern Rocky Mountains (SRM) (sites 1, 2, 3, 4, 5, 6, 7, 8, 12, 13, 15) and San Juan Mountains (SJM) (sites 18, 19). We recognize that the San Juan Mountains are part of the southern Rocky Mountains, but annual cross correlations of sites 18 and 19 with other more northerly sites in the SRM were lower, suggesting a separate region. Site 20, draining the Colorado Plateau (CP) was not correlated strongly with the other sites so was designated as its own region. Correlations in the Lower Basin are not nearly as strong, and the Lower Basin (LB) sites (21, 22, 23, 24, 25, 26, 27, 28, 29) were grouped into one region for simplicity. We considered the Gila River (GR) basin as a separate region. Most of the Colorado River streamflow comes from the southern Rocky Mountains, and only 19% comes from the middle Rocky Mountains.

Gage record lengths that underpin natural flow estimates vary across the 29 inflow nodes (Lukas et al., 2020b), and Reclamation has extended natural flows back to 1906 using multiple linear regression and nearest neighbor methods following a procedure developed by Lee and Salas (2006). There is thus a question as to whether these extension procedures may introduce artifacts into the correlations. The shortest natural flow record (Green River near Greendale, UT) begins in 1950. To evaluate the effect of record extension on our cross-correlation method, we evaluated cross correlations for the period 1950-2018. While the correlations differed slightly, the pattern was essentially the same, demonstrating that our approach to partitioning the Upper Basin was robust.

While the hydrologic groupings are somewhat consistent with the primary headwater branches of the river network, our analysis demonstrates that the hydrology of the Yampa River and the White River are more similar to the hydrology of the headwaters of the upper Colorado River, rather than to the other headwater areas of the Green River. At their confluence in northwestern Colorado, the Yampa River and the upper Green River have nearly the same average annual flow and constitute co-equal headwater sources. Thus, streamflow of the Green River further downstream results from runoff from two different hydrologic regions. These divergent source areas have the potential to respond differently to a warming climate and associated changes in storm paths.

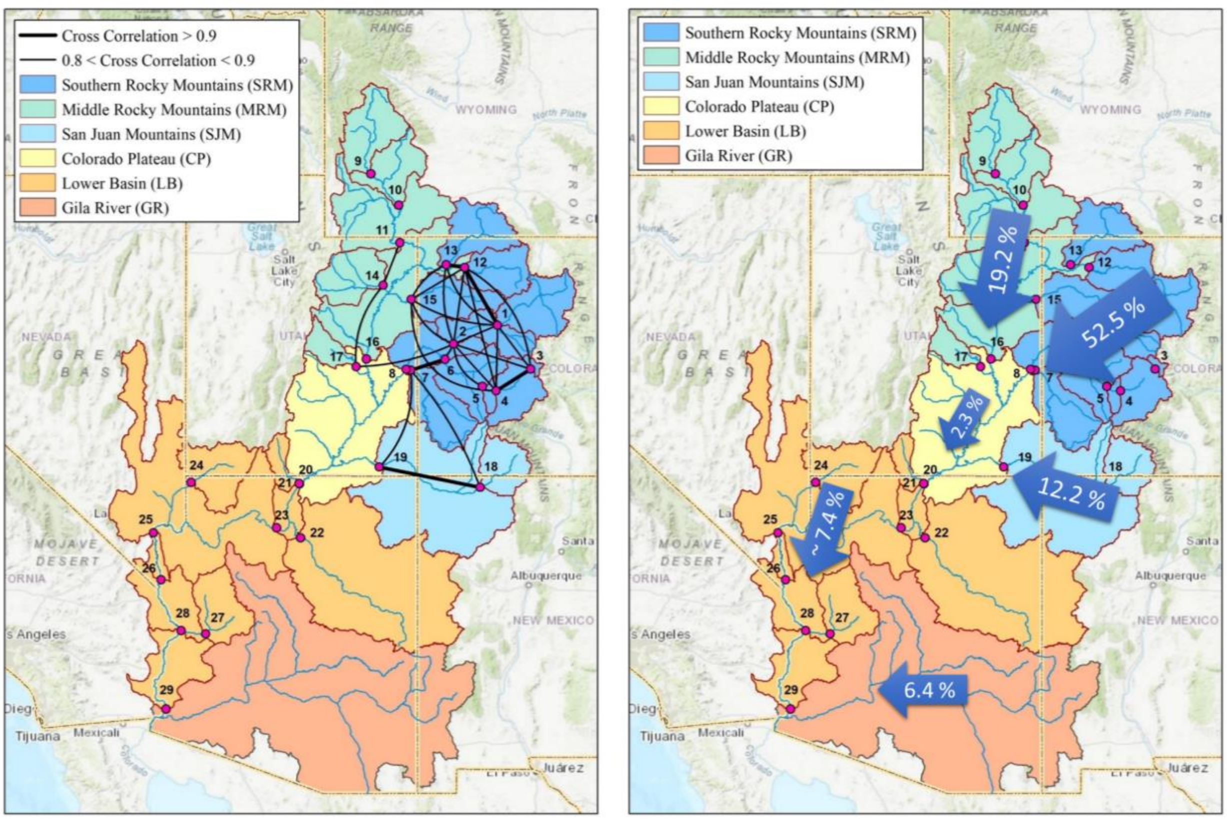


Figure 6. Maps showing hydrologically related parts of the Colorado River Basin, based on statistical correlation of local inflow for each year between 1906 and 2018. The black lines between gages in the left figure indicate the strength of the correlations used to decide on the grouping of local watersheds upstream of each CRSS inflow node. Cross correlations greater than 0.8 are shown in black lines, and bold black lines are those cross correlations greater than 0.9. These correlations are the basis for defining

regions of hydrologic similarity. The percent of the total natural runoff originating from each region is shown in the right figure. These percentages are based on Reclamation's Natural flow record from 1906 to 2018 and the estimate by Lukas et al. (2012) of 1.1 maf/yr mean annual natural flow for Gila River from 1915-2010.

4. Climate and Hydrologic Trends

Key points

- The most precipitation occurs in the southern Rocky Mountain. The southern Rockies, middle Rockies, and San Juan Mountain regions are the three most productive in terms of runoff.
- When streamflow trends are examined from the start of the record of estimated natural flow (1906 to present), there is a statistically significant downward trend.
- When streamflow trends are examined starting in 1930 after the Early 20th century Pluvial, there is no statistically significant downward trend in natural streamflow.
- Thus, trend analysis does not indicate whether the on-going 21st drought that began in 2000 is an extension of a downward trend or may be regarded as the most recent cycle within a persistent climate regime that has existed since 1930.
- Neither perspective challenges the expectation that future runoff in the Colorado River basin will decrease in the 21st century as the climate warms.

There are many sources of hydroclimatic and hydrologic data, each of which has strengths and weaknesses. Many studies have presented gridded datasets for temperature and precipitation (Maurer et al., 2002; Hamlet and Lettenmaier, 2005; Livneh et al., 2013; Livneh et al., 2015a; PRISM Climate Group, 2019; Daly et al., 2008). Gridded data products are generated by interpolation of records from gages that may be spread out in space and cover different time periods. Differences in gridded products arise due to the choice of interpolation approaches used, generally aimed at limiting bias and interpolation error, and possibly accounting for elevation effects. Gridded data products are useful in that they take advantage of the expertise applied in their production and are easy to aggregate over large areas.

McAfee (2020) reviewed available gridded data products that predict weather and climate data for the Colorado River Basin, and summarized the advantages and disadvantages of 13 gridded data sets with different input data, spatial resolution, methods of interpolation among data stations, and length of time of available data. McAfee (2020) observed that "all of the higher resolution products explicitly account for changes in temperature with elevation." The choice of which data set to analyze depends on the purpose of the analysis. McAfee (2020) explained why data sets differ:

> Common choices that must be made in developing a gridded data product include 1) which station network or networks to use, 2) which stations to use from those networks, 3) whether additional data from satellites, radar, or reanalysis is included, 4) what statistical method to use for interpolation, 5) how to account for changes in temperature and precipitation related to elevation, aspect, slope, or other aspects of the terrain, and 6) whether to apply any additional corrections, such as filling gaps in the data, accounting for undercatch, or homogenizing—correcting shifts in the measured climate that are due to changes in the station or the area around the station rather than to actual changes in regional climate.

Thus, different gridding procedures can produce artificial temporal trends due to the incorporation of stations with different record lengths and locations (Hamlet and Lettenmaier, 2005). Hamlet and Lettenmaier (2005) developed methods for gridding data to limit the introduction of artificial trends and produced a gridded dataset that is accepted as most suitable for long-term trend analysis. McAfee (2020) observed that strengths of the Hamlet and Lettenmaier (2005) gridded dataset are that long-term temperature and precipitation trends match data available from the U.S. Historical Climatology Network (USHCN) and date back to 1915. However, the Hamlet and Lettenmaier (2005) dataset may over-estimate the rate at which temperature decreases with elevation (i.e., lapse rate), resulting in underestimation of temperature at higher elevations (McAfee, 2020).

We examined spatial patterns and historical trends in precipitation and temperature in the Colorado River Basin using an updated version of the Hamlet and Lettenmaier (2005) dataset from Xiao et al. (2018), that covers the period 1916-2014. We examined trends in naturalized streamflow estimated by Reclamation (2020) that covers the period 1906-2018.

Spatial patterns of temperature and precipitation, averaged over the entire period of the dataset, were consistent with regional stream-flow patterns (Figure 7). The most precipitation occurs in the southern Rocky Mountains. The middle and southern Rocky Mountain regions have the lowest annual mean temperature. The southern Rocky, middle Rocky, and San Juan Mountain regions are the three most productive in terms of runoff.

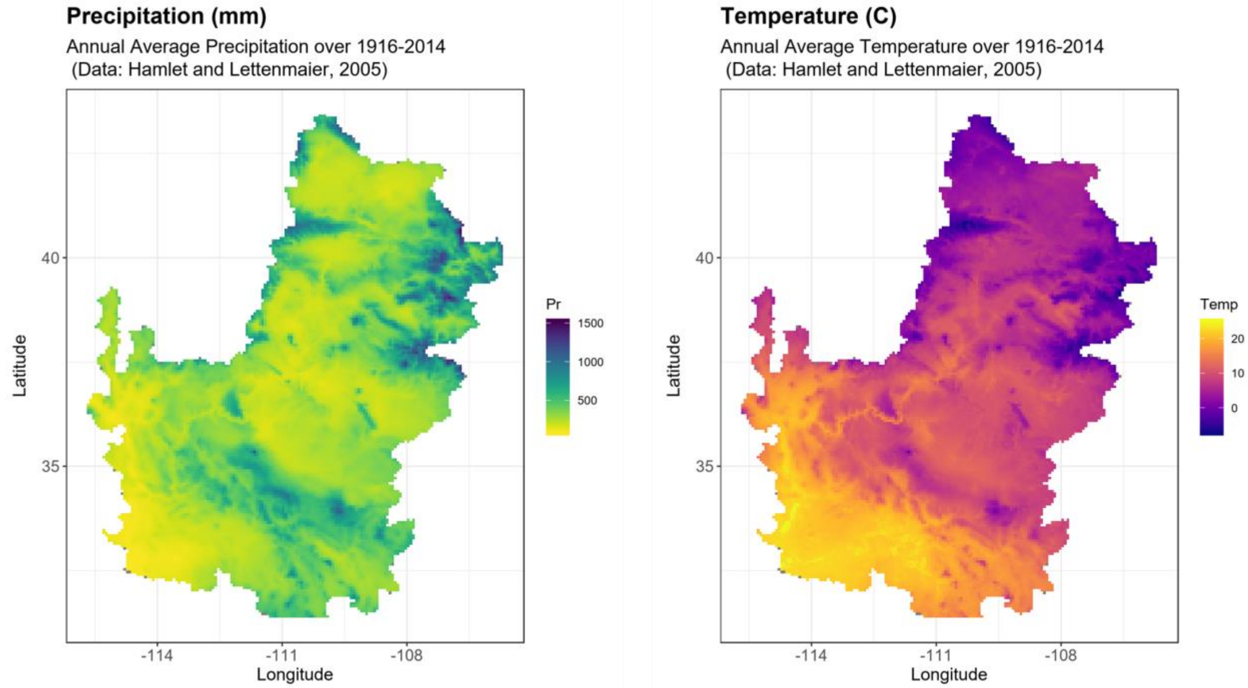


Figure 7. Maps showing long-term average data for Colorado River Basin between 1916 and 2014: a) average annual precipitation, and b) average annual temperature (Hamlet and Lettenmaier, 2005; Xiao et al., 2018).

Some studies (Walker et al., 2020; Dean et al, in review) have shown that 1930 was a statistically significant break point in the natural record of flow of the upper Colorado and Green Rivers. The average natural flow of the Colorado River at Lees Ferry was 17.82 maf/yr in the early 20th century period and was 13.93 maf/yr at Lees Ferry after 1930. The early period is referred to as the "Early 20th Century Pluvial Period" (Sidebar 4). To account for the potential bias due to this early period, we examined temporal trends in natural streamflow, precipitation, and temperature, both for the full period of record and the period after 1930 that excludes the Early 20th Century Pluvial period. Seasonal trends in precipitation, temperature, and streamflow were also examined for the fall/winter season of snow accumulation (O/N/D/Ja/F), the snowmelt season (Mar/Ap/May/Jun), and the season of the North American monsoon (Jul/Au/S). This trend analysis was done for each of the six regions identified above (Figures 8-10, Tables 1-12).

Overall, over both the full period (1916-2014) and the post-Pluvial period (1930-2014) of record, precipitation appears not have changed (Figure 8, Table 1 and Table 4), but temperature has warmed significantly (Figure 9, Table 2 and Table 5). For streamflow, the full record shows statistically significant decreasing trends for four of the five regions (recalling that there are no reported naturalized flow data for the Gila River) (Figure 10, Table 3). The region where there is not a statistically significant trend is the Colorado Plateau, which contributes only a small fraction (2.3%) of the Colorado streamflow. However, when the early 20th Century Pluvial Period is excluded, long-term trends in streamflow do not exist (Table 6). There are, in the seasonal data, sometimes increasing and sometimes decreasing statistically significant trends that depend on season and location (Table 12). Fall/winter flows have increased in three of the five regions, snowmelt season flow has increased in the Colorado Plateau (small contribution region) and Monsoon season flows have decreased in three of the five regions, also representing small fractions of Colorado streamflow. We are hesitant to read too much into these trends given the small quantities and uncertainties associated with the calculation of natural flows and concerns over Lower Basin natural flow values in the Reclamation Natural Flow Database (Sidebar 2).

The take home message here is that significant trends of decreasing streamflow disappear when the early 20th Century Pluvial period is not considered. This is an important observation and differs from prior work that did not separately evaluate the post-Pluvial period. Xiao et al. (2018) found that half of the decline in streamflow since 1916 (i.e., including part of the Pluvial Period) was due to increasing temperature, and we found that annual average temperature had increased in every region since 1930 (Figure 9, Table 2), but was not associated with post-1930 streamflow trends. Xiao et al. (2018) concluded that changes in where precipitation occurred, shifts to the Colorado Plateau in Utah from the southern Rocky Mountains, were another cause of decreasing streamflow, but we found no statistically significant change in annual precipitation in any of the regions of the Colorado River Basin since 1930 (Figure 8, Table 1), leading us to suggest that Xiao et al's. conclusions were, at least in part, affected by the early 20th Century Pluvial period. Thus, when streamflow trends are examined from the start of the record (1906) to present, there is a statistically significant downward trend. However, when streamflow trends are examined starting in 1930 after the Early 20th century Pluvial, trends are generally not statistically significant. Therefore, while there are observable downward trends over the full record the question of whether they will continue into the future is not settled, and while in the post 1930 record there have been periods of significant drought, a statistically significant downwards trend is not present.

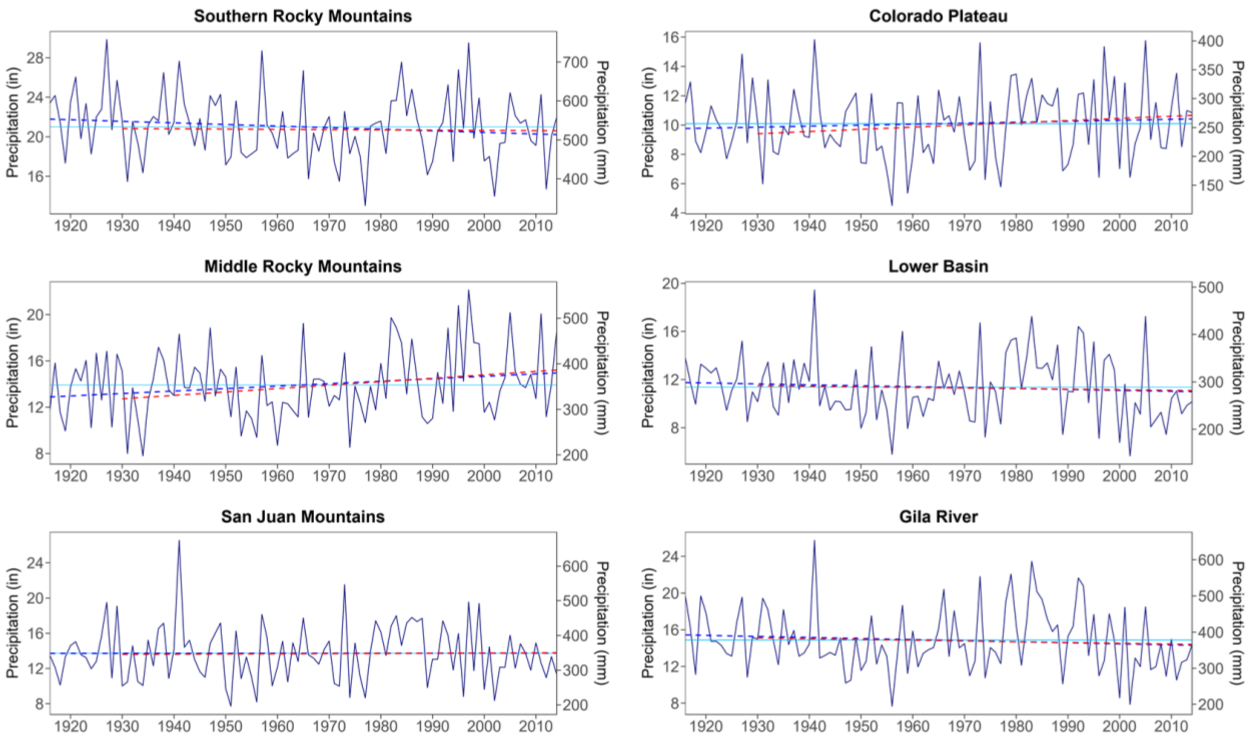


Figure 8. Water year annual precipitation from 1916 to 2014 in each region. The light blue line represents the long-term average over the full period. Blue and red dashed lines are trends over the full period and post-pluvial period, respectively.

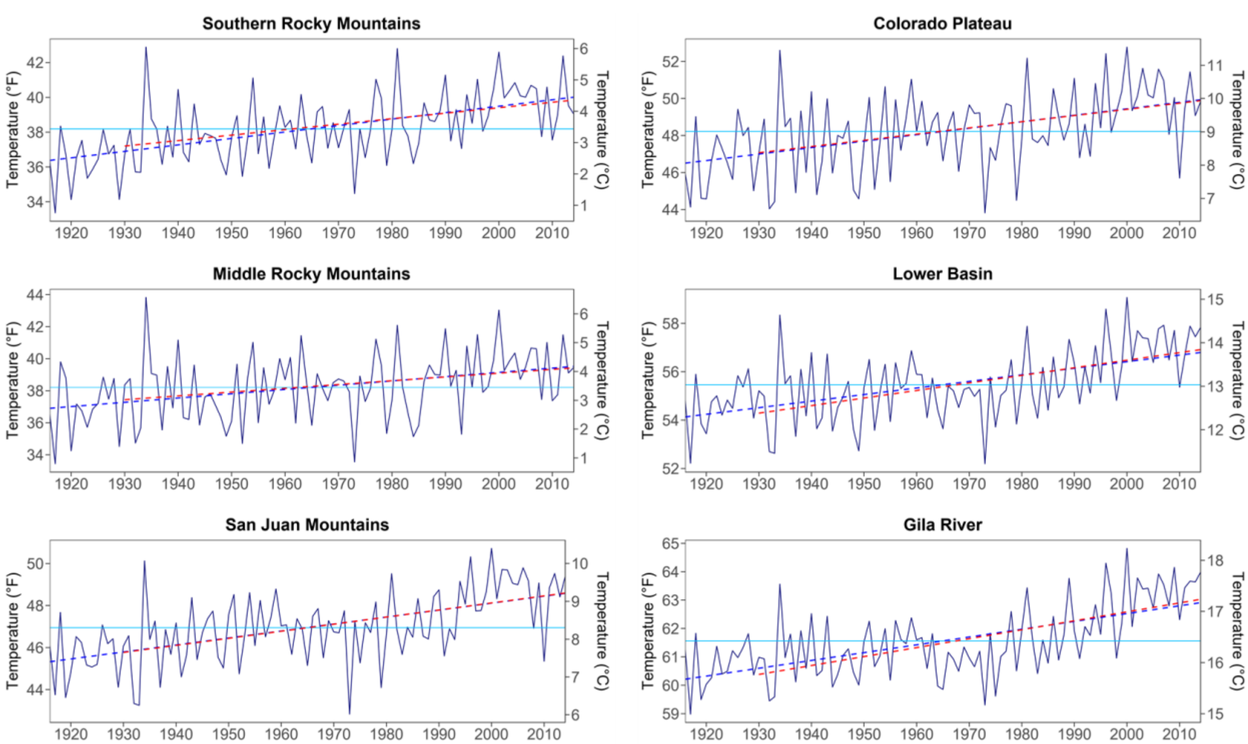


Figure 9. Water year annual temperature from 1916 to 2014 in each region. See Figure 8 caption for further details.

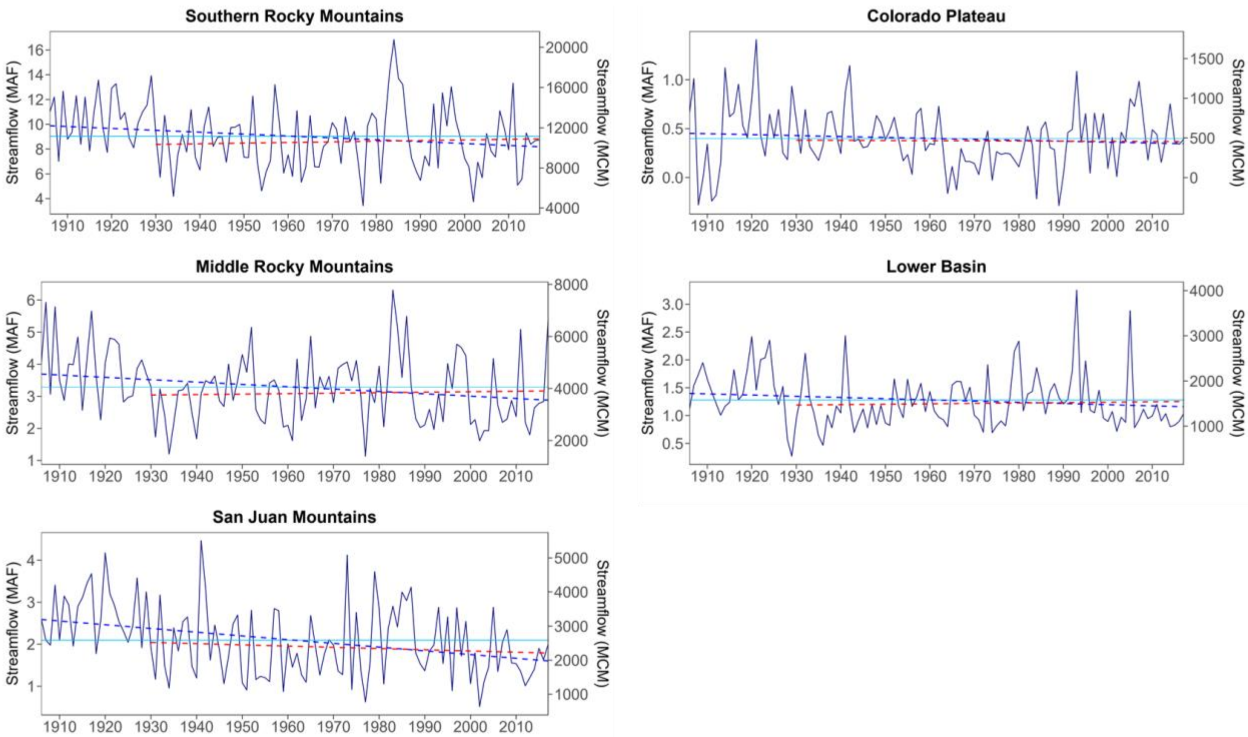


Figure 10. Water year annual streamflow from 1906 to 2018 in each region. See Figure 8 caption for further details.

Table 1. Trend analysis of water year precipitation (1916-2014)

Region	Annual Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	21	-0.016	-0.08	0.2174	×
2- Middle Rocky Mountains	13.92	0.021	0.09	0.1699	×
3- San Juan Mountains	13.73	0	0.01	0.8513	×
4- Colorado Plateau	10.09	0.007	0.04	0.5334	×
5- Lower Basin	11.37	-0.008	-0.07	0.2984	×
6- Gila River	14.87	-0.012	-0.08	0.2152	×

Table 2. Trend analysis of water year temperature (1916-2014)

Region	Annual Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	38.2	0.037	0.4	0	✓
2- Middle Rocky Mountains	38.2	0.027	0.26	0.0002	✓
3- San Juan Mountains	47	0.033	0.4	0	✓
4- Colorado Plateau	48.2	0.035	0.33	0	✓
5- Lower Basin	55.5	0.027	0.37	0	✓
6- Gila River	61.6	0.028	0.42	0	✓

Table 3. Trend analysis of water year streamflow (1906-2018)

Region	Annual Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	9.0323	-0.0153	-0.15	0.0214	✓
2- Middle Rocky Mountains	3.2853	-0.0073	-0.16	0.0118	✓
3- San Juan Mountains	2.0952	-0.0089	-0.22	0.0006	✓
4- Colorado Plateau	0.3989	-0.001	-0.06	0.3748	✕
5- Lower Basin	1.2783	-0.0022	-0.15	0.0185	✓
6- Gila River	-	-	-	-	-

Table 4. Trend analysis of water year precipitation – pluvial excluded (1930-2014)

Region	Annual Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	20.71	-0.003	0	0.9728	✕
2- Middle Rocky Mountains	13.96	0.03	0.11	0.1243	✕
3- San Juan Mountains	13.69	0.002	0.03	0.6847	✕
4- Colorado Plateau	10.04	0.015	0.09	0.2319	✕
5- Lower Basin	11.29	-0.005	-0.03	0.7015	✕
6- Gila River	14.76	-0.008	-0.05	0.5212	✕

Table 5. Trend analysis of water year temperature – pluvial excluded (1930-2014)

Region	Annual Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	38.5	0.031	0.31	0	✓
2- Middle Rocky Mountains	38.4	0.024	0.21	0.0054	✓
3- San Juan Mountains	47.2	0.034	0.35	0	✓
4- Colorado Plateau	48.5	0.034	0.27	0.0002	✓
5- Lower Basin	55.6	0.031	0.36	0	✓
6- Gila River	61.7	0.031	0.42	0	✓

Table 6. Trend analysis of water year streamflow – pluvial excluded (1930-2018)

Region	Annual Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	8.6005	0.0052	0.02	0.8092	✕
2- Middle Rocky Mountains	3.1016	0.0015	0	0.9971	✕
3- San Juan Mountains	1.9157	-0.0029	-0.03	0.7266	✕
4- Colorado Plateau	0.3746	-0.0002	0	0.9684	✕
5- Lower Basin	1.2208	0.0007	-0.02	0.8372	✕
6- Gila River	-	-	-	-	-

Table 7. Trend analysis of seasonal precipitation (1916-2014)

	Fall/Winter (O/N/D/Ja/F)					Snowmelt (Mar/Ap/May/Jun)					Monsoon (Jul/Au/S)				
Region	Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend	Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend	Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	8.92	-0.005	-0.06	0.3741	×	7.2	-0.013	-0.12	0.0775	×	4.88	0.003	0.02	0.7395	×
2- Middle Rocky Mountains	5.32	0.008	0.09	0.1957	×	5.06	0.009	0.1	0.1291	×	3.54	0.004	0.03	0.6633	×
3- San Juan Mountains	5.42	0.007	0.07	0.3155	×	3.67	-0.009	-0.1	0.1434	×	4.64	0.003	0.02	0.7168	×
4- Colorado Plateau	4.02	0.007	0.07	0.3394	×	2.77	0	0.01	0.9422	×	3.3	0	0	0.947	×
5- Lower Basin	4.64	0.002	-0.04	0.6031	×	2.68	-0.007	-0.14	0.0343	✓	4.05	-0.002	-0.06	0.3549	×
6- Gila River	6.09	-0.001	-0.04	0.5216	×	2.55	-0.006	-0.1	0.1451	×	6.23	-0.004	-0.05	0.4534	×

Table 8. Trend analysis of seasonal temperature (1916-2014)

	Fall/Winter (O/N/D/Ja/F)					Snowmelt (Mar/Ap/May/Jun)					Monsoon (Jul/Au/S)				
Region	Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend	Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend	Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	21.2	0.03	0.23	0.0006	✓	42.3	0.048	0.33	0	✓	61	0.033	0.45	0	✓
2- Middle Rocky Mountains	19.3	0.022	0.13	0.0538	×	43.5	0.033	0.24	0.0005	✓	62.7	0.027	0.35	0	✓
3- San Juan Mountains	30.7	0.031	0.22	0.0013	✓	52	0.037	0.33	0	✓	67.3	0.031	0.43	0	✓
4- Colorado Plateau	29.1	0.035	0.16	0.0167	✓	54.8	0.035	0.3	0	✓	71.3	0.035	0.47	0	✓
5- Lower Basin	41	0.029	0.26	0.0002	✓	59.3	0.027	0.23	0.0007	✓	74.5	0.024	0.36	0	✓
6- Gila River	49	0.025	0.29	0	✓	64.9	0.032	0.31	0	✓	78.1	0.026	0.36	0	✓

Table 9. Trend analysis of seasonal streamflow (1906-2018)

	Fall/Winter (O/N/D/Ja/F)					Snowmelt (Mar/Ap/May/Jun)					Monsoon (Jul/Au/S)				
Region	Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend	Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend	Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	1.2279	0.0013	0.07	0.2695	×	5.7448	-0.0125	-0.16	0.0107	✓	2.0254	-0.0055	-0.18	0.0046	✓
2- Middle Rocky Mountains	0.4725	0.0008	0.09	0.1565	×	1.8685	-0.0057	-0.2	0.0018	✓	0.9414	-0.0024	-0.16	0.0098	✓
3- San Juan Mountains	0.3286	-0.0004	-0.04	0.5334	×	1.2747	-0.0047	-0.18	0.0052	✓	0.4818	-0.0042	-0.35	0	✓
4- Colorado Plateau	0.0979	-0.0009	-0.17	0.0076	✓	0.0735	0.0031	0.3	0	✓	0.2219	-0.0034	-0.41	0	✓
5- Lower Basin	0.3995	0.0011	0.09	0.1494	×	0.3709	-0.0011	-0.17	0.0091	✓	0.5017	-0.0025	-0.28	0	✓
6- Gila River	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 10. Trend analysis of seasonal precipitation – pluvial excluded (1930-2014)

Region	Fall/Winter (O/N/D/Ja/F)					Snowmelt (Mar/Ap/May/Jun)					Monsoon (Jul/Au/S)				
	Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend	Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend	Average P (in)	Trend (in/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	8.8	0.001	0.01	0.9304	×	7.1	-0.013	-0.1	0.193	×	4.81	0.01	0.08	0.2862	×
2- Middle Rocky Mountains	5.33	0.013	0.13	0.0802	×	5.14	0.008	0.08	0.2896	×	3.5	0.009	0.08	0.2629	×
3- San Juan Mountains	5.46	0.008	0.08	0.3073	×	3.59	-0.009	-0.07	0.3256	×	4.64	0.003	0.01	0.9124	×
4- Colorado Plateau	4.02	0.011	0.11	0.1482	×	2.77	0.001	0.03	0.7241	×	3.25	0.004	0.04	0.6244	×
5- Lower Basin	4.65	0.003	-0.02	0.8051	×	2.64	-0.008	-0.12	0.1188	×	4.01	0	-0.03	0.7128	×
6- Gila River	6.09	-0.001	-0.04	0.619	×	2.5	-0.006	-0.07	0.3765	×	6.17	-0.002	-0.04	0.6031	×

Table 11. Trend analysis of seasonal temperature – pluvial excluded (1930-2014)

Region	Fall/Winter (O/N/D/Ja/F)					Snowmelt (Mar/Ap/May/Jun)					Monsoon (Jul/Au/S)				
	Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend	Average T (°F)	Trend (°F/yr)	Tau	P-value	Significant Trend	Average T (°F)	Trend (°F/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	21.5	0.023	0.16	0.0302	✓	42.7	0.045	0.28	0.0001	✓	61.4	0.028	0.35	0	✓
2- Middle Rocky Mountains	19.4	0.02	0.1	0.1706	×	43.8	0.03	0.21	0.0054	✓	63	0.021	0.23	0.0015	✓
3- San Juan Mountains	31	0.03	0.19	0.0119	✓	52.2	0.042	0.31	0	✓	67.6	0.028	0.34	0	✓
4- Colorado Plateau	29.4	0.034	0.13	0.0763	×	55	0.038	0.28	0.0001	✓	71.7	0.027	0.35	0	✓
5- Lower Basin	41.1	0.036	0.25	0.0006	✓	59.4	0.033	0.25	0.0007	✓	74.7	0.021	0.27	0.0002	✓
6- Gila River	49.1	0.031	0.31	0	✓	65	0.038	0.31	0	✓	78.3	0.024	0.29	0.0001	✓

Table 12. Trend analysis of seasonal streamflow – pluvial excluded (1930-2018)

Region	Fall/Winter (O/N/D/Ja/F)					Snowmelt (Mar/Ap/May/Jun)					Monsoon (Jul/Au/S)				
	Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend	Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend	Average F (maf/yr)	Trend (maf/yr)	Kendall's Tau	P-value	Significant Trend
1- Southern Rocky Mountains	1.2248	0.0027	0.2	0.0047	✓	5.452	-0.0015	-0.02	0.7578	×	1.8851	0.0012	0	0.952	×
2- Middle Rocky Mountains	0.4692	0.0019	0.21	0.0035	✓	1.7456	-0.001	-0.06	0.409	×	0.8852	0.0004	-0.05	0.5212	×
3- San Juan Mountains	0.3143	0.0004	0.11	0.1452	×	1.1881	-0.0022	-0.05	0.4985	×	0.4026	-0.0018	-0.18	0.0127	✓
4- Colorado Plateau	0.0858	-0.0008	-0.12	0.0883	×	0.1059	0.0035	0.29	0.0001	✓	0.1762	-0.0033	-0.39	0	✓
5- Lower Basin	0.382	0.0037	0.26	0.0004	✓	0.363	-0.0011	-0.13	0.0758	×	0.4685	-0.0023	-0.19	0.0078	✓
6- Gila River	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

5. Severe Droughts in the Colorado River Basin

Key points

We defined the following drought scenarios based on the observed and tree-ring reconstructed flows:

- **Millennium drought**: the 19-year drought during 2000-2018 recorded in the observed natural flow with the annual mean flow of 12.44 maf/yr.
- **Mid-20th century drought**: the 25-year drought during 1953-1977 recorded in the observed natural flow with the annual mean flow of 12.89 maf/yr.
- **Paleo tree ring severe drought**: the 25-year drought during 1576-1600 estimated by the tree-ring flow reconstruction with the annual mean flow of 11.76 maf/yr.

During much of the 20th century, water planning in the Colorado River Basin was based on gaged records despite the limited length of those records. Today, there is an increasing consensus that gaged flows alone, some of which date back to the late 1800s, do not adequately represent the potential range of natural variability that has occurred in the past few centuries and that might occur in the future. This is what E. C. LaRue tried to warn about in the early 20th century, before the Colorado River Compact was signed in 1922, when he provided flow estimates beyond the gaged records through an early effort of what is today called "paleoclimate reconstruction" (Kuhn and Fleck, 2019). Later, Schulman (1946) successfully applied tree-ring science for the first time to estimate paleo hydrology in the Colorado River Basin. Since then, many efforts have been conducted to improve the Colorado River reconstructions (Stockton and Jacoby, 1976; Michaelsen et al., 1990; Hidalgo et al., 2000; Woodhouse et al., 2006; Meko et al., 2007; Meko et al., 2017).

Today, there are multiple tree-ring reconstructions available that estimate the hydrology of the Colorado River at Lees Ferry (Sidebar 5). The recent tree-ring reconstructions of the Colorado River flow provide robust information about past hydrology and a more complete picture of the range of variability experienced in the Colorado River beyond what is recorded in the gaged records. These reconstructions include a number of megadroughts estimated to have been more severe than any measured droughts. It is plausible that events similar to these megadroughts estimated from tree-ring hydrology could occur in the future, because they have happened in the past. For example, Meko et al. (2012) showed that events similar to the severe and sustained mid-1100s drought (originally estimated by Meko et al. (2007) may have a frequency of occurrence of once every 400-600 years. The probability of such a drought occurring in the future may be more likely because of the effects of a warming climate. Udall and Overpeck (2017) concluded that megadroughts in the medieval period, which caused flow reduction of -16%, would, if they were to recur in a warmer future climate, result in even greater flow reduction to -21.5% and -34.5% under a 1°C and 3°C future warming, respectively. Such studies indicate the importance of considering the tree-ring reconstructions in future planning.

We analyzed the natural flow record of the Colorado River at Lees Ferry starting in 1906 and the tree-ring-reconstructed flows estimated by the most skillful model of Meko et al. (2017), hereafter referred to as M17-SK (Figure 11) covering the period 1416 to 2015, in order to quantify the severity of past droughts.

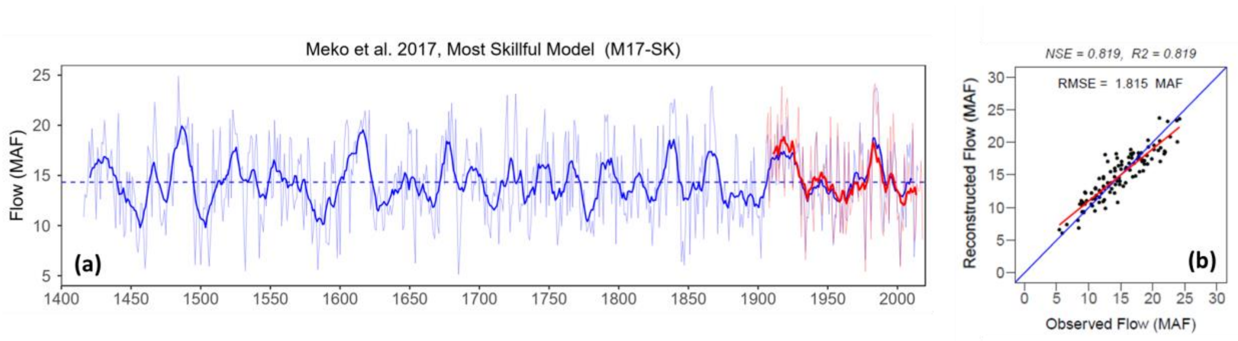


Figure 11. Tree-ring reconstructed flow of the Colorado River at Lees Ferry estimated by the most skillful model of Meko et al. (2017). (a) Annual time series of the reconstruction (light blue line) and its 10-year moving average (blue line), along with annual time series of the observed natural flow (light red line) and its 10-year moving average (red line). (b) Relationship between observed and reconstructed flow of the Colorado River at Lees Ferry (R_2, Nash Sutcliffe Efficiency (NSE), and RMSE).

Here, we present our results in the form of Sequence-Average and Cumulative Flow Loss plots (Figure 12 to Figure 15) which show the mean flow and cumulative magnitude of departure from average conditions for different durations. The cumulative departure from average conditions, or "flow loss", of each *n*-year length of sequence represents the cumulative flow loss, in acre feet, during those *n* years relative to the long-term average natural flow of 14.76 maf/yr for the 1906 to 2018 period. Cumulative flow loss plots (Figure 13 and Figure 15) are a recasting of the sequence-average data constructed so as to enable interpretation in terms of what the total loss over each duration is, relative to the mean. As discussed above, annual flows were larger before 1929 and less after 1930. Our use of the long-term average for 1906-2018 is a reference that is commonly understood by water-supply managers.

The plots presented here are intended to assist the reader to visualize the data and detect the droughts of different intensity and duration. In these plots, red dots represent the averaging periods that start post-2000 associated with the 21st century drought. Comparison with the other data on these plots demonstrates that the post-2000 average flow is far less than that of the entire 1906-2018 period. The severity of the 21st century drought is notable in the historic record (Figure 12 and Figure 13) where the first or second most severe droughts for all sequence lengths up to 19 years started during the 19 years since 2000. Note also that there are only 19 years of data post 2000, thus the red dots end beyond a sequence length of 19. However, the lowest 20- and 21-years sequences, begin in 1999 and 1998 respectively, and, while not red dots in our labeling, are comprised predominantly of 21st century flows. The current 21st century drought is thus the worst in the historic record when considering flows averaged over longer than the 19 years of post-2000 data we have so far. Thus, we refer to the 21st century drought as the "millennium drought". The characteristics of the "***millennium drought***" scenario were computed from the historical record for the 2000-2018 period as mean flow of 12.44 maf/yr and a cumulative flow loss of 44.08 maf.

Examination of Figure 12 reveals that the most severe 25-year drought occurred between 1953-1977. During this sustained drought, the average flow at Lees Ferry was 12.89 maf/yr, which was 87% of the long-term average from 1906 to 2018. For purposes of defining scenarios, we defined the "***mid-20th century drought***" scenario as the 25-year drought that occurred between 1953-1977.

In the M17-SK reconstructed flow based on tree-ring estimation methods, the most severe and sustained (25-year) drought occurred during the 1576-1600 period (Figure 14 and Figure 15), in which the average of reconstructed flow at Lees Ferry (11.76 maf/yr) was 82% of the long-term average. We defined this drought as the "***paleo tree ring severe drought***" scenario. Therefore, overall, three drought scenarios were defined (Table 13).

Note that while we identified, and used in our study scenarios, the 1576-1600 period, examination of Figure 11 (10-year moving average) shows multiple severe droughts only slightly less severe than this period suggesting that extreme droughts in the Colorado River Basin occur naturally, and at multi-century time scales, not infrequently.

Table 13. Drought scenarios

Scenario	Flow data	Period	Duration	Mean flow (maf/yr)	Cumulative flow loss (maf)
Millennium drought	Observed natural flow	2000-2018	19 years	12.44	44.08
Mid-20th century drought	Observed natural flow	1953-1977	25 years	12.89	46.75
Paleo tree ring severe drought	Tree-ring reconstructed flow (Meko et al., 2017)	1576-1600	25 years	11.76	75

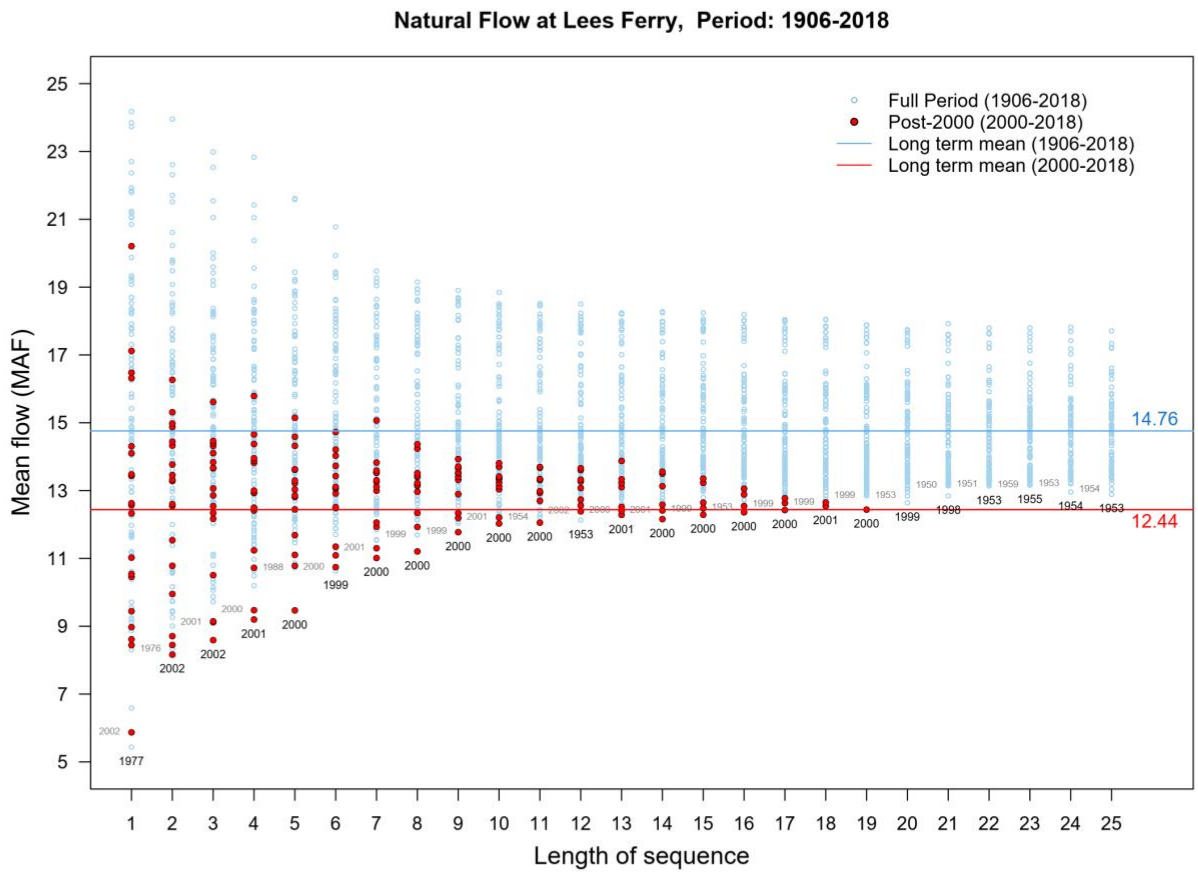


Figure 12. Sequence-Average plot of the natural flow of the Colorado River at Lees Ferry. Each dot represents water year mean annual flow averaged over the length of sequence. There is a dot for each sequence (including overlaps) within the record. Dot labels give the start year of the lowest (black number) and second lowest (grey number) sequence length average. The spread of the dots for each sequence length characterizes how mean flow may vary for different sequence lengths.

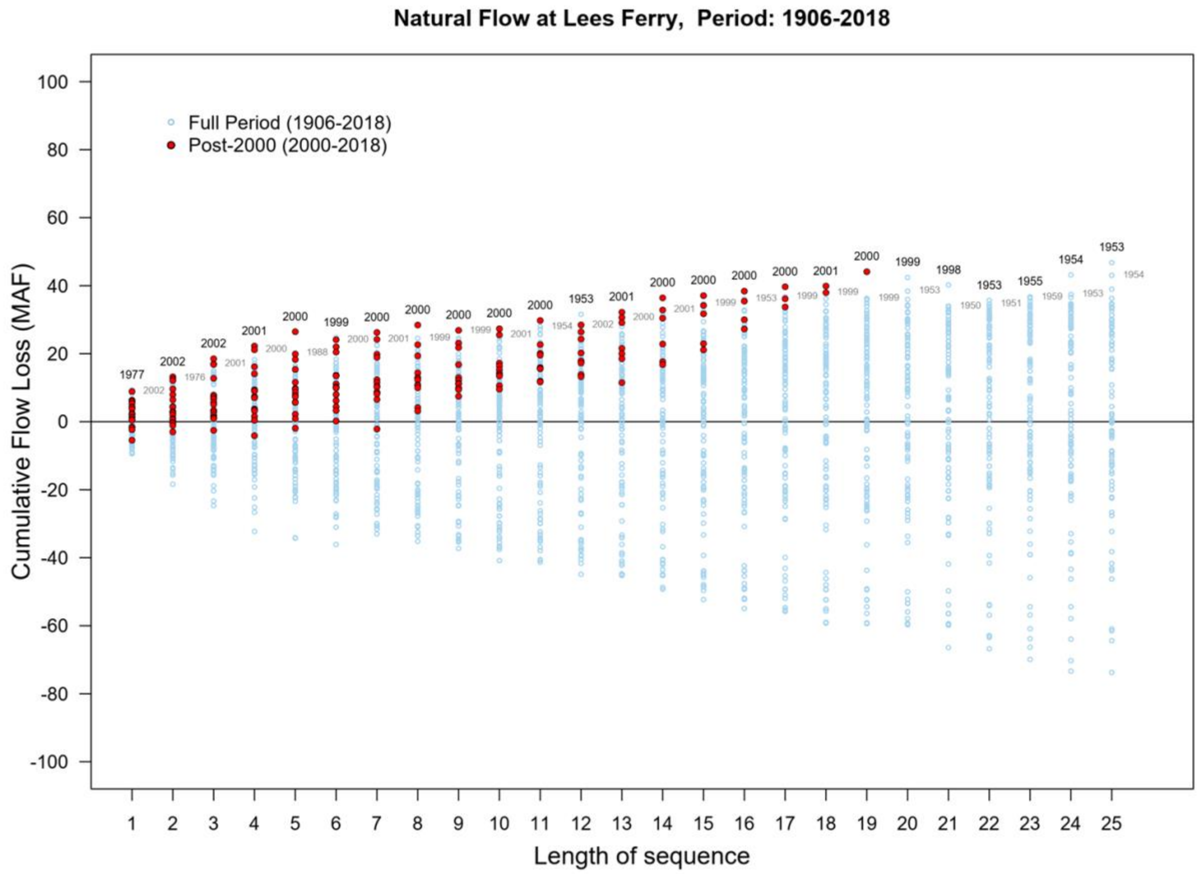


Figure 13. Cumulative Flow Loss plot of the natural flow of the Colorado River at Lees Ferry. Each dot represents water year mean annual flow loss aggregated over the length of sequence. There is a dot for each sequence (including overlaps) within the record. Dot labels give the start year of the highest (black number) and second highest (grey number) sequence length average. The spread of the dots for each sequence length characterizes how cumulative flow loss may vary for different sequence lengths.

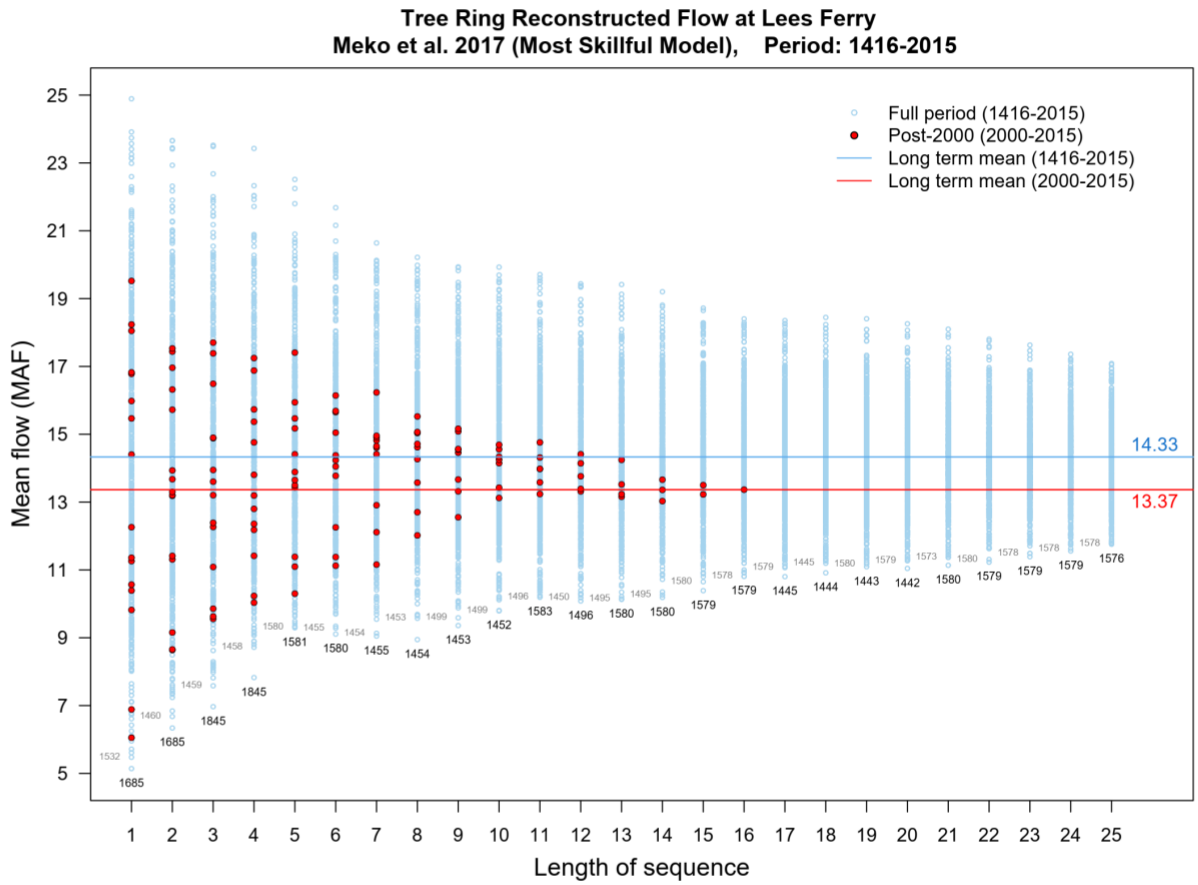


Figure 14. Sequence-Average plot of the tree-ring reconstructed flow (Meko et al., 2017) of the Colorado River at Lees Ferry. See Figure 12 caption for further details.

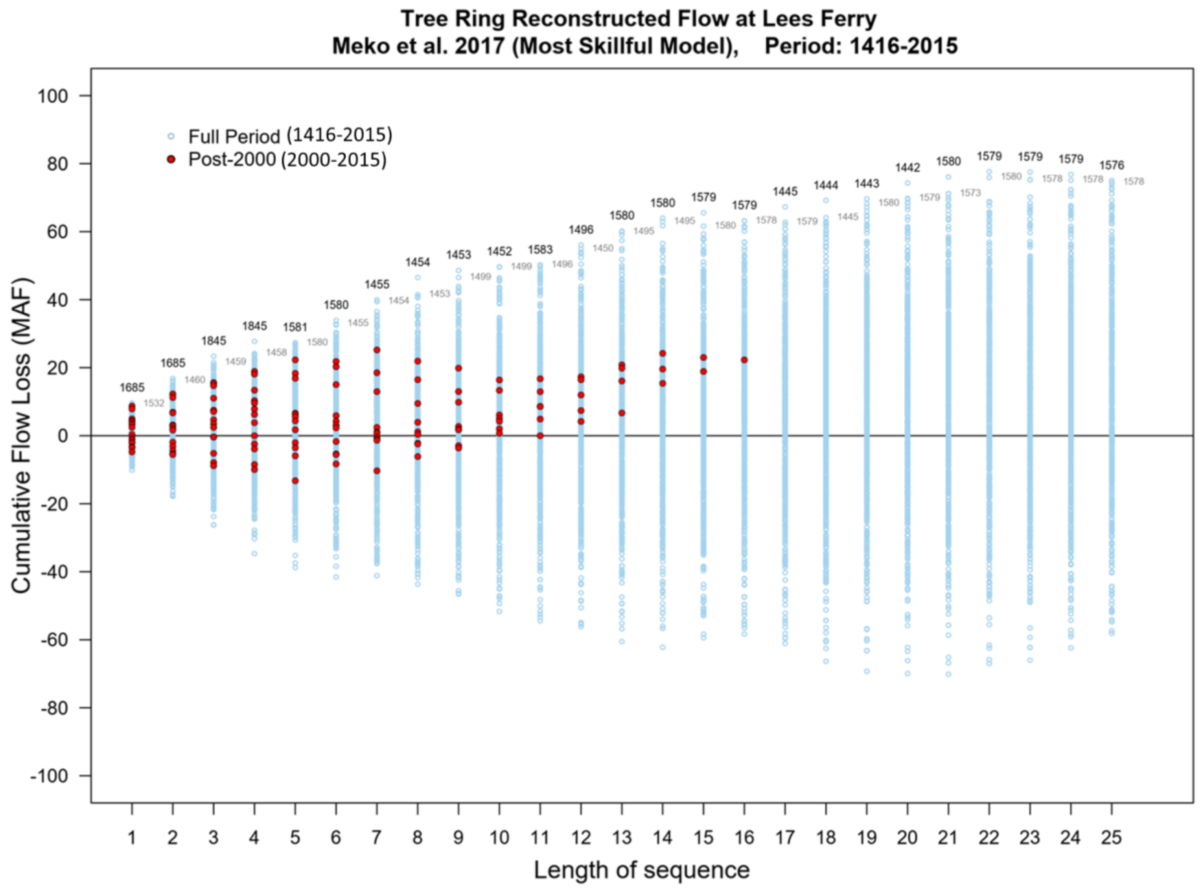


Figure 15. Cumulative Flow Loss plot of the tree-ring reconstructed flow (Meko et al., 2017) of the Colorado River at Lees Ferry. See Figure 13 caption for further details.

6. Changing Climate and Hydrology

Key points

- Atmospheric General Circulation Models (GCMs) project future warming in the Colorado River Basin.
- GCM precipitation projections are highly variable in the Colorado River Basin.
- There is a consensus among most of the studies that the future runoff of the Colorado River Basin will decline as it warms.
- Analyzing the GCMs indicated that the future might include megadroughts that are even worse than the drought scenarios quantified in this study.

The analysis described in the preceding section demonstrates that the natural variability of the regional climate of the Colorado River Basin produces periods of unusually wet and unusually dry conditions. The unusually dry conditions include extended periods of drought when the average annual streamflow at Lees Ferry is much less than the long-term average of the period between 1906 and 2018. These extended periods can last many decades. Because these long periods of drought have occurred in the past, we argue that they might occur in the future. Exacerbating the potential of future droughts is the demonstrable fact that the Earth's climate is changing as the atmosphere warms. In some parts of the planet, a warming atmosphere is causing increased rainfall and increased intensity of storms. In the Colorado River basin, notably, significant temperature increases have occurred since the 1970s and such increases have been found to significantly decrease the flow of the river, with up to half of the current loss attributed to anthropogenic climate change (Woodhouse et al., 2016; Udall and Overpeck, 2017; Xiao et al., 2018; Milly and Dunne, 2020).

In this paper, we do not explicitly incorporate climate change scenarios into the streamflow sequences used for simulating future hydrology in the Colorado River Basin. Instead, we simply develop scenarios from historic or tree-ring-estimated streamflow. The past droughts indicate that long-duration periods of very low flow can happen. A progressively warming climate has the potential to cause additional reductions in flow beyond what has occurred in the past. While the scenarios suggested in our report do not estimate the additional impact of a warming climates, our scenarios are based on observed records and include scenarios that are worse than the observed record in terms of sequence-averages. Furthermore, when juxtaposed with climate model projections, our scenarios are not dissimilar from the worst-case projections.

In this section, we survey some of what is known about climate change in the Colorado River Basin and analyze available streamflow projections from ensembles of climate models using the same sequence-average approaches to compare and add context to the possibility of our scenarios occurring in the future as the climate changes.

The possibility of future climate related changes in Colorado River Basin runoff was recognized when the *Interim Guidelines* were negotiated (U.S. Bureau of Reclamation, 2007) and were recognized in the *Colorado River Basin Water Supply and Demand Study* (U.S. Bureau of Reclamation, 2012). Since the early 2000s, most studies of the potential of changing watershed runoff have followed a general approach pioneered by Nash and Gleick (1991) and later enhanced by Christensen et al. (2004) wherein climate change scenarios are translated into projected future hydrologic changes in the basin. Almost all approaches begin with using Global Climate Models (GCMs) driven by a scenario concerning the amount of future emission of greenhouse gases into the atmosphere. Although GCMs are currently the best tools for exploring future climate changes on continental and greater scales, these models still have weaknesses in representing some climate features at smaller scales and this is especially true in the Colorado River Basin. Inadequately characterized topography, large biases in precipitation data, and unknown future natural variability especially with respect to precipitation are some of the known GCM limitations. Of particular concern is that GCMs do not adequately capture the frequency of drought and pluvial events that occurred in the past and may underestimate the risk of future megadroughts (Ault et al., 2012; Ault et al., 2013). For example, Udall and Overpeck (2017) discussed that half of the CMIP5 models and one-quarter of CMIP3 models used in Reclamation's projections for the Colorado River Basin (U.S. Bureau of Reclamation, 2014) are unable to simulate the 21st century drought. In addition, the process of downscaling coarse-resolution GCM outputs for use in high-resolution hydrology models adds an additional element of uncertainty. Such downscaling is implicitly tied to the statistics of the 20th century climate, another concern. Individual future years projected from Reclamation's 2012 Basin study using the Christensen et al. (2004) methods predict implausibly large annual flows of 45 maf/yr, 80% higher than the highest historical year.

Despite these limitations, GCMs do have significant value for decision making. Their strengths include their ability to project future warming with a high level of certainty, which is the main driver of shifts in hydroclimate toward lower spring snowpacks, earlier snowmelt, lower annual runoff volumes, and increasing water demand (Lukas et al., 2020a).

6.1. Projected Future Climate

Large scale climate change studies, referred to as Coupled Model Intercomparison Projects (CMIP) are periodically conducted. These assemble information from many climate models run by different teams around the world using a range of emission scenarios, to compare model projections for different scenarios, and to use aggregation of information from multiple models to account for the uncertainty in any one model. These comparisons go under names such as

CMIP3 (IPCC, 2007) and CMIP5 (IPCC, 2014). In general, projections from the CMIP3 and CMIP5 climate studies, show significant future warming in the Colorado River Basin, with this warming expected to be slightly greater in the Upper Basin (Lukas et al., 2020a). While temperatures in the Colorado River Basin are definitively increasing, as shown in section 4 of this paper, the precise magnitude of future increases in temperature for any given future period are difficult to anticipate as there is variability across the models and emission scenarios. Uncertainty around future temperatures is greater after 2050 because medium and high emissions trajectories diverge at that point, and because climate system responses are more variable with greater emissions. Increasing temperatures are important because they cause higher evapotranspiration and thus lower flows if precipitation stays the same.

The GCM precipitation projections are in general agreement in projecting a north-south gradient across the western U.S., in which an increase and a decrease in the annual precipitation are expected to be seen in the northern and southwestern U.S., respectively (Lukas et al., 2020a). However, the Upper Colorado River Basin is located in the transition area and the average of GCMs projections are closer to zero-change line (Lukas et al., 2020a). The exact location of the north-south precipitation gradient varies by several hundred miles depending on the model and the emissions scenario. Drying north of the Colorado River mainstem would be especially problematic as the mainstem supplies much of Colorado’s Front Range through transbasin diversions. Overall, GCM precipitation results are highly variable and thus, unlike temperatures, uncertainty remains significant. There is uncertainty in both the direction (i.e. increase or decrease) and magnitude of future precipitation in the Colorado River Basin. Several efforts have attempted to quantify the flow loss per degree of temperature increase assuming constant precipitation and these are discussed below (Woodhouse et al., 2016; Udall and Overpeck, 2017; Hoerling et al., 2019; Milly and Dunne, 2020). Current precipitation records, as shown in an earlier section of this paper, do not show a statistically significant change in precipitation.

6.2. Impacts on Hydrology from Projected Climate Changes

Much work has been done to translate the climate change scenarios into basin future hydrology. In the earliest studies, empirical statistical relationships were used to this end (Stockton and Boggess, 1979; Revelle and Waggoner, 1983). Later, Nash and Gleick (1991) and Christensen et al. (2004) pioneered an approach that currently has become the most common method to investigate the effects of climate change on water resources (Figure 16). In this approach, emission scenarios are used as input to GCMs, which project the climate change in response to those scenarios. Then, the climate output of GCMs is bias-corrected and regionally downscaled and used as input to a higher resolution hydrologic model (e.g., the VIC model) to obtain the future hydrology, which can be used in system modeling like CRSS. Many later studies followed this general approach using different methodologies for each step (Gao et al., 2011; U.S. Bureau of Reclamation, 2012; Woodbury et al., 2012; Alder and Hostetler, 2015; Milly and Dunne, 2020). There is a consensus among most of the studies that the future runoff of the Colorado River Basin will decline as it warms, although shorter periods of high flows are also likely to occur (McCabe and Wolock, 2007; Vano et al., 2014; Woodhouse et al., 2016; Udall and Overpeck, 2017; McCabe et al., 2017; Milly and Dunne, 2020; Lukas et al., 2020a). Some have questioned the usefulness of the Nash and Gleick (1991) and Christensen et al. (2004) approach given the uncertainty cascade and the wide range of outputs. More recent studies have attempted to separate out the known temperature effects from the more uncertain precipitation effects.

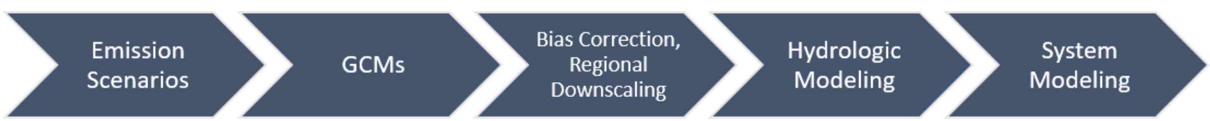


Figure 16. General processing steps from GCMs to basin-scale hydrology and water planning

Various studies have estimated the temperature sensitivity of streamflow in the Colorado River Basin. Attempts to quantify temperature sensitivity, which is defined as the percent change in annual flow due to 1°C change in annual temperature, have produced numbers ranging from -2%/°C to -16%/°C (Vano et al., 2012; Vano and Lettenmaier, 2014; Vano et al., 2014; Udall and Overpeck, 2017; Hoerling et al., 2019; Milly and Dunne, 2020). The most recent study, Milly and Dunne (2020), used a Monte-Carlo simulation with a hydrologic model constructed to quantify important nuances in the representation of radiation and albedo to address the wide disparity in sensitivity estimates. They showed that snow pack reduction as a result of climate change will have deleterious effect on water availability in snow-fed regions. They indicated that as temperature rises, the snow pack and hence the reflection of the solar radiation decreases, leading to an increase in net radiation, which is the ultimate driver of evapotranspiration. The associated increase in evapotranspiration leads to the runoff decrease. They estimated that in the

Colorado River Basin, annual mean discharge has been dwindling by 9.3% per 1°C of warming due to increased evapotranspiration, mainly driven by snow loss and consequent decrease of reflection of solar radiation (Milly and Dunne, 2020). The Milly and Dunne (2020) number is at the upper end but within the range of results (-3% to -10%) reported by Vano et al. (2014) in a survey of Colorado River temperature sensitivity derived from 5 hydrology models. In the real world temperature sensitivity cannot be measured directly because precipitation does not remain constant. And it is important to note that temperature sensitivity will be modulated by changes in precipitation with higher values occurring with less precipitation and lower values with more precipitation. Still, it remains a useful concept to understand how and why climate change is affecting Colorado River flows.

Less work has been done to quantify how the basin will respond to changes in precipitation, a measure known as precipitation elasticity. Vano et al. (2014) put the precipitation elasticity as between 2 and 3, meaning that for every 1% change in precipitation runoff will change by 2% to 3%, increasing the precipitation change percentage by a factor of 2 to 3. Elasticity applies to both increases and decreases in precipitation. Vano and Lettenmaier (2014) found that a simple way to forecast future runoff is to combine GCM temperature and precipitation projections simultaneously using measures of temperature sensitivity and precipitation elasticity. This approach compares favorably with the more complex Christensen et al. (2004) method. Finally, unlike temperature where human-caused flow reductions have been found in multiple studies, only one study has attempted to attribute recent (small) changes in precipitation to climate change. That study (Hoerling et al., 2019) found that flow reductions since the late 20th century were primarily the result of precipitation reductions due to climate change.

Further, recent research in headwater catchments shows that forest disturbance in warmer future may impact streamflow (Goeking and Tarboton, 2020). Contrary to the common assumption that reductions in forest cover result in reduced evapotranspiration and increased streamflow, recent research demonstrates that this is not always true in the Colorado River Basin and nearby areas, where forest cover loss sometimes causes decreased runoff. In the Colorado River Basin, the forest biomass changes may be responsible, at least in part, for diminished streamflow originating in the Upper Basin over the last two decades (Sidebar 6).

6.3. Severity of Droughts in Projected Climate Changes

There are 112 CMIP3 GCM simulations (based on considering various emission scenarios, climate models, and runs) available where VIC has been used to compute naturalized streamflow at Lees Ferry for the period 1950 to 2099 (U.S. Bureau of Reclamation, 2012). We used these data to examine droughts in the historic period (1950-2018) and projected into the future (2020-2099). Sequence-average plots for each of these CMIP3-VIC simulations compared to the observed and tree ring reconstructed flows (Figure 17) show that many of the CMIP3-VIC sequences project droughts more severe than observed for the historic period. Some do not have droughts as severe as observed. If a GCM model produces droughts during the historic period that differ from what was observed, the ability of the GCMs to project future droughts may be questioned. We thus selected the 10 scenarios from the 112 available CMIP3-VIC scenarios that best reproduced the severity of the observed record of droughts during the common historic period (1950-2018) at Lees Ferry, quantified using the mean square error between the minimum sequence-averages of the observed natural flow and CMIP3-VIC projected flow (Figure 17).

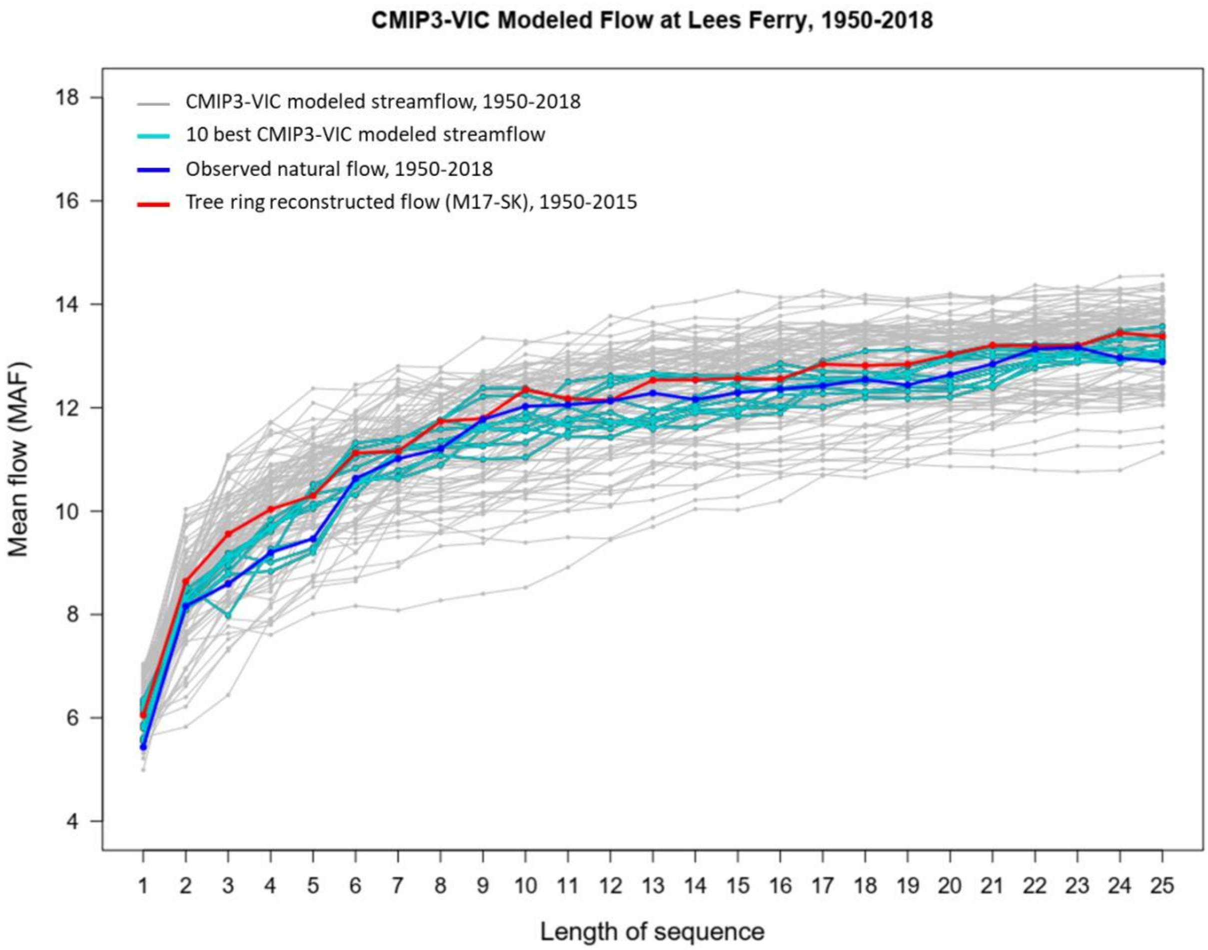


Figure 17. Minimum sequence-averages of the CMIP3-VIC projected streamflow at Lees Ferry over 1950-2018 compared to the historic sequence-averages and 10 selected simulations that best represent Lees Ferry sustained droughts.

Potential extreme droughts for the full set of CMIP3-VIC scenarios (some of which may be unreasonable), and 10 best scenarios were examined for the period 2020-2099 (Figure 18). Very extreme droughts with flows as low as 7 maf/yr for durations of 25 years are projected in the future for some of the 112 CMIP3 scenarios. When we limit analysis to only those 10 GCM scenarios that do a reasonable job of predicting the historic droughts (Figure 18), ***the sequence-averages show drier conditions in the future than the past.*** Note that Figure 18 also depicts the sequence average lower bound for the tree ring record. Thus, it could be argued, that at least for the purposes of planning, we should evaluate the system using drought scenarios that are worse than the severe drought scenarios from the historic record. Among the GCMs that did predict historic droughts well, at least a few GCMs did project future droughts worse than the tree ring record, indicating that it is not unreasonable to generate scenarios for planning purposes from the most severe tree ring drought.

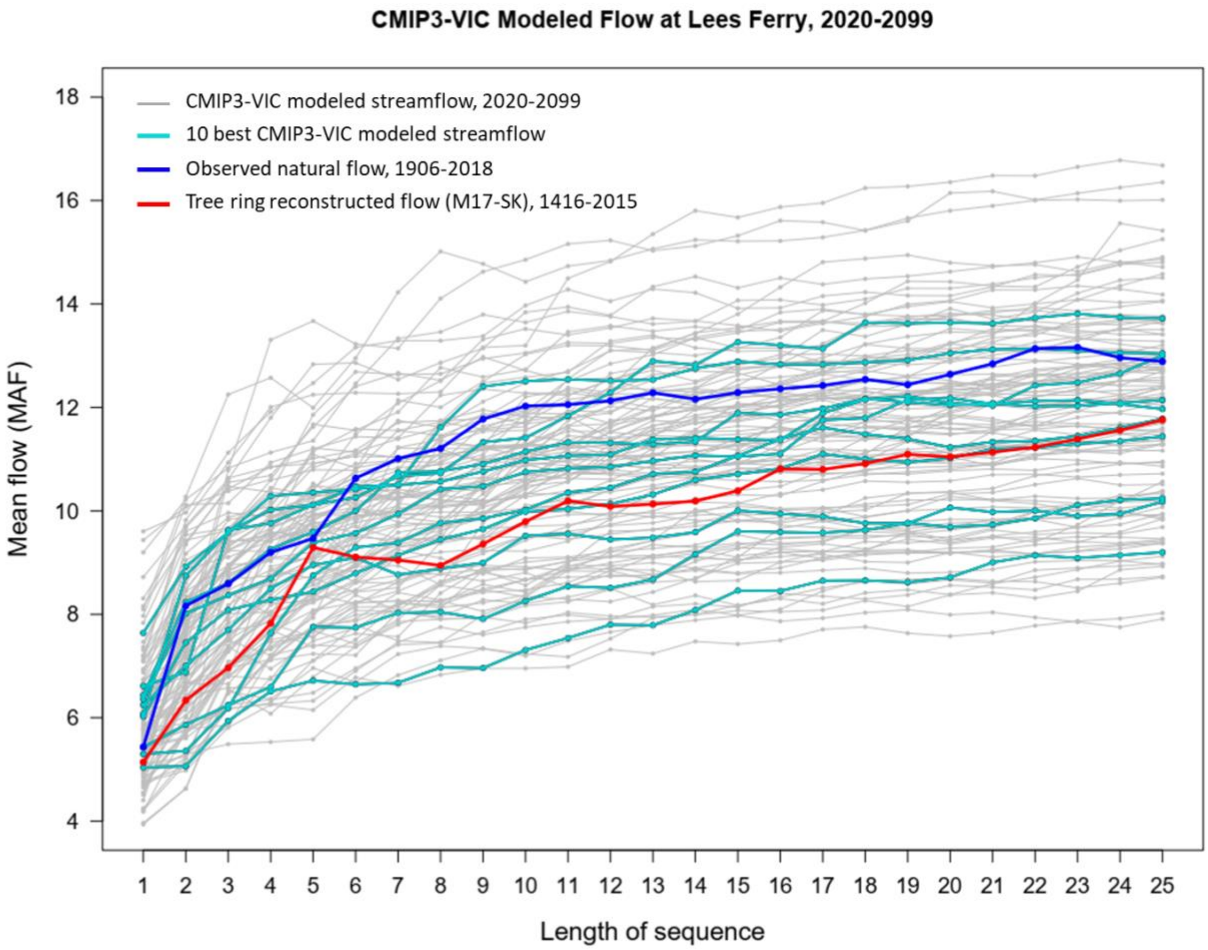


Figure 18. Minimum sequence-averages of the CMIP3-VIC projected streamflow at Lees Ferry over 2020-2099 compared to the historic and tree ring sequence-averages and 10 selected simulations that best represent Lees Ferry sustained droughts

The rich information of hydroclimatic variability in tree-ring reconstructions, presented in the previous section, can be combined with the primary aspects of climate models, presented immediately above, to develop future hydrology scenarios (Brekke and Prairie, 2009; Gray and McCabe, 2010) and to estimate the risk of future droughts (Ault et al., 2014). Ault et al. (2014) used both paleoclimate and climate model projections to estimate the risk of persistent droughts occurring this century in U.S. Southwest. They suggested that the risk of decadal megadrought is at least 80%, the risk of multidecadal (> 35-year) megadrought is 20%-50%, and the risk of an unprecedented 50-year megadrought under the most warming scenario is 5%-10% (Ault et al., 2014). Also, Ault et al. (2016) found that temperature increases alone, without changes in precipitation, raise the megadrought risk to more than 90% by the end of the 21st-century. Surprisingly, Ault et al. (2016) even found high megadrought risk with substantial increases in precipitation (e.g. 20%) under high warming. Williams et al. (2020) found that in the U. S. Southwest the current period from 2000-2018 is the 2nd worst drought in the last 1200 years as measured by soil moisture reconstructed from tree-rings. The speed and severity of the onset of the current drought was exceeded by only one other event.

The temperature-induced decreases in streamflow of the 2000-2018 drought, the high likelihood of additional decreases as the climate continues to warm, the evidence of droughts in the tree-ring records more severe than have occurred in the last century, and the risk of extended megadroughts in the 21st century all strongly suggest that Decision Makers should utilize synthetic hydrology well outside of the 20th century hydrology to evaluate overall Colorado River system risk in the 21st century.

7. Quantifying the Future Hydrology of Droughts

Key points

- Stochastic simulation is described as a way to generate sequences of streamflow that are different from, but statistically equivalent to past records to serve as diverse inputs to systems planning and operations models to test their resilience for what may occur in the future
- The Index Sequential Method (ISM), which has been widely used previously in the Colorado River Basin, limits the analyses to only past events and the order of the past data and does not provide enough variety of “statistically plausible” sequences to broadly test for what may occur in the future.
- Stochastic methods have been used in various studies to overcome limitations of ISM .
- We used drought scenario resampling of flows at Lees Ferry to provide plausible annual streamflow traces.

- We used a nonparametric resampling approach referred to as "Water Year Block Disaggregation" to split the simulated annual flow at Lees Ferry into monthly flow at each of the 29 CRSS natural inflow sites.

Past data, whether historically observed or reconstructed from analysis of tree rings, contains information useful in planning for the future. It is a fact that past hydroclimate records will not exactly occur in the future because of randomness of nature and ongoing anthropogenic climate change. Stochastic hydrology has evolved as a field to generate sequences, usually of streamflow, that are different from, but statistically equivalent to past (historic or tree ring reconstructed) records, to serve as diverse inputs to systems planning and operations models, to test their resilience for what may occur in the future. As discussed by Wang et al. (2020), there are multiple sources of uncertainty in CRSS output, one of which is uncertainties in future hydrology. Using multiple sequences of the past data with similar statistics allows the model to consider uncertainties of the future hydrology and assess alternative management strategies against a broader range of possible sequences in the future. In this section we overview first the index sequential method which is a simple but limited stochastic method that has been fairly widely used in Colorado River Planning. We then introduce stochastic simulation more broadly, as a useful tool to generate ensembles of synthetic hydrologic sequences to be used as inputs to water resource systems simulations, such as CRSS. Generated data should resemble those sequences that are likely to occur in the planning period (Loucks et al., 2005). We then describe the approach taken here comprised of sampling of water year Lees Ferry flows with replacement from chosen drought scenario periods, with a water year block disaggregation to obtain inflows at the 29 CRSS nodes.

7.1. Index Sequential Method (ISM)

The Index Sequential Method (ISM) has been the primary method applied in several past planning studies in the Colorado River Basin to generate flow sequences that have been used as inputs to CRSS (U.S. Bureau of Reclamation, 2012; Payton, 2020). This method uses synthetic sequences produced from a historic or tree ring record starting at each year in the past record and following the past record until it ends. Then, remaining years from the beginning of the past record are added on at the end to obtain a sequence that is the same length as the past record. By starting with each year in the past record, the number of sequences produced is the same as the number of years in the past record. The sequencing of flows by year is unchanged, except for the "wrap around" at the end of the sequence. For example, consider the case where the historic record is from 1906 to 2017, there will be 112 sequences that are the flows from each year arranged as illustrated in Table 14 and Figure 19.

Table 14. Index Sequential Method (ISM) for data from 1906 to 2017

	Sequence					
Sequence year	1	2	3	…	111	112
1	1906	1907	1908		2016	2017
2	1907	1908	1909	.	2017	1906
3	1908	1909	1910	.	1906	1907
4	1909	1910	1911	.	1907	1908
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
110	2015	2016	2017	.	2013	2014
111	2016	2017	1906	.	2014	2015
112	2017	1906	1907	.	2015	2016

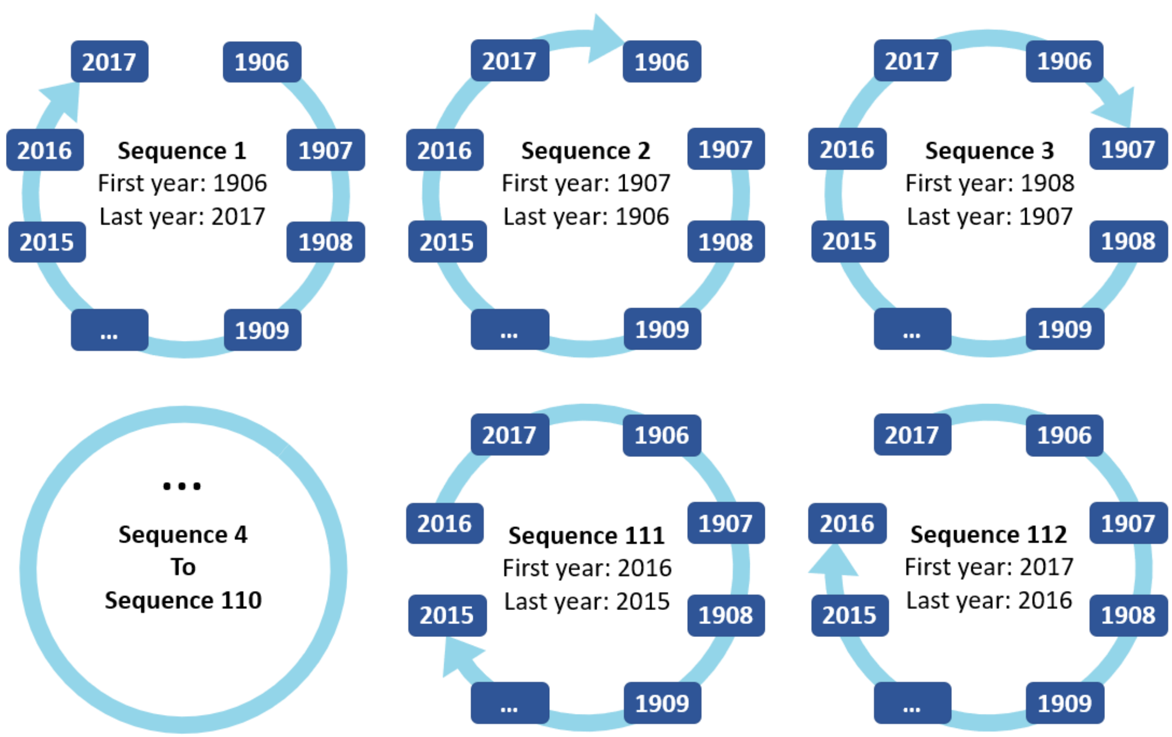


Figure 19. Index Sequential Method (ISM) schematic for data from 1906 to 2017. The numbers in the boxes represent water years. The arrows show the direction to select the water years. The begin and end arrows indicate the first and last years of each of the sequences, respectively.

Note that in this method, the order of the historical record is only slightly modified in each synthetic sequence, but each sequence contains the same values as the observed historical data. This is the main weakness of ISM. It limits the analyses to only past events and the order of the observed data and does not provide enough variety of "statistically plausible" sequences (Prairie et al., 2006). In other words, ISM cannot simulate longer or more intense droughts and pluvials than those in observed data. Readers are referred to Payton (2020) in which the advantages and limitations of using the ISM method and its recent application in the Colorado River Basin studies are comprehensively summarized. Over time, stochastic methods have been used to overcome limitations of ISM and provide novel hydrologic scenarios in which longer and more severe sequences of droughts or wet periods can be considered.

7.2. Stochastic Hydrology

Several methods have been developed for generating synthetic streamflow since the 1960s. Stochastic Streamflow Models (SSMs), provide ensembles of synthetic streamflow traces based on observed streamflow. Most SSMs assume stationarity (Yevjevich, 1963; Fiering, 1967; Valencia and Schaake, 1973; Matalas et al., 1982), while there has been work to adapt them for nonstationary hydrologic processes (Stedinger and Crainiceanu, 2001; Faber and Stedinger, 2001; Henley et al., 2013; Nowak et al., 2010; Sveinsson and Salas, 2016; Salas et al., 2018) and enable the models to capture streamflow changes due to climatic and anthropogenic impacts. Stationarity implies that in a statistical sense the properties of the streamflow sequence are not changing. Trends or break points (see section 4) would indicate a departure from stationarity and call into question a model where it is assumed.

Various stochastic methods (parametric and nonparametric) have been applied in the Colorado River Basin studies to generate streamflow sequences (Tarboton, 1994; Tarboton, 1995; Tarboton et al., 1998; Prairie et al., 2006; Prairie et al., 2007; Barnett and Pierce, 2008; Prairie et al., 2008). Some these studies indicate that the desired variability of the generated streamflow is not simulated using the ISM method (Prairie et al., 2006; Barnett and Pierce, 2008; Prairie et al., 2008). A comprehensive summary of studies in which stochastic methods were used to generate hydrologic traces from the Colorado River Basin historical hydrology can be found in Payton (2020).

7.3. Streamflow Simulation with Water Year Block disaggregation

As discussed in the previous sections, using multiple sequences of streamflow allows the CRSS model to consider uncertainties in the future hydrology and assess alternative management strategies against a broader range of possible sequences in the future. In the current study, we used drought scenario resampling of flows at Lees Ferry to provide plausible aggregate drought scenarios. We then used a nonparametric resampling approach referred to as "Water Year Block Disaggregation" to split this flow into monthly flow at each of the 29 CRSS natural inflow sites.

The three drought scenarios considered in this study are the historical millennium drought (2000-2018), the historical mid-20th century drought (1953-1977), and the most severe 25 year drought estimated from analysis of tree rings (1576-1600) (Meko et al., 2017). These droughts have durations of 19, 25, and 25 years, respectively (Table 13). We resampled the data that comprise these three drought scenarios to provide a range of traces in which the years of low runoff of a drought might occur. In this drought scenario resampling approach, we selected years at random with replacement (each year may be repeated) from each drought scenario to construct 100 42-year traces; 42 years was chosen to provide data to use in CRSS to project from 2019 to 2060, our mid-century modeling time frame. By selecting 100 traces drawing only from years in a drought scenario, we obtained traces that provided a very stringent stress test on the system, but which are grounded in reality by drawing upon yearly flow values that have all occurred in the past. The annual year-to-year correlation of flows at Lees Ferry is close to 0, providing a rationale for random resampling with replacement. The sequences produced have the statistics of the drought period selected, but persist for 42 years. From a statistical perspective, these droughts will have a lower probability than the equivalent 19- or 25-year historic droughts, but, by being resampled from the historic data, are plausible extreme scenarios. System response for these droughts should be tested and adaptation to such a scenario need to be considered in drought contingency planning.

In the two drought scenarios, which were proposed here based on the droughts in the gaged records (i.e. millennium drought and mid-20_{th} drought in Table 13), the drought scenario resampling approach was used to resample the annual flow at Lees Ferry. To obtain monthly streamflow at each of the 29 sites needed to implement the CRSS model (12 months × 29 sites = 348 values) (Figure 20), the natural flow (from Reclamation's Natural Flow Database) at each of these sites and months is taken to apply in the simulation year. This approach is referred to as water year block disaggregation and has its roots in other block bootstrap approaches that have been applied in hydrology (Vogel and Shallcross, 1995; Srinivas and Srinivasan, 2005; Srinivas and Srinivasan, 2006). A block of flows sampled from the historic record, by construction retains the spatial and temporal dependencies of the historic record. It is a non-parametric approach, in that no distributional or correlation model assumptions are needed. In our approach, if in the first simulation year, a resampling of 2017 was the result for the flow at Lees Ferry, the 29 sites × 12 monthly flows (natural flows at CRSS nodes) for 2017 were assumed for the first simulation year. Then if in the second simulation year, resampling gives annual flow at Lees Ferry from 2014, the 29 sites × 12 monthly flows for 2014 were used in that year. Thus, the last month of 2017 water year flow would be followed by first month of 2014 water year flow at each site. This approach continues for all the years being simulated. This approach preserves spatial and temporal correlations within water years, because it merely represents a resampling of the data. Across water years correlations may not be exactly preserved because of the year-to-year transitions. However, the water year break Sept-Oct is, in the western US, a point where streamflow resets from one year to the next. Spring runoff peaks have typically waned by the end of September, and the first new winter snow that builds up for the next seasons flow is just starting. For these reasons, September to October correlations are typically small and this is not seen as a major shortcoming. A drawback of this approach is that it does not introduce spatial and within year temporal variability into the simulations. This could be a shortcoming for short term, low storage planning scenarios. However, given that the Colorado system has a high degree of storage, and short term (less than a year) regional droughts are much less of a concern for water management and Colorado River Basin drought planning, this is not considered to be a limitation worth worrying about, and the simplicity of the water year block resampling over more complex methods to attempt to reproduce this is seen as an advantage.

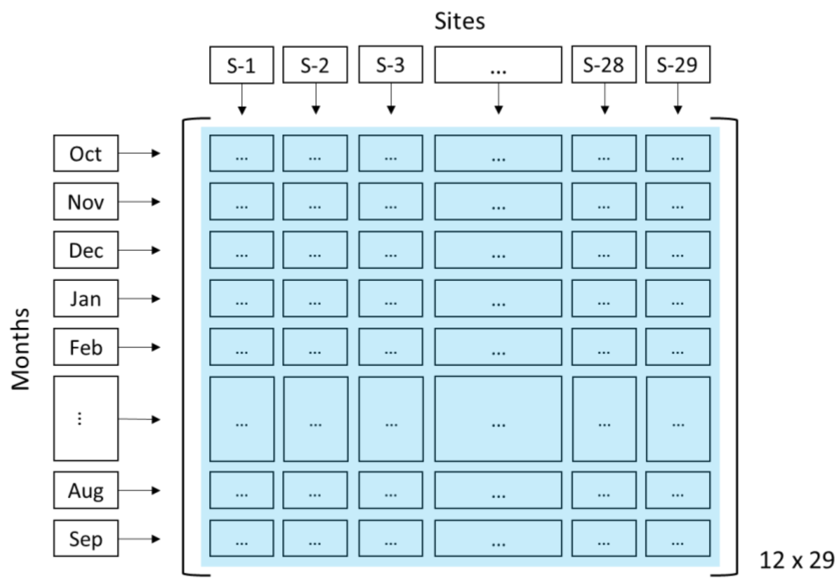


Figure 20. Defined “block” for each water year (12 months × 29 sites = 348 values)

In the paleo tree ring severe drought scenario, the “water year block disaggregation” scheme was applied to disaggregate the reconstructed annual flow at Lees Ferry temporally and spatially. At the first step, the annual flows in the paleo tree ring severe drought period (1576-1600) were resampled using the drought scenario resampling method. However, for the paleo scenarios, there is not historic naturalized flow at 29 sites x 12 months. To address this, for each resampled water year, the nearest observed water year of natural flow at Lees Ferry to the tree-ring reconstructed flow was chosen as the “parallel” year (Figure 21). The corresponding blocks to these parallel years were selected to do the temporal and spatial disaggregation. To preserve the consistency between the generated flows, the ratio of flow between Lees Ferry tree-ring water year and the nearest historic water year (Figure 21) was used to adjust entire block of 348 values.

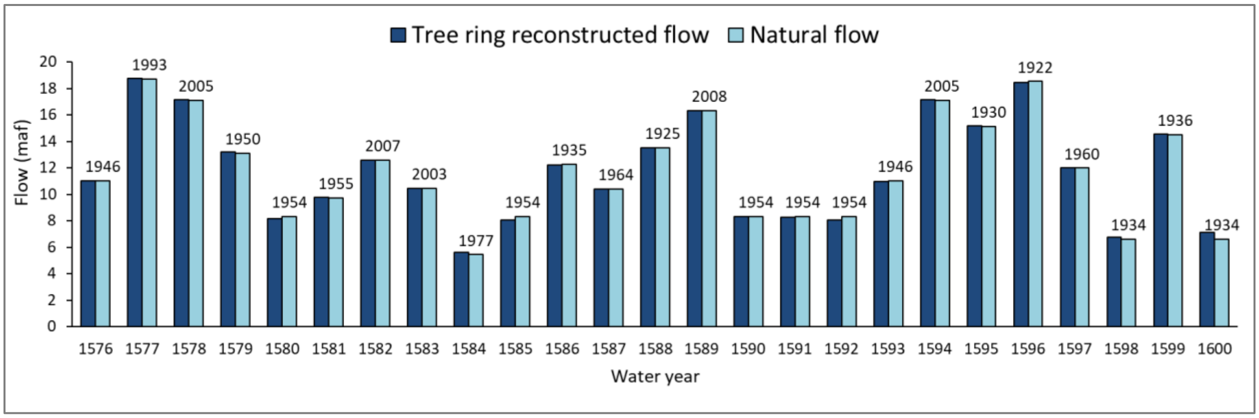


Figure 21. Nearest year of historic natural flow to tree-ring reconstructed flow at Lees Ferry. X axis represents water years of the tree-ring reconstructed flow and the numbers above the bars represent the "parallel" years in the natural flow.

We applied this approach to block resampling the streamflow data. However, the method is quite general and can be applied to other data needed by other models. For example, in other studies that are part of the general Colorado Futures investigations (Mihalevich et al., in review) there is a need for air temperature data consistent with the streamflow simulations. An intermediate output of the drought scenario resampling and block disaggregation approach is a sequence of randomized years that represent the years that comprise each scenario. Selecting other variable data such as temperature or humidity for these years, effectively extends the approach to these other variables. However, a complication can arise when there are not temperature data available for the years when streamflow data are available. In these cases, we picked the available temperature of a year that its streamflow value at Lees Ferry is closest to the simulated streamflow.

8. Streamflow Scenario Results

Key points

- Lowest sequence-average and cumulative flow loss relative to the 1906-2018 natural flow mean were used to quantify drought severity for each of the scenarios developed.
- The 10 to 90 percentile range of five year cumulative flow losses is from 20.13 to 29.88 maf, for the millennium drought scenario and represents a significant but plausible loss of flow to plan for. The recent 2000-2004 drought falls in the middle of this range.
- The drought scenarios developed are shown to be plausible both in the context of natural, tree-ring, and GCM projections of streamflow.

- When used as input to CRSS, the drought scenarios developed indicate, that without adaptation of operations or management paradigms, the probability that Lake Powell would fall to below power pool and penstock intake levels is high.

We used the methods described above to generate 100 streamflow traces for each of the three drought scenarios (millennium, mid-20th century, paleo). Each trace comprised 42 years of monthly streamflow for 29 sites in the Colorado River Basin. In the following sections, we assess the severity of each drought scenario and show the impacts of each one on Lake Powell water storage.

8.1. Simulated Streamflow

To compare the severity of the drought scenarios, we considered the lowest sequence-average and highest cumulative flow loss at Lees Ferry from each of the 100 traces. This is shown (Figure 22) for the millennium drought scenario. The lowest sequence-average plot for a drought scenario shows the variability of the minimum of the mean flow for different durations based on each of the 100 simulated flow traces (Figure 22-a). The highest cumulative flow loss plot for a drought scenario illustrates the variability of the maximum of the cumulative flow loss (relative to the average flow of 14.76 maf/yr from 1906 to 2018) for different durations based on each of the 100 simulated flow traces (Figure 22-b).

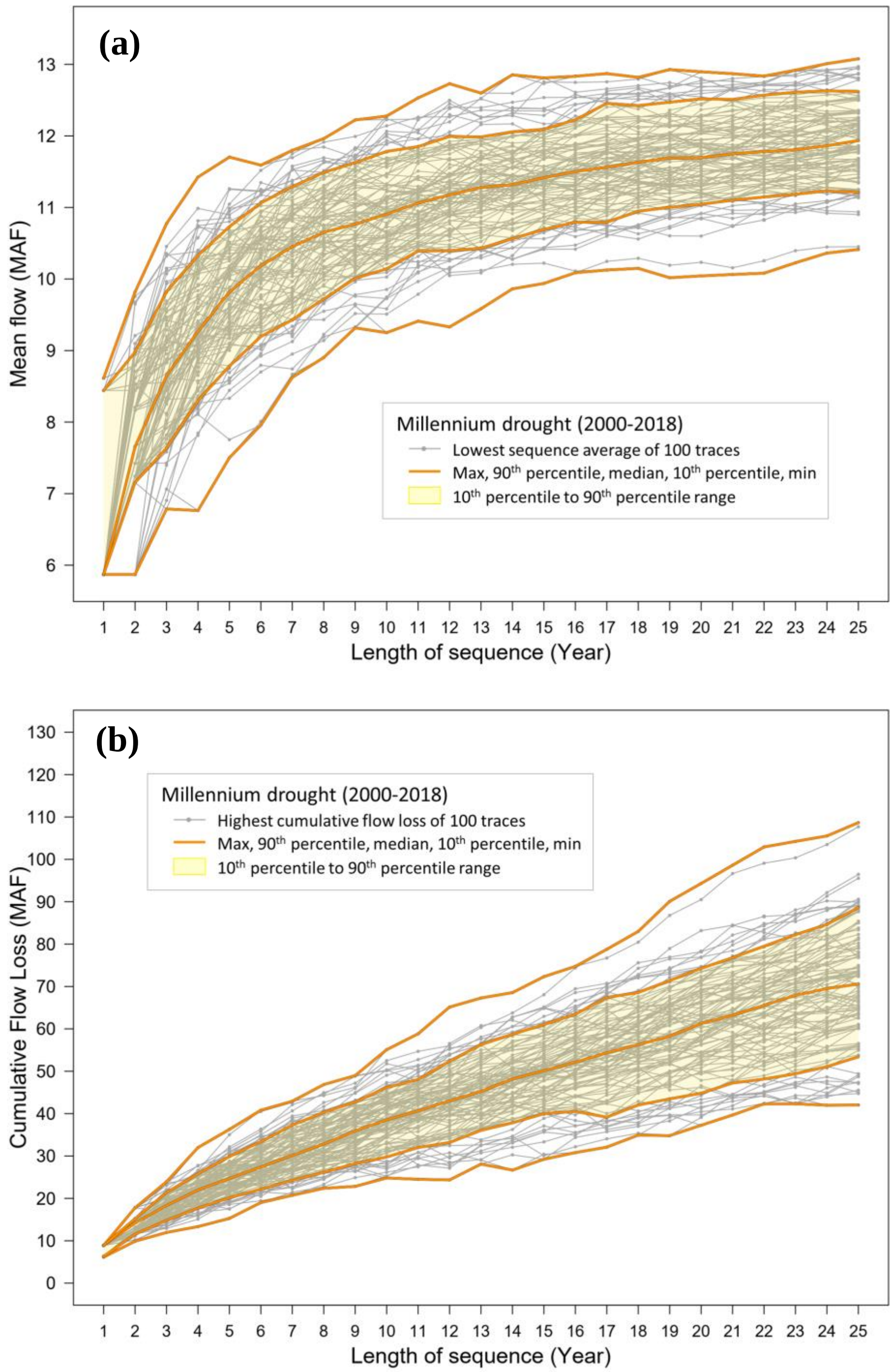
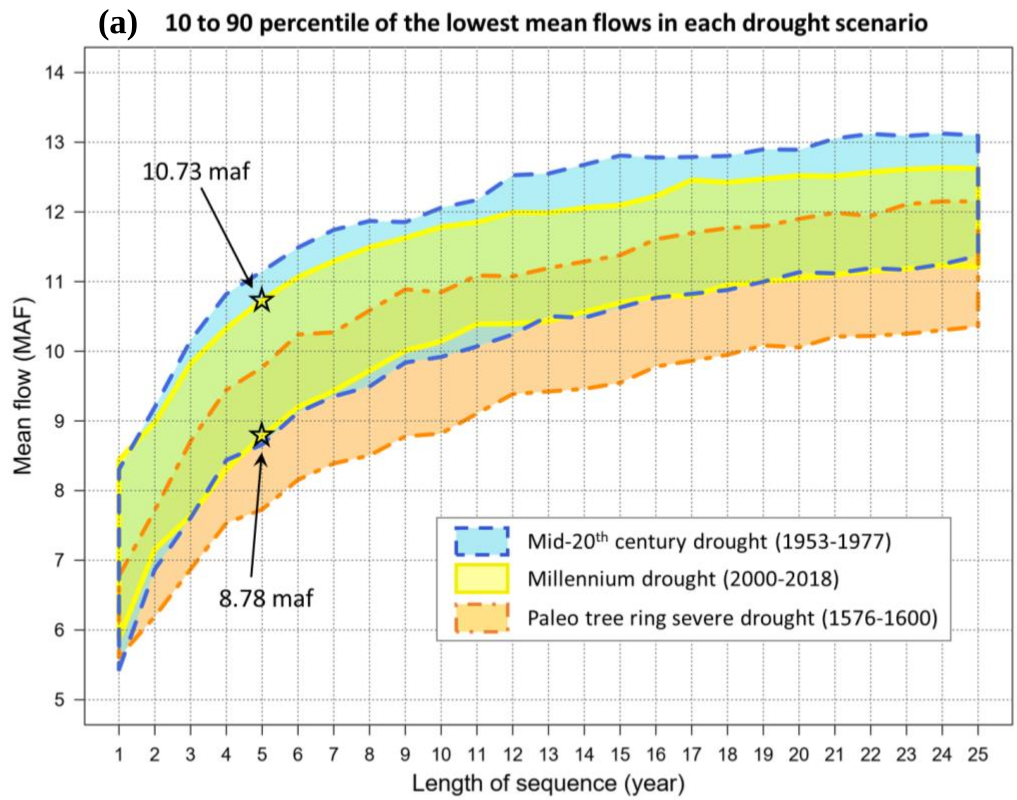


Figure 22. The (a) lowest sequence-average, and (b) highest cumulative flow loss of the simulated annual flows at Lees Ferry in the millennium drought scenario. Each grey dot represents the extreme case (i.e. either minimum mean flow in sequence-average plot or maximum flow loss in cumulative flow loss plot) in each of the 100 simulated flow traces over the length of sequence. Each grey line corresponds to one of the 100 traces and represents the extreme case in each of them. Orange lines show the minimum, 10th percentile, median, 90th percentile, and maximum of values for each sequence length across these extreme cases.

We applied this approach to the simulated annual flows at Lees Ferry for each drought scenario (millennium, mid-century, paleo) to assess its severity (Figure 23). This figure depicts all three drought scenarios using just the 10th percentile to 90th percentile range, so as to avoid outliers. For example, in the millennium drought scenario, five-year flow sequences have 10th percentile and 90th percentile mean flows of 8.78 and 10.73 maf/yr respectively (Figure 23-a). In terms of cumulative flow loss over 5 years, the range is from 20.13 to 29.88 maf relative to average flows (i.e. 14.76 maf/yr from 1906 to 2018) (Figure 23-b). The recent five-year drought we observed in the early 21st century with mean flow of 9.47 maf/yr over 2000-2004 (shown earlier in Figure 12) falls near the middle of this range. In the paleo severe drought scenario, the simulated flows represent even more severe droughts over various length of sequences than those of the millennium drought scenario while the simulated flows in mid-20th century drought scenario represent similar or slightly less severe droughts (Figure 23).

(a)



(b)

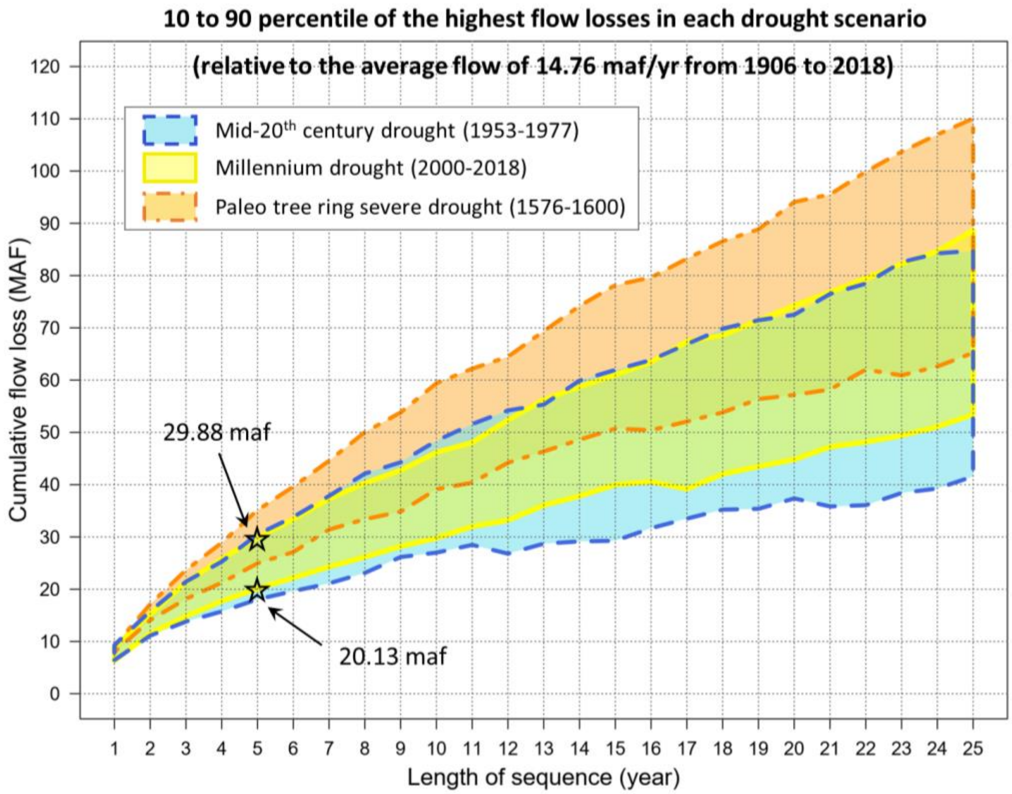


Figure 23. The (a) lowest sequence-average, and (b) highest cumulative flow loss of each of the drought scenarios at Lees Ferry

To place the severity of these scenarios in a historical context, the range of the lowest sequence-average of each scenario was positioned on the sequence-average plots of the observed and tree ring reconstructed flows (Figure 24 to Figure 26). This shows where the range of extreme cases for each of the 100 traces for each scenario falls, with respect to past flows. We see that the scenarios being generated do have the most extreme traces worse than any historic flows, but the 10 to 90% range is typically consistent with what has previously occurred. These scenarios are thus consistent with the idea that if it has happened in the past, it can happen again, and should be planned for.

We also evaluated the 10 best CMIP3-VIC climate model projections (as selected earlier in section 6.3) by overlaying them on the sequence-average plots of the past flows (Figure 27). The spread of climate projection traces is wider than from our resampled scenarios, and they do extend somewhat lower in the sequence-average plot space than the proposed drought scenarios. Climate projections are thus indicating possibly more severe conditions than the resampled scenarios. Resampled and climate projection scenarios were combined (Figure 28), where 10 to

90% ranges show the degree to which climate projections are more severe than historic and resampled streamflow traces.

As was done previously, sequence-averages can also be recast as cumulative flow loss relative to a reference flow over the duration (Figure 29 to Figure 31). The position of scenario extreme losses relative to historic and paleo tree ring losses can be used to quantify the probability of the recurrence of droughts with this severity, assuming the variability of the past records as a basis for probability estimation. Probabilities associated with five- and ten-year durations are shown (Figure 29 to Figure 31). This estimation of probability assumes stationarity, which for a changing climate is questionable, but nevertheless provides some degree of quantification. In the millennium drought scenario, the probability of simulated droughts with different durations are low in terms of observed natural flow and are a little higher in terms of tree ring reconstructions (Figure 29). For example, for a length of sequence of 5 years, representing a 5-year drought, 90% of the simulated flow traces have largest 5-year cumulative flow loss greater than 20.13 maf, which, put in the context of the natural flow record, would have a probability of less than 1.83% (Figure 29-a). Put in the context of the tree ring reconstructed record the 90% of traces with 5 year 20.13 maf cumulative flow loss have a probability of less than 6.21% (Figure 29-b). In the mid-20th century drought scenario, the simulated droughts are less severe and as a result their estimated probabilities are slightly higher than those in the millennium drought scenario (Figure 30). For instance, the worst 5-year droughts in 90% of the simulated flow traces have cumulative flow loss greater than 18.06 maf, and probability less than 4.59% and 9.56% in terms of observed and tree ring reconstructed flows, respectively. In the paleo tree ring severe drought scenario, the cumulative flow loss of simulated flow traces is higher than the other two drought scenarios, leading to estimated probabilities that are lower, and are 0 for many of the levels calculated, indicating that the droughts produced by this scenario are worse than droughts in the historic or tree ring record (Figure 31). However, given what is projected in terms of climate change (Figure 28) they are not inconsistent with this. Note also that Williams et al. (2020) found, while examining soil moisture droughts estimated from tree-ring reconstructions that the millennium drought, which would otherwise have been a moderate drought, had, due to climate change become comparable to mega droughts in the tree ring soil moisture record.

Overall, despite these low drought probabilities, we should remind the reader that they are plausible scenarios that may occur in the future because they are resampled from past flows that already occurred. In the case of the millennium drought scenario we note that the simulated flows are resampled from the 2000-2018 period of the observed natural flow, which we have recently observed and recorded, and which has been experienced by the current generation of water managers and users. Further, a comparison between the simulated drought scenarios and 10 best CMIP3-VIC projections showed that the lowest sequence-average range of simulated scenarios are within the lowest range of climate projections (Figure 27 and Figure 28). This once again warns us of a potentially changing future. We believe that these drought scenarios can provide us flow inputs that stress the system enough to plan for a changing future.

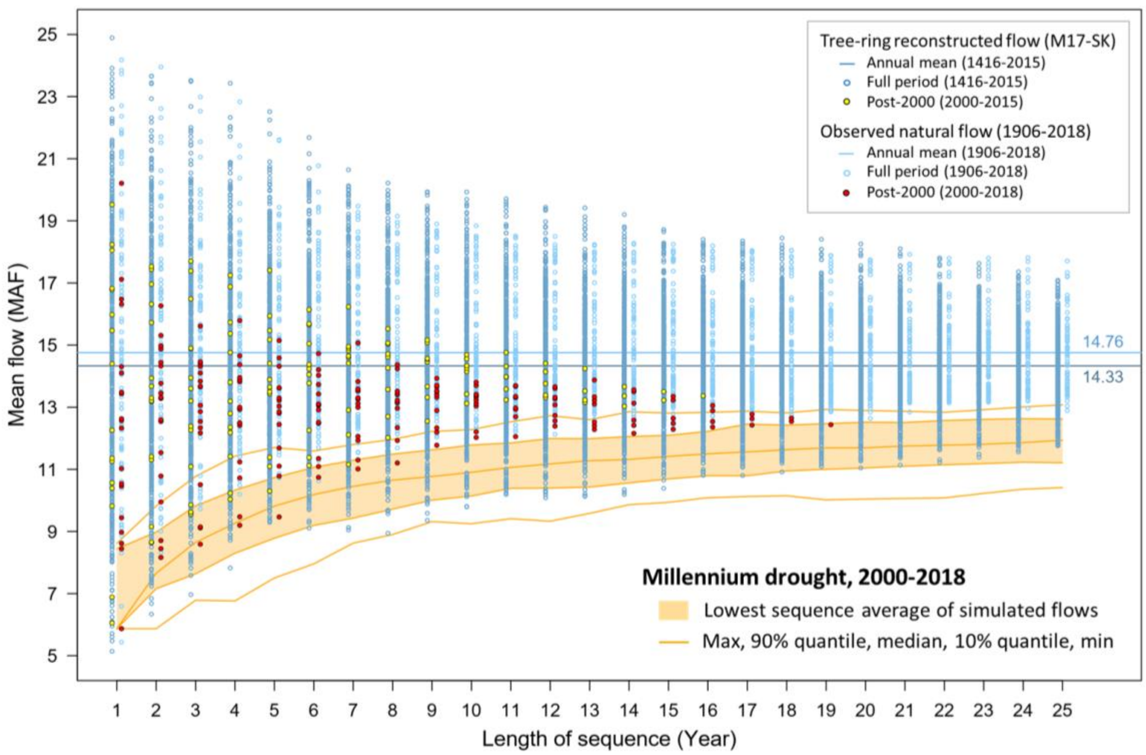


Figure 24. The lowest sequence-average of millennium drought in comparison with observed and tree ring reconstructed flows

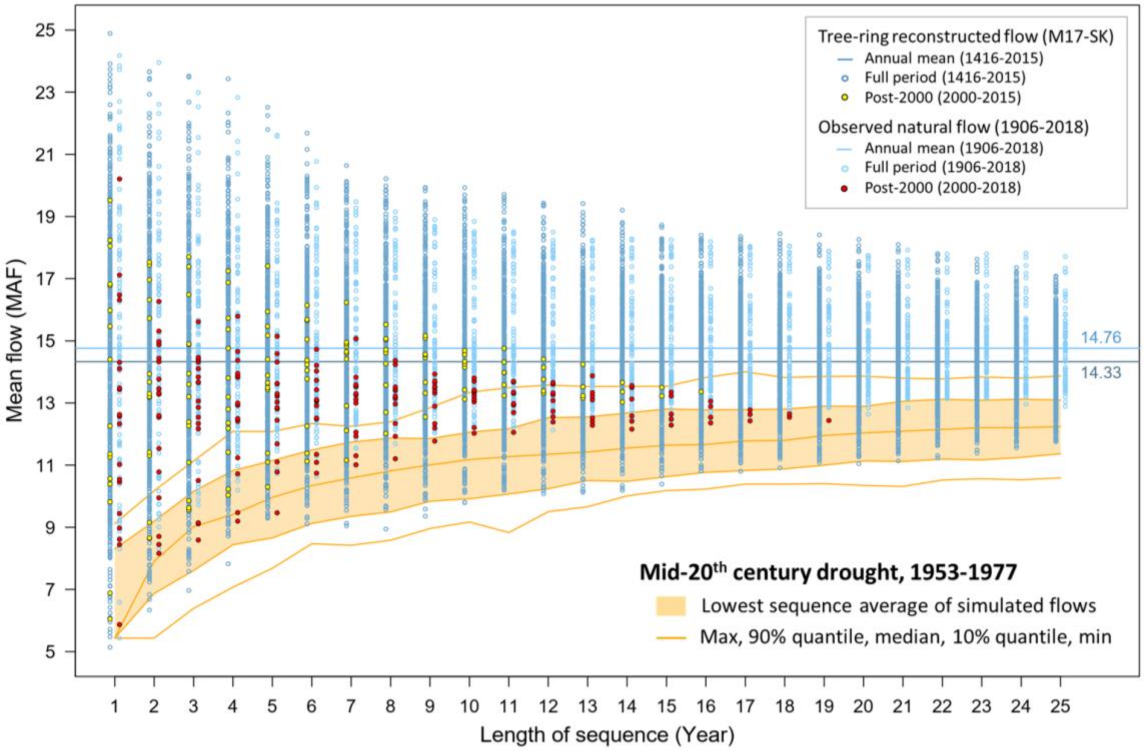


Figure 25. The lowest sequence-average of mid-20th century drought in comparison with observed and tree ring reconstructed flows

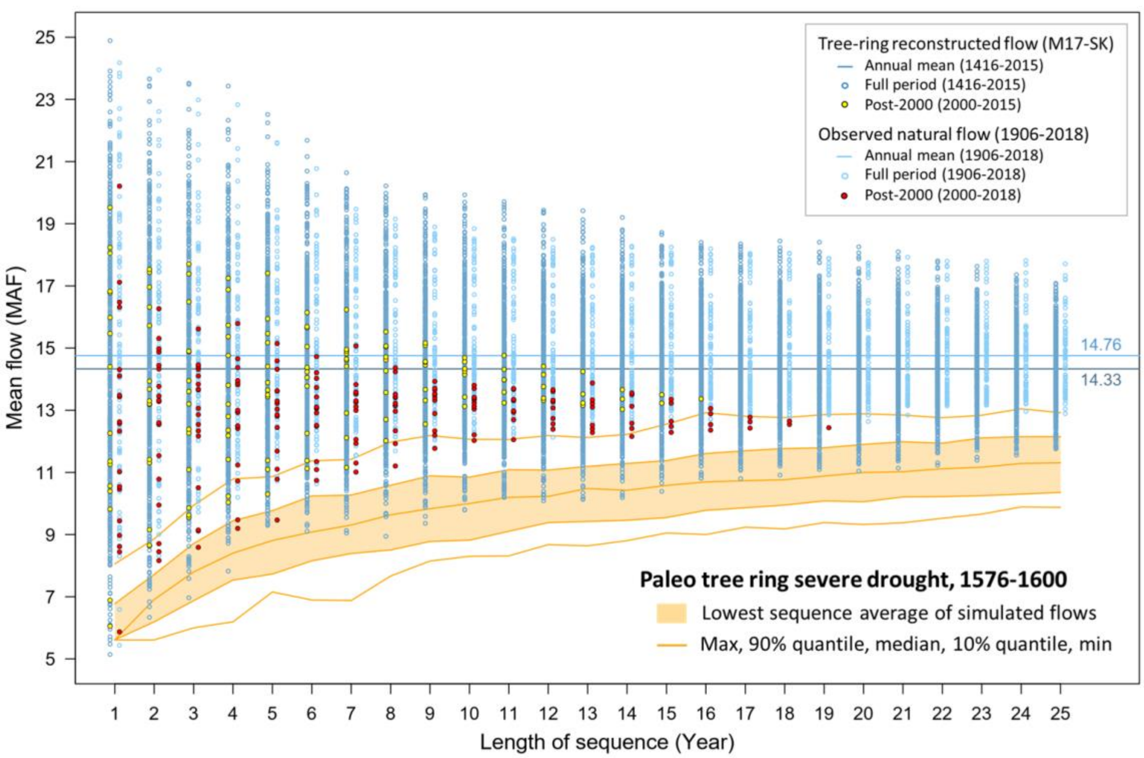


Figure 26. The lowest sequence-average of paleo tree ring severe drought in comparison with observed and tree ring reconstructed flows

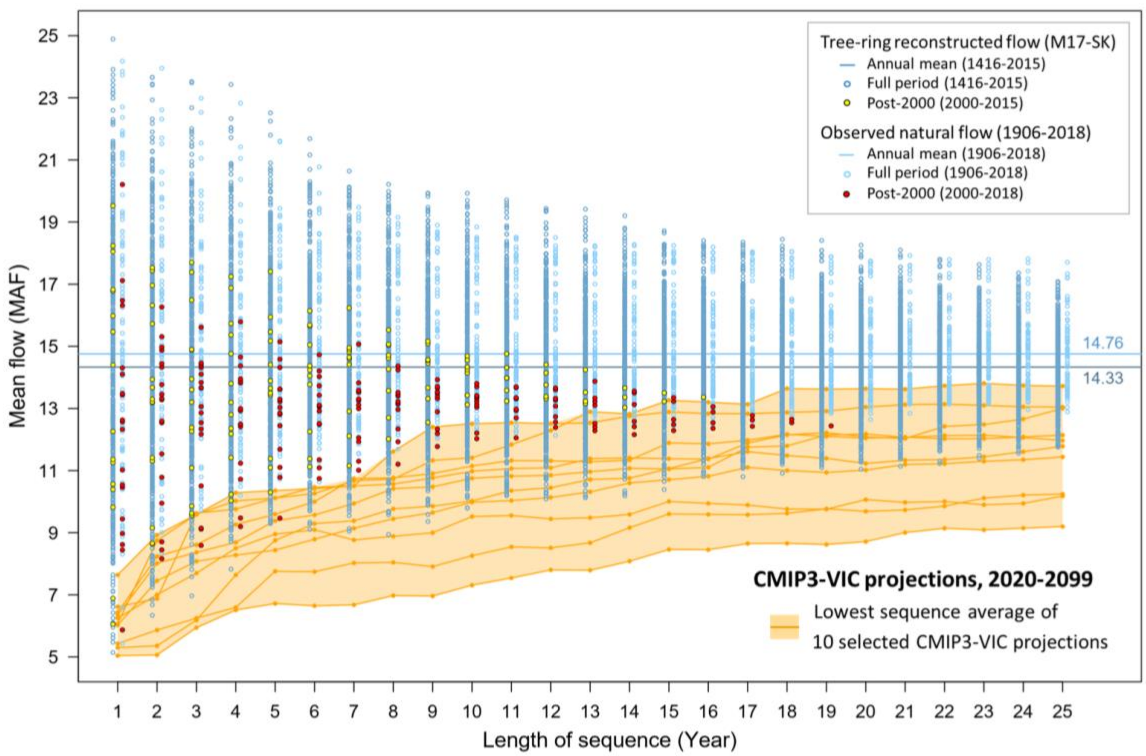


Figure 27. The lowest sequence-average of 10 best CMIP3_VIC streamflow projections

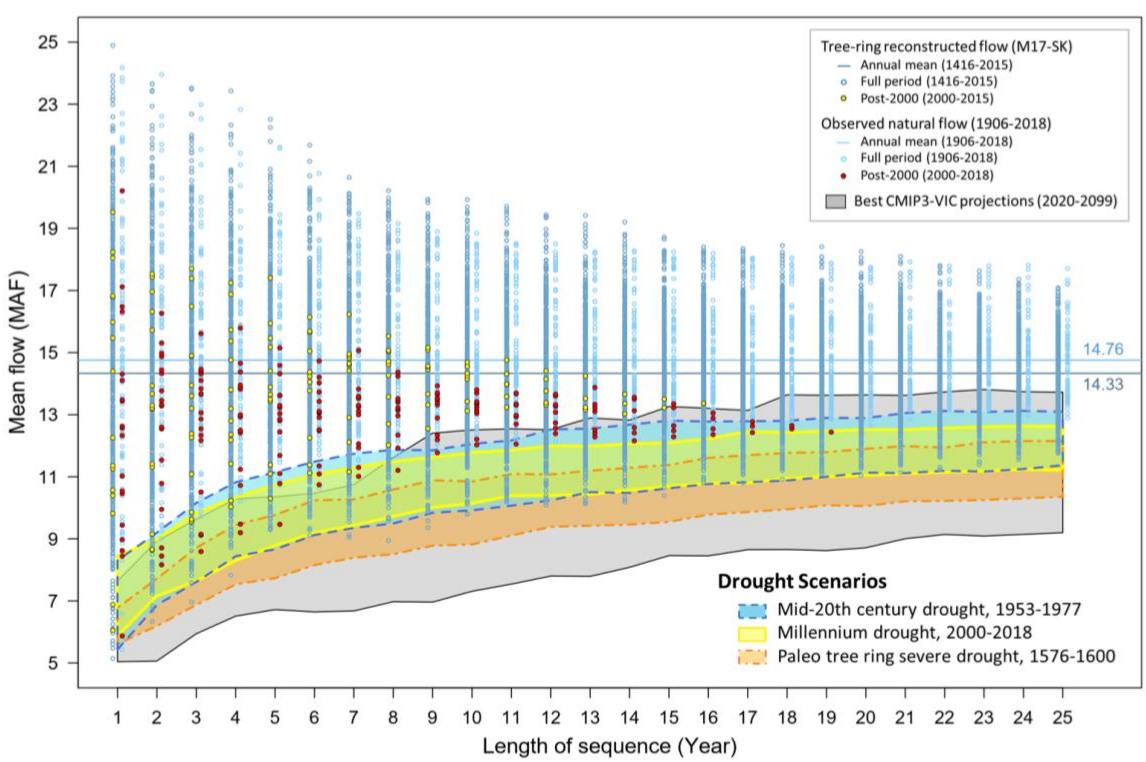


Figure 28. The lowest sequence-average of drought scenarios and 10 best CMIP3-VIC projections

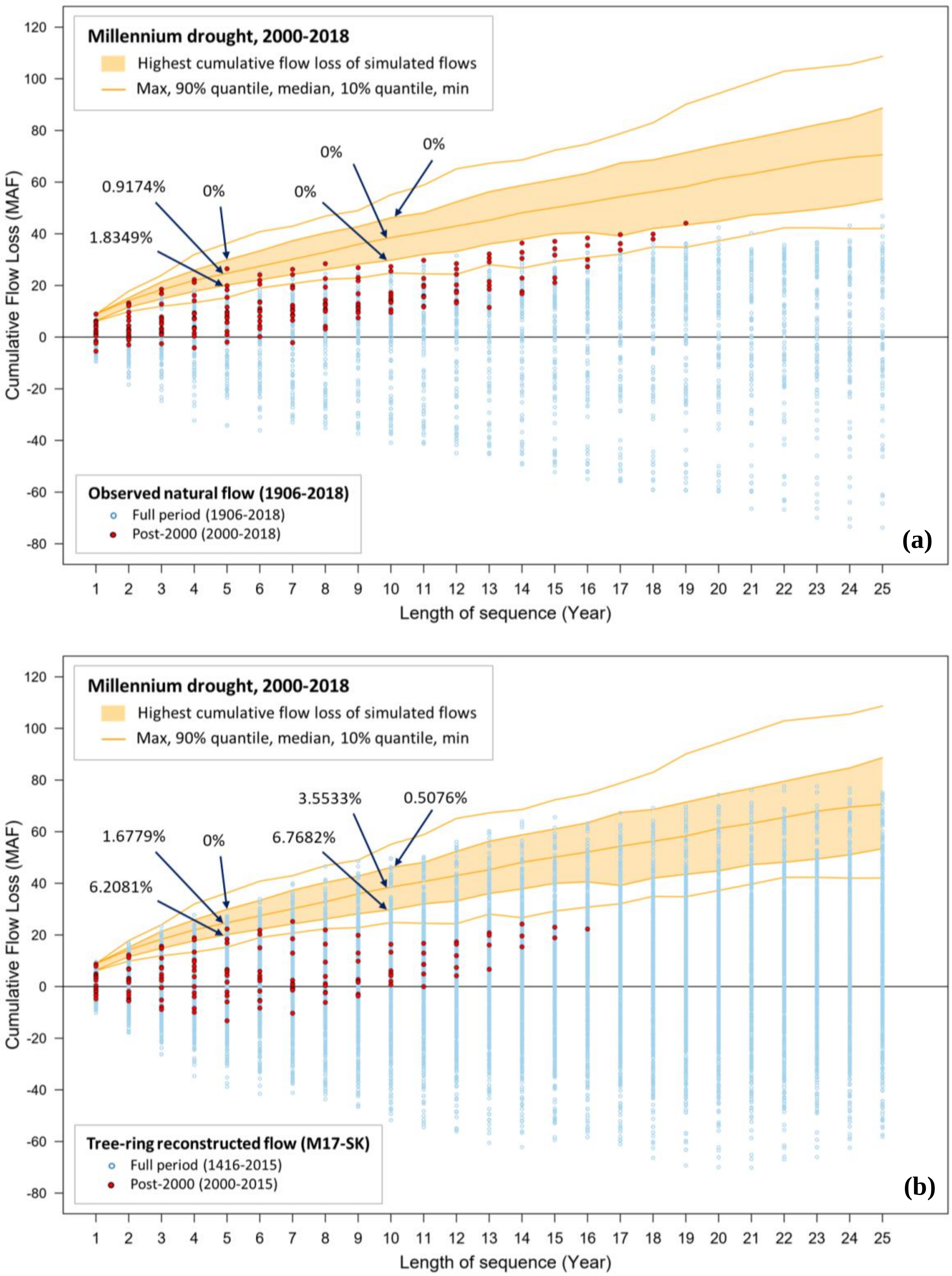


Figure 29. Highest cumulative flow loss of millennium drought in comparison with a) natural, and b) tree ring reconstructed cumulative flow loss.

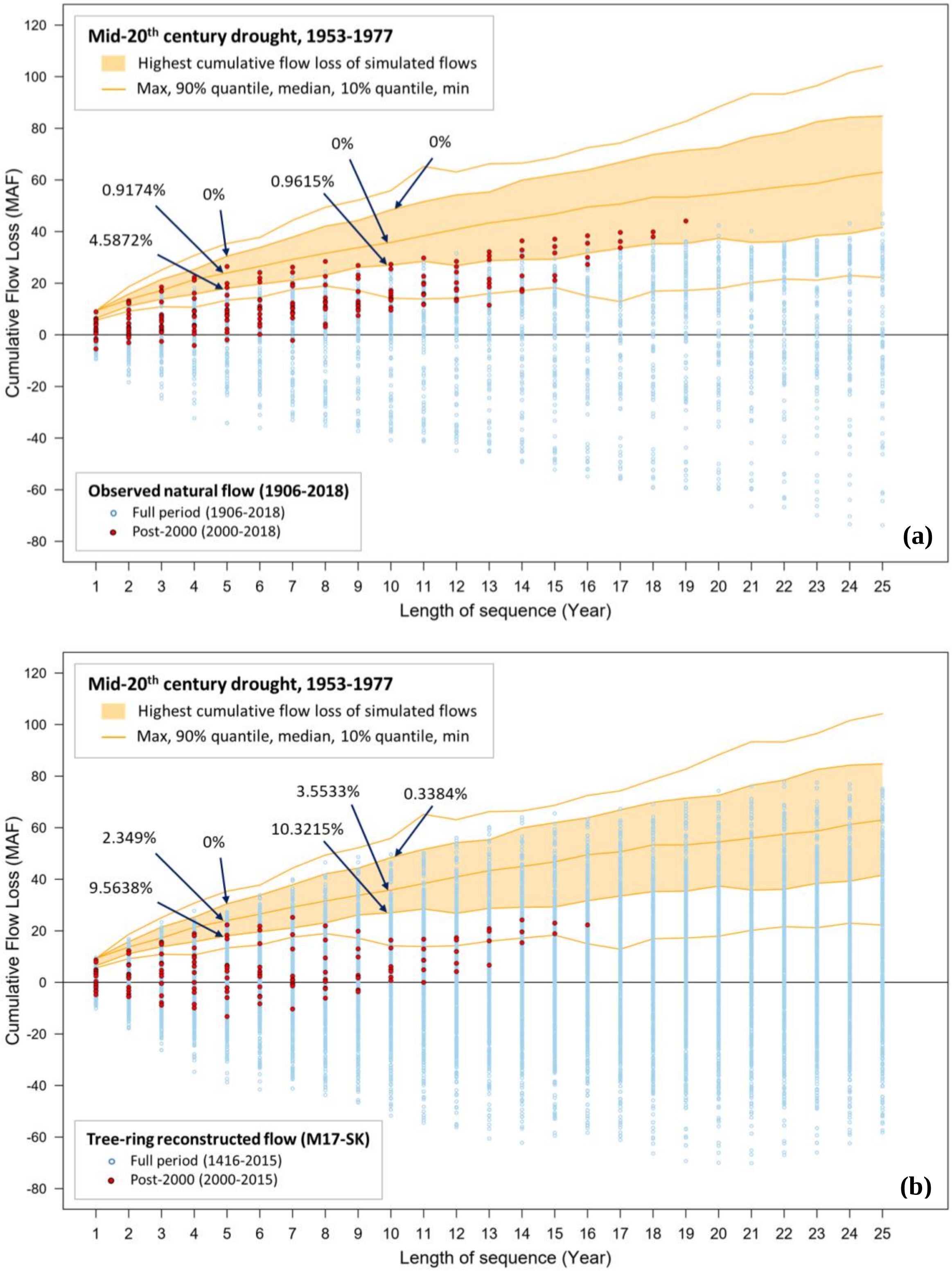


Figure 30. Highest cumulative flow loss of mid-20th century drought in comparison with a) natural, and b) tree ring reconstructed cumulative flow loss.

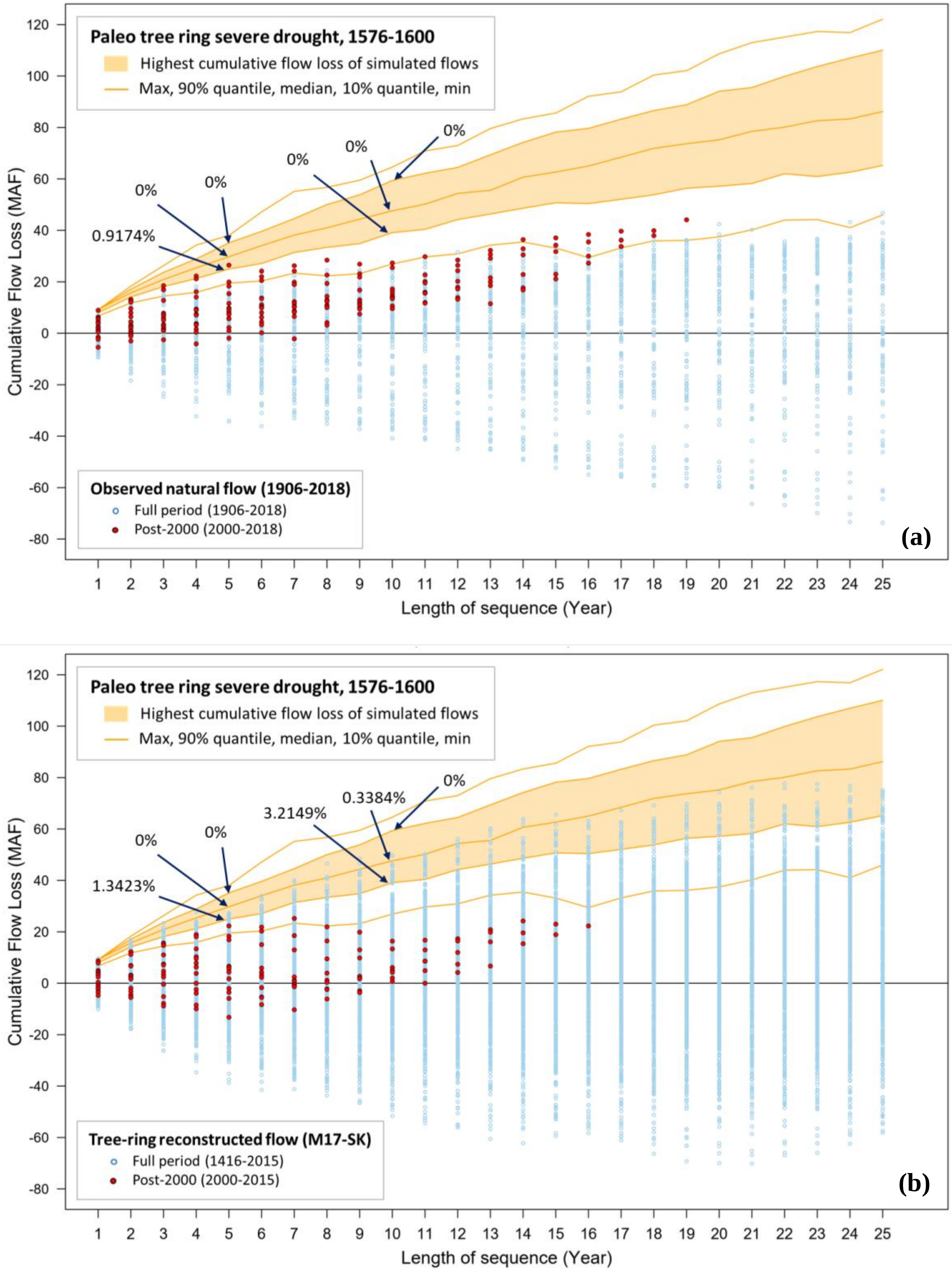


Figure 31. Highest cumulative flow loss of paleo tree ring severe drought in comparison with a) natural, and b) tree ring reconstructed cumulative flow loss.

8.2. Impacts of Various Hydrologic Scenarios on Lake Levels (CRSS Results)

Each of the 100 traces from each scenario was disaggregated to provide inflows to CRSS at the 29 inflow points. The hydrologic scenarios were analyzed using the April 2020 version of CRSS representing the projected initial reservoir conditions for December 2020 and the current interpretation of the Law of the River as represented in the model. These assumptions include the 2007 Interim Shortage Guideline operation rules and the 2019 Drought Contingency Plan. The exceedance probability of Lake Powell pool elevations was compared with the CRSS runs that use the Direct natural flow from Reclamation's 1906-2018 data set. Figure 32 demonstrates the effect of the resampled conditions persisting over a 20-year duration and Figure 33 demonstrates this over a 40-year period. The former represents the situation of a historically plausible drought magnitude and duration beginning today, and the latter represents these conditions persisting 40 years into the future. In either case, a considerable fraction of the scenarios and sequences indicate that the reservoir elevation would fall below minimum power pool, and even in some cases below the penstock intake levels. This would be catastrophic both for water supply, power generation and the ecosystem downstream from Lake Powell, and motivates the need to develop alternative management paradigms to account for the possibility of the inflow scenarios developed here.

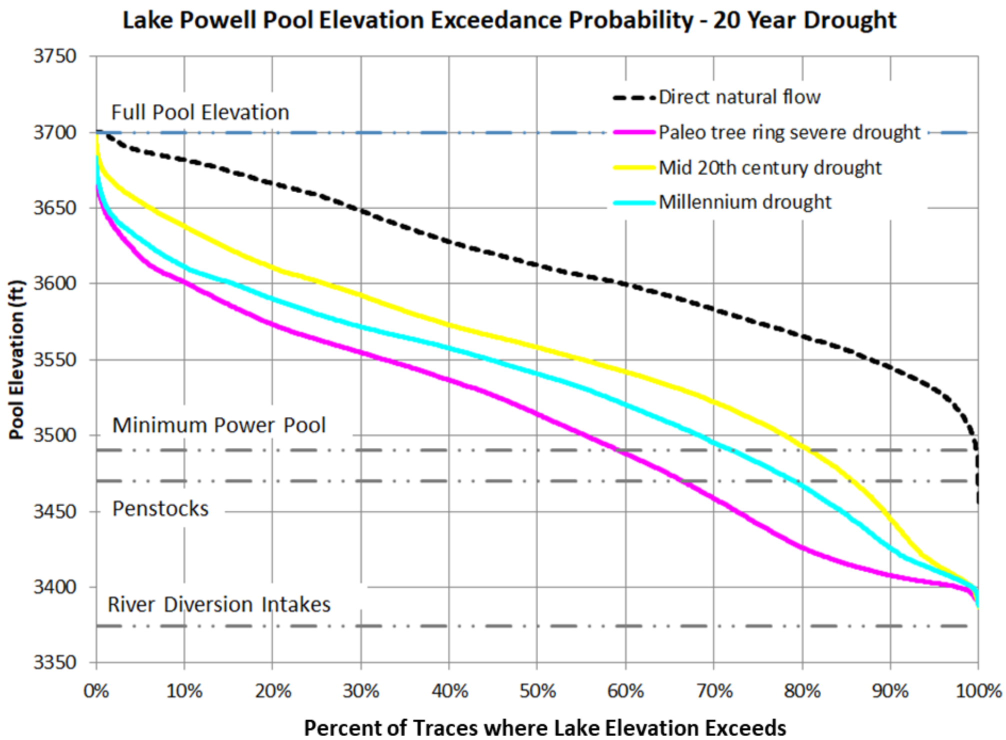


Figure 32. Lake Powell pool elevation in response to each of the drought scenarios over a 20-year period

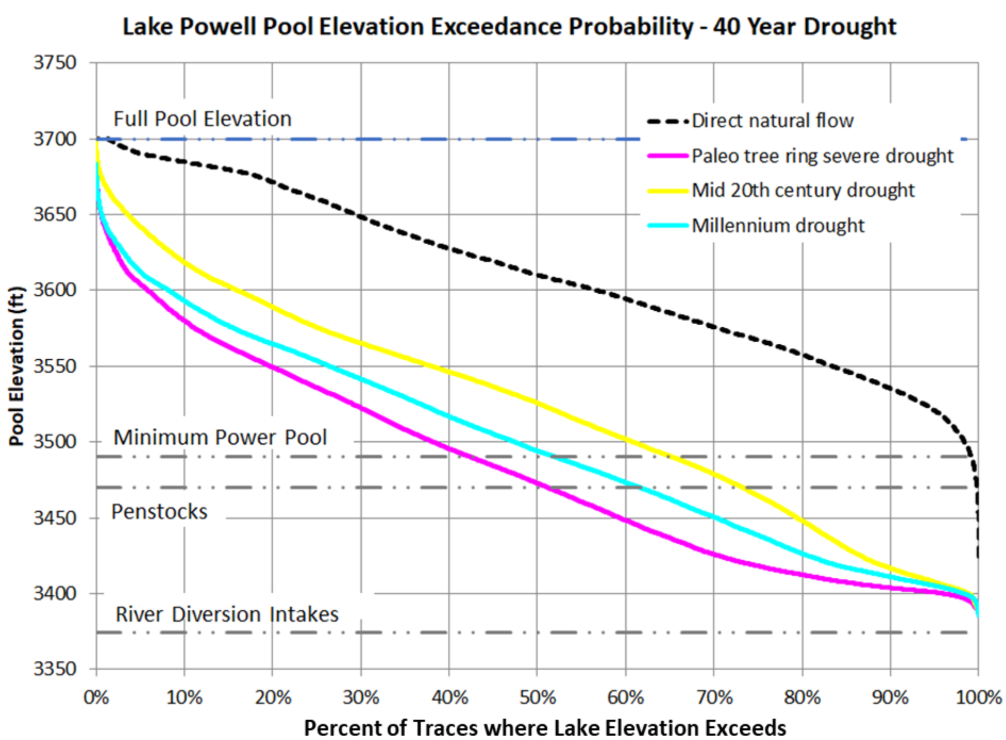


Figure 33. Lake Powell pool elevation in response to each of the drought scenarios over a 40-year period

9. Discussion

Climate warming has already been shown to reduce runoff in the Colorado River Basin, a highly utilized basin where demand already exceeds supplies. Future warming is projected to cause additional significant losses. This will occur on top of severe and sustained droughts, which have occurred in the past, and have high likelihood of occurring in a warming climate. To better manage the Colorado River System in this uncertain future and mitigate vulnerabilities, water managers need to evaluate the system behavior under defensible worst-case possible scenarios.

This paper has examined available information on the hydrology of the Colorado River Basin and constructed plausible drought scenarios for planning that address the multiple factors and uncertainties involved and are intended to be used as a basis for testing alternative operation and management paradigms. We have considered sources of uncertainty related to flow naturalization, climate change, vegetation change and the representativeness of data used in inferring trends and simulating future flows. The scenarios we present, while extreme, are grounded in past streamflow records and the maxim that if it has occurred in the past, it may occur again. These scenarios therefore serve as plausible stress tests for future hydrology of the Colorado Basin.

This paper has documented, through analysis of historic streamflow data that the Colorado River suffers from periodic severe and sustained drought, and that water management planning should take this into account. The most recent 19 years (2000-2018) for which complete naturalized flow data are available are the driest in the observed record (1906-2018). However, this period is not without precedent in paleo reconstructions using tree-rings and also not as severe as some climate projections. Conversely the first 24 years of the commonly used observed record (1906-1929), known as the Early 20th century pluvial period, are the wettest on record.

Because the observed 1906-2018 record starts with a wet period and ends with a dry period, trend analyses of streamflow and precipitation produce a statistically significant downward trend. However, when the Early 20th century pluvial period is removed, precipitation and streamflow trends no longer have a statistically significant downward trend. There is also evidence documented in early USGS papers (La Rue, 1916), and publicized in a recent book (Kuhn and

Fleck, 2019) that flows prior to 1906 were not as wet as the 1906-1929 pluvial period. Furthermore, tree ring reconstructions provide evidence of multiple severe sustained droughts in the post 800 paleo period for which tree-ring reconstructed streamflow was evaluated. These data thus show that climate change notwithstanding, extreme droughts in the Colorado River Basin occur naturally, and frequently at multi-century time scales, further underscoring the need for planning scenarios where they are considered.

In the changing non-stationary climate that we are now experiencing, long term (e.g, greater than 50 years) trend analyses may not be helpful as they imply a future climate inferred from a different past climate. Future flow projections using both the downward trend starting in 1906 and the flatter trend since the 1930s may lead to incorrect conclusions. The downward trend since 1906 is because of the high flows from 1906 to 1929. The only true analog of this period of high flows over the last 1200 years occurred in the early 1600s, indicating how unusual that period was (and also implying that a repeat is unlikely). Indeed, climate science suggests that megadroughts are far more likely than pluvials as the 21st century warms. Thus the 1906-2018 trend line is based on an extremely unusual event and using that trend line to project 21st century flows is not defensible.

Similarly, the flat trend since the 1930s may wrongly imply that our current drought is no different from low flows in the 1930s and 1950s that influence the trend line. That is also not true. Those low flows were driven by precipitation declines, not by heat as is the current drought. And, critically, we have reasons to believe that virtually certain future warming will push flows lower, even if precipitation increases somewhat buffer those losses. It also should be noted that the current 2000-2018 drought is worse by over 400 kaf/yr (7.6 maf total difference) than the worst 19-year long drought in the 20th century and also features almost all of the worst n-year (n from 1 to 19) long drought sequences in the historic record. Using this historic period to generate drought sequences, as we did, provides plausible future low flows, which when set in the context of climate change may not be as severe as what we face in the future recognizing that hotter and drier conditions are making matters worse.

Tree ring reconstructions of streamflow serve to extend the observable record and provide evidence of multiple severe sustained droughts in the past. This data shows that extreme droughts in the Colorado River Basin occur naturally, and at multi-century time scales, frequently, further underscoring the need for planning scenarios where they are considered. The tree rings thus provide an ample source of believable potential low future flows from which to sample.

Climate change is an important factor and source of uncertainty that affects future streamflow. Temperature has increased across the Colorado River Basin, a trend that is virtually certain to continue, and a factor that will likely reduce flows further. We used information from CMIP studies coupled to hydrology models to evaluate the range of changes projected by climate models in the future, and juxtaposed these over our analyses of historic data and simulated scenarios to frame simulations in a climate change context. The CMIP results are worse than we generated, but not exceedingly so. The simulations based on the paleo tree ring drought are more severe than the most severe historic drought, but plausible when juxtaposed and considered in the context of climate change.

The 1906-2018 flow record that underpins much of this paper is "naturalized" flow as quantified by the Bureau of Reclamation. Naturalized flow is streamflow that would have occurred without the alterations due to dams, withdrawals and use. Its estimation is challenging and different authorities use different methods to estimate it. It also serves as an underpinning for many tree ring reconstructions. Two sidebar analyses note challenges associated with natural flow estimation and potential discrepancies due to the way main stem losses below Lake Mead are computed. There has been consideration of revisions to improve natural flow estimation methods, and we caution here that while such work is important, it may change the basis for much of the tree-ring hydrology. This point underscores an important uncertainty in overall streamflow availability, all the more reason to be cautious and plan for worst case scenarios.

In much prior work drought scenarios have been developed using the index sequential method, which is a recycling of flows for a selected period. This introduces limited, and in our view, insufficient variability. In this white paper, we developed three drought scenarios to be used as hydrology inputs to Colorado River System Simulation and management models and stress the system. We suggest that these scenarios should be used, by the water management community as inputs to CRSS and other planning tools as severe, but realistic possible future flow conditions. It is prudent to consider and develop plans and management paradigms for coping with such severe droughts. The scenarios we developed for testing of alternative drought and management planning paradigms were stochastically generated and comprised 100 42-year sequences for use in a 42-year planning period. They were based on the most severe recent drought (millennium drought 2000-2018), most severe 20th century drought (1953-1977) and most severe paleo drought (1576-1600). Block resampling by water year from each of these droughts provided multiple plausible realizations with which to stress test the system. These scenarios are based on historical droughts that occurred in the past and are plausible while having low probabilities.

Stakeholders should consider these drought scenarios to evaluate paradigms for water allocation under these circumstances as part of drought planning. We evaluated these droughts using minimum sequence averages and cumulative flow losses and showed where they fell in comparison to full historic and paleo streamflow records as well as climate projections. Our evaluations suggest that while more extreme than observed historic droughts, these scenarios are reasonable for testing the system given the uncertainties of projecting future flow. When used as input to the currently configured CRSS they indicate considerable periods with Lake Powell at a level below its hydropower penstocks, indicating the need for rethinking the management paradigms for operation of these reservoirs in the face of future droughts.

10. Conclusions

In the Colorado River Basin 85% of the annual average runoff originates from 15% of the watershed at higher elevation in western Colorado, southwestern Wyoming, and northeastern Utah. Spatial correlation among annual natural flow originating in each CRSS subwatershed suggested a natural partitioning of the Upper Basin into 4 hydrologically similar parts grouped by the region where flow originates, rather than by tributary.

When streamflow trends are examined from the start of the historic record (1906) to present, there is a statistically significant downward trend. When streamflow trends are examined starting in 1930 after what was an unusually wet period from 1906-1929 (Early 20th century pluvial), streamflow trends are generally not statistically significant. In the changing non-stationary climate that we are now experiencing, such long-term trend analyses may not be helpful in inferring the future.

Severe and sustained droughts in the Colorado River Basin were identified using the average of streamflow, and the cumulative loss relative to the mean flow, over varying sequence lengths. Using this approach, we identified and defined three periods from which to generate drought scenarios. The millennium drought from 2000-2018 is characterized by a water year average flow of 12.44 maf/yr, significantly below the 1906-2018 mean of 14.76 maf/yr. This leads to a 19-year cumulative loss of 44 maf, close to the total storage in the Colorado system. The mid-20th century drought from 1953-1977 has a water year average flow of 12.89 maf/yr. These are both droughts in the historic record whose potential recurrence should be planned for. The mid-20th century drought was primarily due to reduced precipitation, while the millennium drought had a substantial warming component. It may be prudent for planning purposes to consider the occurrence of these in combination. Tree ring reconstructions of streamflow serve to extend the observable record and provide evidence of multiple severe sustained droughts in the past. This paleo tree ring severe drought from 1576-1600 had an average flow of 11.76 maf/yr, notably lower than the historic droughts, and is representative of extreme droughts that occur naturally within the Colorado River Basin.

Climate change is occurring on top of the natural occurrence of droughts. Although GCM precipitation projections are highly variable in the Colorado River Basin, there is a consensus among most of the climate studies that the future runoff of the Colorado River Basin will decline as it warms and that the future might include megadroughts that are even worse than the drought scenarios quantified in this study.

There is a need to have diverse input sequences to simulate and test systems operation and management paradigms. It is insufficient to only evaluate the impact of past drought scenarios repeated exactly. We used resampling of the flows at Lees Ferry for the drought scenarios we identified to provide an ensemble of 100 plausible annual streamflow traces. We used a nonparametric resampling approach referred to as “Water Year Block Disaggregation” to split the simulated annual flow at Lees Ferry into monthly flow at each of the 29 CRSS natural inflow sites. These sequences are available for use in CRSS and other planning tools as severe, but realistic possible future flow conditions, that should be planned for. Lowest sequence average and cumulative flow loss relative to the 1906-2018 natural flow mean were used to quantify drought severity for each of the scenarios developed. The 10 to 90 percentile range of five year cumulative flow losses is from 20.13 to 29.88 maf, for the millennium drought scenario and represents a significant but plausible loss of flow to plan for. The recent 2000-2004 drought falls in the middle of this range. When used as input to the currently configured CRSS the scenarios developed indicate considerable periods with Lake Powell at a level below its hydropower penstocks, indicating the need for rethinking the management paradigms for operation of these reservoirs in the face of future droughts.

Supporting data

The data used, and scenarios developed in this study is publicly available in HydroShare http://www.hydroshare.org/resource/6d351874f16947609eab585a81c3c60d (Salehabadi and Tarboton, 2020).

Sidebars

Sidebar 1: How Much Water Flows in the Colorado River?

Kuhn and Fleck (2019) summarized the intricate and intertwined scientific and political history of estimating the Colorado River's average annual streamflow. The first stream gage in the watershed was established in 1889 on the Gila River at Buttes, Arizona (USGS gage 09474500), where the river leaves the Mexican Highlands and enters the Sonoran Desert. The first gage in the Upper Basin was established in 1894 on the Green River (USGS gage 09315000). This gage was originally established a short distance upstream from the San Rafael River and was moved 33 km upstream to its present location in 1938 (Allred and Schmidt, 1999).

LaRue (1916; 1925) estimated the volume of streamflow based on comprehensive synthesis of available Colorado River gaging data, correlation with gaging data from adjacent watersheds, correlation with the record of rise and fall of the Great Salt Lake, and compilation of data concerning consumptive uses and losses. The evaluation of the record of changes in the elevation of the Great Salt Lake was especially insightful, and those changes had been carefully measured since 1871 and estimated back to 1859.

Later in the 20th century, staff and consultants to the Bureau of Reclamation, federal commissions, state agencies, and some irrigation districts made their own estimates of the Colorado River's flow. Kuhn and Fleck (2019) explained the scientific and political context of the many estimates that ranged between approximately 14 and 18 maf/yr. One reason for the wide range of these estimates was whether they only sought to summarize measured streamflow that began at Yuma in 1903 or if those estimates considered conditions before 1903 when observers reported much less streamflow. Another reason for large differences in estimated streamflow was whether the consumptive losses caused by increasing trans-mountain diversions and irrigated agriculture in the early 20th century were considered. Additionally, there were significant evapotranspiration losses that occurred throughout the ~800 km between the downstream end of the Grand Canyon and Yuma, primarily when the river flooded onto extensive, vegetated floodplains during the intense early summer heat (Sidebar 2). These losses were not considered in the same way in different studies. Different studies have sought to estimate the long-term actual flow or the long-term "natural flow," as described in Sidebar 3.

There was significant focus on estimating the streamflow of the lower Colorado River as it flows across the Basin and Range, because the river was the water supply to the Imperial Valley (Cory, 1913; Sykes, 1937) and to the Yuma Reclamation Project (Sauder, 2009). Water supply to these areas was substantial in years of large runoff and was limited when the Colorado River's streamflow was small. Laguna Dam, just north of Yuma and upstream from the Gila River confluence, was constructed in 1905, was the first dam spanning the Colorado River, and allowed water to be diverted to the Yuma District. LaRue (1916) estimated that the annual flow of the river at this point was 16.2 maf/yr between 1895 and 1914 (Table S1-1). Measurement of flow near Laguna Dam was difficult, because the channel bed was sand, and early measurement records were known to be inaccurate.

LaRue (1916) also estimated that more than 90% of the Colorado River's flow came from the Upper Basin, and he established a gaging station at Lees Ferry (USGS gage 09380000) in 1921, because the site was accessible by car and the flow could be accurately measured (Topping et al., 2003). Establishment of Lee Ferry, approximately 3 km downstream from Lees Ferry, as the boundary between the Upper Basin and the Lower Basin as described in the Colorado River Compact established this point as the focus for estimates of Colorado River streamflow. Lee Ferry is downstream from the Paria River, and the transfer of water from the Upper Basin to the Lower Basin is the combined flow of the Colorado River measured at the Lees Ferry gage and of the Paria River measured at Lees Ferry (USGS gage 09382000) that was established in 1923.

LaRue (1925) estimated that the average annual flow at Lees Ferry between 1895 and 1922 was 15.2 maf/yr, and he estimated that the average annual consumptive losses upstream from Lees Ferry were 1.5 maf/yr during that period. Thus, the flow of the river in the absence of any human activity would have been 16.7 maf/yr during that period. Kuhn and Fleck (2019) described subsequent estimates of annual flow, some of which represented scientific refinements of LaRue's methods and others that were more simple and served political agendas.

All studies of the river network revealed that ~25% more water flowed from the upper Colorado River than from the Green River, and estimates of that pattern has been consistent for more than a century (Figure S1-1). At Lees Ferry, ~80% of the total flow of the Colorado River comes from these two watersheds.

Table S1-1. Early estimates of the total annual flow of the Colorado River

		1895-1914	1895-1922	1851-1922	1878-1920	1897-1943	1914-1957
		LaRue (1916)[1]	LaRue (1925)	LaRue (1925)[2]	LaRue (1925)[3]	Reclamation (1946)	Iorns et al (1965)
Upper Colorado River (actual)	nr Cisco or @ mouth	6.72	6.87				5.53
Green River (actual)	nr Greenriver or at mouth	5.68	5.73				4.56
San Juan River (actual)	nr Bluff or at mouth	2.30	2.35				2.03
Colorado River (actual)	@ Lees Ferry	15.0	15.2	16.0		14.4	12.7
Colorado River (natural)	@ Lees Ferry	16.2	16.7	16.6	15.0	16.3	15.0[4]
Colorado River (actual)	@ Laguna Dam	16.2					

1 tables, p. 192, 194
2 Plate LXXIV
3 calculated by Kuhn and Fleck (2019)
4 Table 6

Figure S1-1. Map showing the volume of annual discharge of the Colorado River as estimated by LaRue (1916, plate XX).

Sidebar 2 : Natural Flows of the Lower Colorado River Downstream from Hoover Dam

In answering questions concerning the water supply available from the Colorado River during the negotiation and ratification of the 1922 Compact, Reclamation Service Director Arthur Powell Davis used a simple assumption that the natural (then referred to as the “virgin”) flow of the river at Lee Ferry (Sidebar 1) and at Laguna Dam (located just upstream from the confluence of the Colorado and Gila Rivers) was approximately the same (Kuhn and Fleck, 2019). LaRue (1916) had estimated that the total annual flow at Lees Ferry was 92.5% of the total flow at Laguna Dam.

Reclamation’s (1946) comprehensive report on the development of the river, *The Colorado River: a natural menace becomes a national resource*, presented a water budget for the Lower River (Appendix 1, Water Supply). Reclamation (1946) estimated that the natural flow of the river at Lee Ferry was 98.9% of the flow at Laguna Dam for the period 1897 to 1943, which was consistent with Davis’ assumption.

Average natural flow, Colorado River at Lee Ferry[A] (Table CXL)	16.27 maf/yr
Average inflows: Lees Ferry to Boulder Dam[B]	+ 1.06 maf/yr
Average virgin flow at Boulder Dam	= 17.33 maf/yr
Average inflows: Boulder Dam to Laguna Dam	+ 0.15 maf/yr
Average “natural channel losses”: Boulder Dam to Laguna Dam	- 1.03 maf/yr
Average virgin flow at Laguna Dam	= 16.45 maf/yr
Average virgin inflow, Gila River (Table CXLVI)	+ 1.27 maf/yr
Average virgin flow at Northerly International Boundary	= 17.72 maf/yr

Today’s estimates of the natural flow of the same river segment is more consistent with LaRue’s (1916) earliest estimate and can be reconstructed from Reclamation’s (2020) Natural Flow Data Base. Based on these data, the water budget for the lower Colorado River between 1906 and 1943, comparable to the time period evaluated by Reclamation (1946) was:

Average natural flow at Lees Ferry[C]	16.30 maf/yr
Average natural inflow from the Paria River	+ 0.020 maf/yr
Average gain to Hoover Dam[D]	+ 0.90 maf/yr
Average natural flow at Hoover Dam	= 17.22 maf/yr
Average gain to Imperial Dam[E]	+ 0.45 maf/yr
Average natural flow at Imperial Dam	= 17.67 maf/yr

For the entire period for which Reclamation has made estimates (1906-2018), the budget for natural flows of the Lower Colorado River was:

Average natural flow at Lees Ferry	14.76 maf/yr
Average natural inflow from the Paria River	+ 0.020 maf/yr
Average gain to Hoover Dam	+ 0.82 maf/yr
Average natural flow at Hoover Dam	= 15.60 maf/yr
Average gain to Imperial Dam	+ 0.43 maf/yr
Average natural flow at Imperial Dam	= 16.03 maf/yr

Thus, Reclamation's (2020) modern estimates of the natural flow of the Lower River for either the 1906-1943 or the 1906-2018 periods indicate that the natural flow of the Colorado River at Lee Ferry is ~92% of the natural flow at Imperial Dam. However, there is some question as to whether the natural channel losses estimated by Reclamation (1946) and Reclamation (2020) were estimated in the same way (J. Prairie, Bureau of Reclamation, oral conversation with E. Kuhn). Modern methods for estimating the lower river's natural flow may not account for the natural losses caused by evapotranspiration on flooded bottomlands that occurred each spring and summer during the snowmelt flood that were described by LaRue (1916; 1925), thus over-estimating the natural flows.

A Lee Ferry is downstream from the Paria River
B Primarily from the Little Colorado and Virgin Rivers
C Lees Ferry is upstream from the Paria River
D Boulder Dam was renamed Hoover Dam in 1947.
E Imperial Dam is located 9 miles upstream from Laguna Dam.

Sidebar 3: Estimating Streamflow in the Absence of Human Influence

It is insufficient to develop water-supply-management policy solely on the basis of stream-flow gaging data. LaRue (1925) recognized that consumptive uses and losses in the Colorado River Basin had increased between 1895 and 1922, and estimates of the supply of water available for diversion from the Colorado River were confounded by different amounts of upstream depletions in each year that were already occurring. Thus, he estimated the river's annual flow in each year adjusted to a common level of development—1922. These data can also be used to also estimate what the flow would have been in each of these years if there had been no upstream human activities by adding the estimated uses to the gaged flow (Sidebar 1). Similarly, Reclamation (1946) estimated flows for every gage in the watershed to a common level of development that existed in 1943, and Iorns et al. (1965) estimated flows to conditions in 1957. Kuhn and Fleck (2019) summarized other studies which also estimated Colorado River flows in the absence of human activities. Today, the Bureau of Reclamation, Colorado Basin River Forecasting Center (CBRFC), Upper Colorado River Commission (UCRC), and the state of Colorado make similar estimates, although the calculation methods and the extent to which upstream consumptive losses are accounted for is slightly different in each case (Table S3-1).

Table S3-1. Adjusted flow in the Colorado River Basin calculated by different agencies

Agency	Adjusted Flow	Official Definition	Calculation method	Reference
Reclamation	**natural flow** 29 inflow points throughout basin (see Fig. 5, main report)	Flow that would have occurred at a location, had depletions and reservoir regulation not occurred in the upstream watershed	Differs for Upper Basin and Lower Basin: Upper Basin: Calculations made in RiverWare based on reservoir operations data and consumptive use losses $Q_{NF} = historicFlow + totalDepletion \pm reservoirRegulation$ Calculations regularly updated for estimates made since 1983, based on revised estimates of consumptive losses, reservoir data, and USGS gage data. Mainstem Colorado River in Lower Basin: Calculations based on annual Water Accounting Reports that include diversions and return flows, reservoir evaporation, and evapotranspiration by phreatophytes along lower Colorado River. Tributaries in Lower Basin: Natural flows are assumed equal to actual gaged flows	Prairie and Callejo (2005) describe methods used to calculated natural flow dataset since 1971 Lee and Salas (2006) describe methods used to extend records to a common starting point of 1906
Upper Colorado River Commission	**virgin flow** Colorado River at Lee Ferry; estimates since 1896	Estimated flow of the Colorado River if it were in its natural state and unaffected by human activities.	details not available	Upper Colorado River Commission (2018) and earlier annual reports

Table S3-1. Adjusted flow in the Colorado River Basin calculated by different agencies

Agency	Adjusted Flow	Official Definition	Calculation method	Reference
state of Colorado	**historical monthly baseflows** 214 sites in Colorado	Flow without the upstream impact of irrigation diversions and return flows, reservoir operations including evaporation and seepage, and other estimated consumptive uses	$Q_{baseflow} = Q_{gage} + Diversions - Returns \pm \Delta Storage + Evap$ - The calculation is automated by StateMod, a water allocation and accounting model - Trans-basin diversions or imports, and reservoir contents are provided directly to StateMod. - Evaporation is calculated based on historical evaporation rates and reservoir contents. - Return flows are computed based on diversions, crop water requirements, and/or efficiencies.	Colorado Water Conservation Board (2012); Colorado's Decision Support Systems (2016)
Colorado Basin River Forecast Center	**unregulated flow** 9 inflow points in Reclamation 24-month model and 12 points used in mid-term operations model	Flow that would have occurred had measured trans-basin exports and imports, measured diversions, and measured changes in reservoir storage not occurred	$Q_{UF} = Q_{Obs} + Measured\ Diversions + Measured\ Export - Measured\ Import \pm \Delta Storage$ Note: unmeasured depletions and unmeasured return flow are not considered	CBRFC Website
Reclamation	**Unregulated flow**	Flow that would have occurred in the absence of upstream reservoir storage	Similar to method of CBRFC, except at Flaming Gorge, Navajo, and Lake Powell reservoirs	

We analyzed temporal and spatial patterns of Reclamation's estimates of natural flow at 29 inflow sites. Lukas et al. (2020b) described in detail the methods used to arrive at these estimates which are published in Reclamation (2020)'s *Colorado River Basin Natural Flow and Salt Data* database available at https://www.usbr.gov/lc/region/g4000/NaturalFlow/. These data are regularly updated, the most recent update being in January 2020. Natural flows estimated at 20 Upper Basin gages are calculated differently from Lower Basin main stem gages and from Lower Basin tributaries (Table S3-2). Prairie and Callejo (2005) described the method used to calculate natural flows since 1971, and this method uses measured change in reservoir storage and estimated evaporation. At Flaming Gorge and Lake Powell, transmission of reservoir water into and out of the surrounding bedrock (i.e., seepage) is also estimated. The volume of evaporation is based on published rates of evaporation multiplied by reservoir surface area or multiplied by available indices of "reservoir fullness." Estimates of evapotranspiration losses associated with irrigated agriculture are calculated using the modified Blaney-Criddle method that is based on air temperature, crop type, and area planted for each crop. As noted by Lukas et al. (2020b), Reclamation is considering replacing the modified Blaney-Criddle method with another, more accurate method. None of the Upper Basin states uses Blaney-Criddle in calculations of consumptive losses in providing their own estimates to the Upper Colorado River Commission, and thus UCRC estimates of consumptive losses associated with irrigated agriculture differ from those used by Reclamation in calculating natural flows.

In contrast, estimates of the natural flow of the Colorado River in the Lower Basin that are made at five mainstem sites are based on Reclamation's annual Water Accounting Reports (e.g., *Colorado River Accounting and Water Use Report: Arizona, California, and Nevada*) wherein evaporation from Lake Mead, Lake Mohave, and Lake Havasu and evapotranspiration losses from riparian forests are estimated, and diversions and return flows to irrigated areas and metropolitan areas are reported. In further contrast to estimation methods in the Upper Basin, no effort is made to report natural flows for Lower Basin tributaries, and actual measured flows of the Paria, Little Colorado, Virgin, and Bill Williams Rivers are used in CRSS and other models that rely on natural flow data. Similarly, no effort is made to estimate natural flows of the Gila River, and the Gila River is not represented in CRSS.

Table S3-2. Upper and Lower Basin flow naturalization by Reclamation (according to Prairie and Callejo, 2005)

	Upper Basin	Lower Basin
Observed Flow	20 USGS gaged sites	9 USGS gaged sites
Reservoir Regulation	- 8 Mainstem Reservoirs: Fontenelle, Flaming Gorge, Taylor Park, Blue Mesa, Morrow Point, Crystal, Navajo, and Lake Powell - 18 Non-mainstem Reservoirs	3 Reservoirs: - Lake Mead (Change in reservoir and bank storage) - Lake Mohave - Lake Havasu
Consumptive Uses and Losses (CUL)	- Irrigated Agriculture - Reservoir Evaporation (for 42 major reservoirs) - Stock ponds - Livestock - Thermal Power - Minerals - Municipal and Industrial - Exports/Imports	- Water use records from Decree Accounting Reports (U.S. Bureau of Reclamation, 2019) - Reservoir Evaporation (for three reservoirs) - Phreatophytes (ET)
Natural Flow	- Natural flow is calculated for all 20 sites.	- Natural flow is only calculated for 5 mainstem gages. - Historical gaged data are used for the other 4 gages on tributaries.

Reclamation (2020) estimates natural flows beginning in 1906, but the stream-flow gaging measurements that are the foundation of these estimates began at different times. For example, annual measured discharge at Greenriver, Utah (gage 09315000) beginning in 1895, near Ouray, Utah (gage 09307000) beginning in 1948, near Jensen, Utah (gage 09261000) beginning in 1950, and near Greendale, Utah (gage 09234500) beginning in 1951. Lukas et al. (2020b) summarize reclamation's method of extending records back to 1906

> Reclamation used multiple linear regression on the overlapping natural flows that had been calculated from gage records to derive equations to extend all the missing natural flows back to 1906. In 2006, taking advantage of 20 additional years of common natural flow estimates, Lee and Salas used multiple linear regression and nearest- neighbor methods to revise and update the 1983 extensions. They disaggregated the updated annual natural flows to monthly natural flows and incorporated a random error term to

represent the uncertainty in the estimates (Lee and Salas, 2006). Reclamation currently uses the Lee and Salas (2006) extended natural flow for all periods from 1906 until the start of the gage record at a given site.

Thus, the temporal trends in natural flow estimates for the early 20th century at many gages in the watershed are unavoidably affected by this computation method.

The logic of using natural flows as the critical input to water resource modeling has long recognized by hydrologists, at least since the time of LaRue. If one initiates modeling evaluation with natural flows, then one can consider a wide range of alternative strategies of spatial and temporal patterns of consumptive uses and losses. Additionally, many administrative agreements are based on understanding of the sources and quantities of water to the mainstem Colorado River. Assessment of the future flow of the Colorado River are better interpreted in a policy sense if one considers the natural flows available for distribution among competing stakeholders. However, there is significant uncertainty in calculating the estimated natural flows, and those uncertainties are amplified by the presence uncertainties in estimating reservoir evaporation or losses from irrigated agriculture. Tree-ring hydrology studies that extend estimates of natural flows more than a millennium begin with cross-correlation of tree ring widths with the natural flow data base. Should Reclamation revise its use of modified Blaney-Criddle to estimate evapotranspiration losses, then the entire tree-ring hydrology may have to be updated.

Reclamation's semi-decadal *Upper Colorado River Basin Consumptive Uses and Losses Reports* systematically provide the basic data concerning losses associated with irrigated agriculture, municipal and industrial activities, trans-basin diversions, and reservoir evaporation. These reports provide data as early as 1971, and the data are categorized by economic sector, headwater branch (i.e. Upper Mainstem, Green, and San Juan watershed), and state. Wheeler et al (2019) summarized these data for the three headwater branches for the 21st century. Unpublished earlier data are used by Reclamation to calculate natural flows for each gage for the period between the beginning of gaging at each site and 1971.

Sidebar 4: The Early 20th Century Pluvial

The first 24 years of streamflow shown in the Natural Flow Data Base, 1906 – 1929, are often referred to as the Early 20th Century Pluvial. Although several hydrologists and water resources engineers, including E. C. LaRue and Royce Tipton, strongly suspected that this period was unusually wet (Kuhn and Fleck, 2019), it was the 1976 report by Charles Stockton and Gordan Jacoby that first showed just how wet the period actually was when compared with the long-term average. Stockton and Jacoby concluded "the period of 1906 through 1930 was the greatest extended period of high runoff from the UCBR within the last 450 years. Consequently, any estimates of future flow that are based on periods of record that include this wet interval tend to be inflated" (Stockton and Jacoby, 1976). Subsequent reconstructions have confirmed Stockton and Jacoby's conclusion.

Based on the Reclamation Natural Flow Data Base (NFDB), the annual natural flows at Lee Ferry from 1906-2018 average 14.8 maf/yr. For the 1906-1929 pluvial period the average is 17.8 maf/yr. For the post-pluvial period of 1930 -2018, the average is 13.9 maf/yr. Change-point analysis shows this is a significant change (Wheeler et al., 2019; Blythe and Schmidt, 2018). Inspection of the NFDB also shows an interesting south to north trend where the average natural flows of the more southern Colorado River tributaries had higher natural flows when compared with the post-pluvial period. The flowing table shows the average annual natural flow of the pluvial period compared to the post-pluvial period from north to south:

River Segment	pluvial mean	post-pluvial mean	% Difference
Upper Green River	1.5 maf/yr	1.3 maf/yr	15%
Upper Colorado River	2.5 maf/yr	2.0 maf/yr	25%
San Juan River	2.7 maf/yr	1.9 maf/yr	42%
River above Lee Ferry	17.8 maf/yr	13.9 maf/yr	27%
Gila River**	1.5 maf/yr	1.0 maf/yr	50%

** The NFDB does not include the Gila River. The flows for the Gila River were estimated using a mass balance based on the reconstructed 1906-2010 mean of 1.1 maf/yr and estimated natural flows of the Gila River for 1906-1930 by the Bureau of Reclamation published in HD 419 (1947) of 1.5 maf/yr.

Sidebar 5: Evaluating the Tree-ring Flow Reconstructions at Lees Ferry

In this study, to better consider the natural variability, we examined the latest versions of tree-ring reconstructions at Lees Ferry (Table S5-1) based on the following studies and compared them together to select the best reconstruction for conducting the purpose of this study.

- Woodhouse et al. 2006, Lees A series (W06)[1].
- Meko et al., 2007 (M07).
- Meko et al., 2017 most skillful model (M17-SK).
- Meko et al., 2017 longest model (M17-L).

In the generation of these reconstructions, natural flow data from the Bureau of Reclamation were considered the "observed flow". However, different calibration periods and natural flow estimates have been considered in each estimate. The most recent studies (i.e. M17-SK and M17-L) used the most recent and longest record of observed flow to calibrate those models, and this calibration period includes the 21st century drought and has the lowest mean flow in comparison with the observed flow used in the W06 and M07 models. Different regression approaches have been used in these reconstruction models, all of which tend to underestimate extreme events (Esper et al., 2005; Meko, 1997; Meko et al., 2007). In an effort to fully consider the potential for extremely large and extremely small years of runoff, Robeson et al. (2020) bias-corrected the M07 reconstruction (hereafter referred to as M07-BC) using a quantile mapping procedure (Figure S5-1). They showed that several extreme events from the original M07 tree-ring reconstructed flow were more intense than formerly thought. The 1100s megadrought, which is the largest in the 1200+ year record, was adjusted to have been even more extreme (drier and longer) after bias correction. In addition, a period was found in the early 1600s that matches early 20th-century pluvial, which was once considered the wettest period in the last 1200+ years. Robeson et al. (2020) suggested the use of a bias-corrected reconstruction for comparing reconstructed values directly to observed values and indicated that the original reconstructions are inappropriate for such a comparison (Robeson et al., 2020). Because Robeson et al. (2020) had only applied their method to M07, we applied the correction to the more skillful and recent

[1] Note that Woodhouse et al. provided four models for streamflow at Lees Ferry. Lees A is included in the Treeflow website https://www.treeflow.info/content/colorado-r-lees-ferry-az, which reports that Lees-A is judged by the authors (Woodhouse et al.) to be the best for replicating the characteristics of the observed record.

M17-SK reconstruction from Meko et al. (2017). The bias corrected version we developed is referred to as M17-SK-BC.

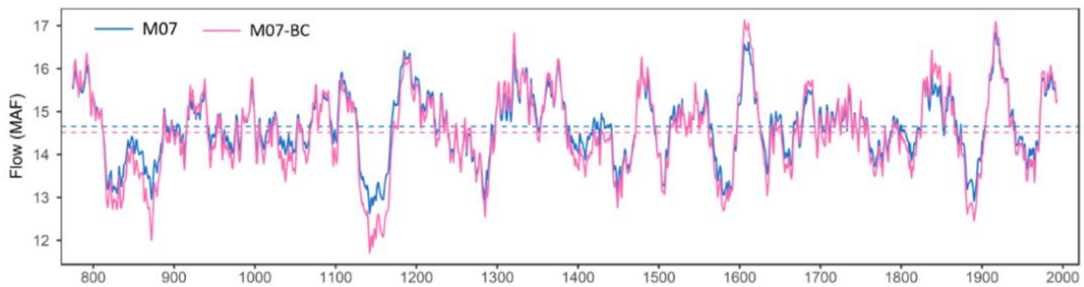


Figure S5-1. 25-year moving averages of the Colorado River at Lees Ferry reconstructed flow (Data from Robeson et al., 2020)

The distribution of the annual observed and reconstructed flows during the overlapping time period, 1906-1997, show a high degree of similarity between the set of reconstructions and observed flow (Figure S5-2).

To evaluate the performance of each reconstruction model, we used statistical metrics that quantified differences, or measured the goodness of fit, between observations and model results. These included

- Coefficient of Determination (R^2),
- Nash-Sutcliffe Efficiency (NSE), and
- Root Mean Square Error (RMSE).

Both R^2 and NSE are dimensionless measures that provide an assessment of the model performance. The coefficient of determination (R^2) describes the proportion of the total variance in the observed data that can be predicted by the model. It ranges from 0 to 1, with higher values indicating better agreement (Legates and McCabe Jr, 1999). Nash-Sutcliffe Efficiency (NSE), proposed by Nash and Sutcliffe (1970) is an alternative goodness-of-fit index that represents an improvement over the R^2 index for model evaluation. It ranges from $-\infty$ to 1, with higher values indicating better agreement. However, it is also valuable to quantify the unscaled error in the same measurement units as the data. To this end, Root Mean Square Error (RMSE), which describes the difference between the observed and modeled data, was also considered in model assessments (Legates and McCabe Jr, 1999).

These metrics were calculated and are shown in each 1:1 scatterplot (Figure S5-3 a-f). According to this figure, M17-L performed poorly (NSE = 0.40, R_2 = 0.44, RMSE = 3.31 maf) while the other models had acceptable performance. M17-SK with NSE = 0.82 and RMSE =1.815 maf, then M17-SK-BC, W06, M07-BC, and M07 were the most successful models in modeling the observed flow. A comparison between the original M07 reconstruction and its bias-corrected one (M07-BC) indicated that the Robeson et al. (2020) bias-correction has improved the NSE (0.766) and R_2 (0.777) over the M07 reconstruction. However, this bias-correction approach that we implemented for M17-SK did not meaningfully improve the M17-SK reconstruction (Figure S5-3 e). NSE was slightly degraded while R_2 slightly improved, but not in any meaningful way.

A further measure of similarity is obtained from the quantile-quantile relationships between the distribution of the observed and reconstructed values during the overlapping time period (Figure S5-4 a-f). Quantile-Quantile plots such as these do not compare the individual observed versus model values. Rather, these plots compare the distribution of observed versus model values. The sets of observed and modeled values are each ranked from smallest to largest and the pairs of ranked values plotted. Specifically, the pair of two smallest values give the first point, the pair of two second smallest values give the second point and so on. The rationale for this approach is that once data are ordered or ranked (smallest to largest), the individual values are interpreted for their position in the distribution, or their quantile. The lowest of the ordered values has the lowest probability in the cumulative probability distribution, as the probability of a new value being lower is small. Probabilities increase as one moves up the ranking. A straight 1:1 line in this quantile-quantile plot of ordered data indicates that the two distributions are the same, even though individual values at a specific point in time may be different. In the quantile-quantile plots, we used the NSE metric to quantify how similar the distributions are for tree ring versus observed flows. The improvement going from M07 to M07-BC from Robeson et al. (2020) is also evident in NSE for the quantile-quantile plot. There is also an improvement in the quantile plot NSE going form M17-SK to M17-SK-BC that achieved by applying the Robeson et al's bias correction method. However, it could be argued that these improvements are by construction. The adjustment of flows to remove distributional bias forces the quantile-quantile plot to become close to straight. Some might argue that this is a shortcoming. There is no reason to assume that the shape of the distribution in the past (tree-ring reconstructions) was the same as the shape of the present (observed) distribution. However, we do note that quantile based bias removal is widely used in the downscaling of climate models, where uncorrected model outputs have considerable bias, and this assumption of similar distributions is made (Li et al., 2010; Gudmundsson et al., 2012; Teutschbein and Seibert, 2012; Chen et al., 2013). On the basis of this, in our evaluation, we do not feel that the M17-SK-BC improvements we made using Robeson et al. (2020) method are an improvement over M17-SK and have not used M17-SC-BC further in this paper.

Table S5-1. Latest versions of tree-ring reconstructed flow at Lees Ferry

Characteristics	Woodhouse et al., 2006		Meko et al., 2007			Meko et al., 2017			
	Observed Flow	**W06**	Observed Flow	**M07**	**M07-BC***	Observed Flow	**M17-SK****	**M17-SK-BC**	**M17-L*****
Period	1906-1995	1490-1997	1906-2004	762-2005	762-2005	1906-2014	1416-2015	1416-2016	1116-2014
Mean flow (MAF)	15.221	14.669	15.025	14.655	14.517	14.81	14.331	14.336	14.281
Median flow (MAF)	14.948	14.969	14.85	14.827	13.823	14.54	14.031	13.881	13.995
Minimum MAF)	5.57	1.693	5.62	2.322	5.13	5.44	5.142	5.892	7.537
Maximum (MAF)	25.275	25.379	25.231	24.311	25.347	24.19	24.891	24.996	22.968

*BC: Bias-Corrected ** SK: Skillful Model *** L: Longest Model

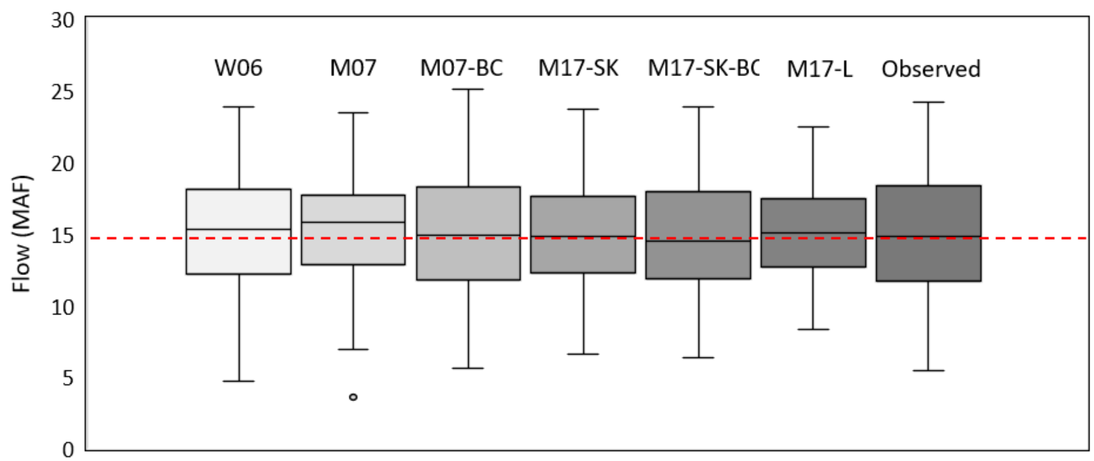


Figure S5-2. Distribution of the Colorado River at Lees Ferry streamflow based on Observed and various tree ring reconstructed flows, 1906-1997. Red dashed line is the long-term mean of observed flow from 1906 to 2017.

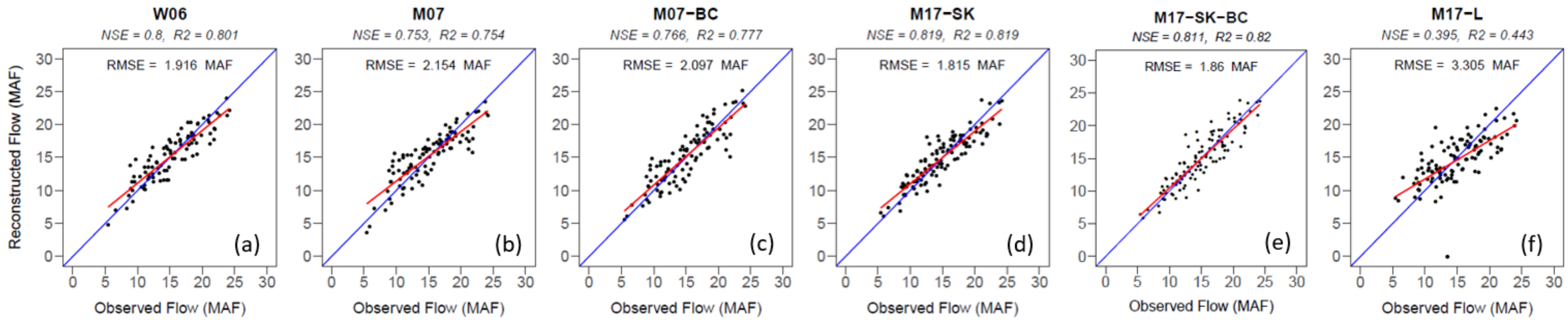


Figure S5-3. Relationship between observed and various reconstructed flow at Lees Ferry (R_2, Nash Sutcliffe Efficiency (NSE), and RMSE). The March 2019 version of Lees Ferry natural flow from 1906 to 2017 was used in these comparisons.

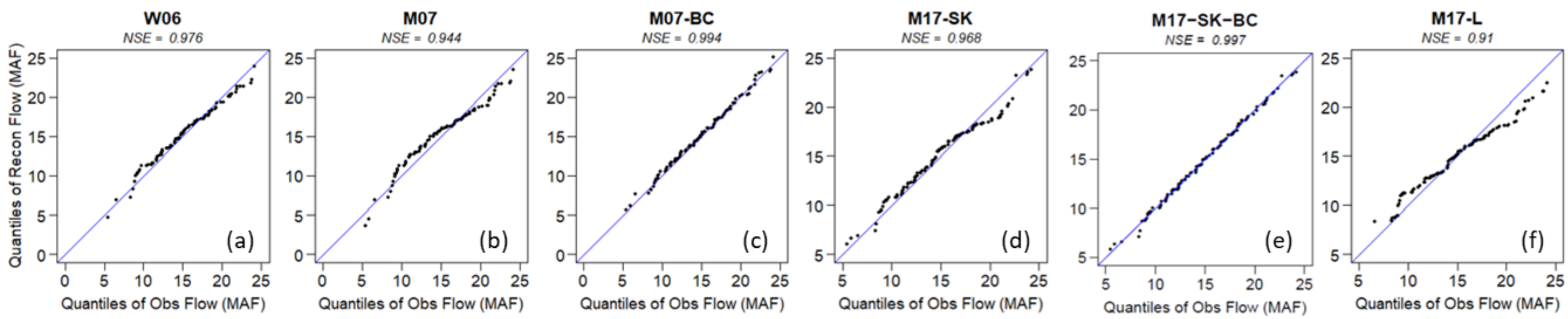


Figure S5-4. Quantile-quantile relationship between observed and various reconstructed flow at Lees Ferry (Nash Sutcliffe Efficiency (NSE)). The March 2019 version of Lees Ferry natural flow from 1906 to 2017 was used in these comparisons.

Figure S5-5 shows Lees Ferry reconstruction "bar codes" representing the dry periods as black bars, in which the 10-year moving average is below the long-term mean of that reconstruction, and wet periods as white bars. Analysis of bar codes indicates that the overall patterns of the dry and wet periods are very similar although different data and methods were used to generate them. Therefore, all the evaluated reconstructions in this study generally agree in representing wet versus dry periods and each of them can be considered to evaluate the pattern of these periods experienced in the Colorado River.

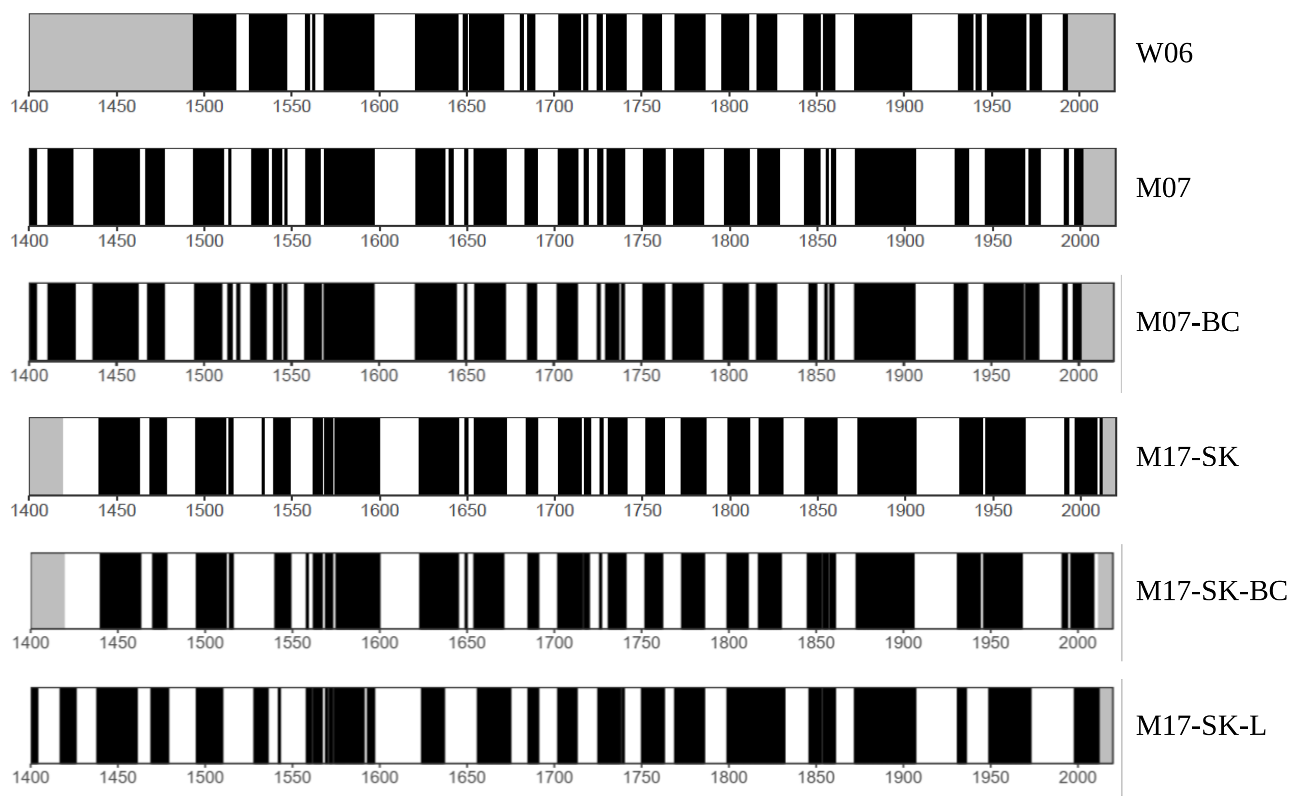
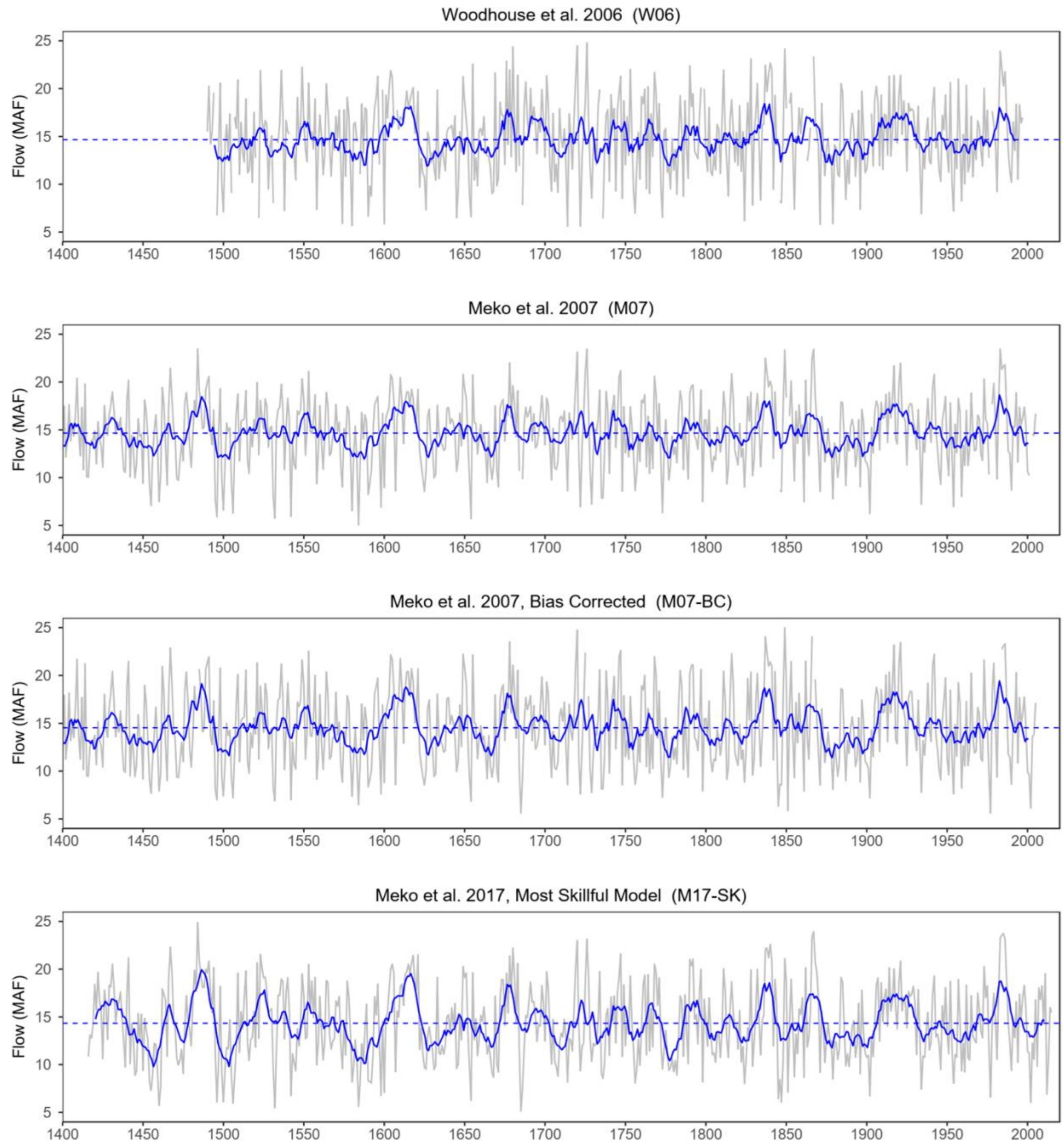


Figure S5-5. Lees Ferry reconstruction "bar codes". Black and white bars represent dry and wet periods, respectively.

Despite agreement among reconstructions on the patterns of wet and dry periods (Figure S5-5), estimates of the magnitude of annual flows are sometimes different (Figure S5-6). As discussed by Robeson et al. (2020), a comparison between M07 and M07-BC indicated that the extreme events from the bias-corrected reconstruction (i.e. M07-BC) are more intense than the original one (i.e. M07). However, the extreme events from M07-BC are not as intense as those from M17-SK reconstruction. Most of the extreme events from M17-SK are more intense than the extreme events from the other reconstructions (Figure S5-6). This indicates that the most skillful model from Meko et al. (2017), i.e. M17-SK reconstruction, estimates the historical megadroughts more severe than the other reconstruction models. It is plausible that events similar to these megadroughts occur in the future.



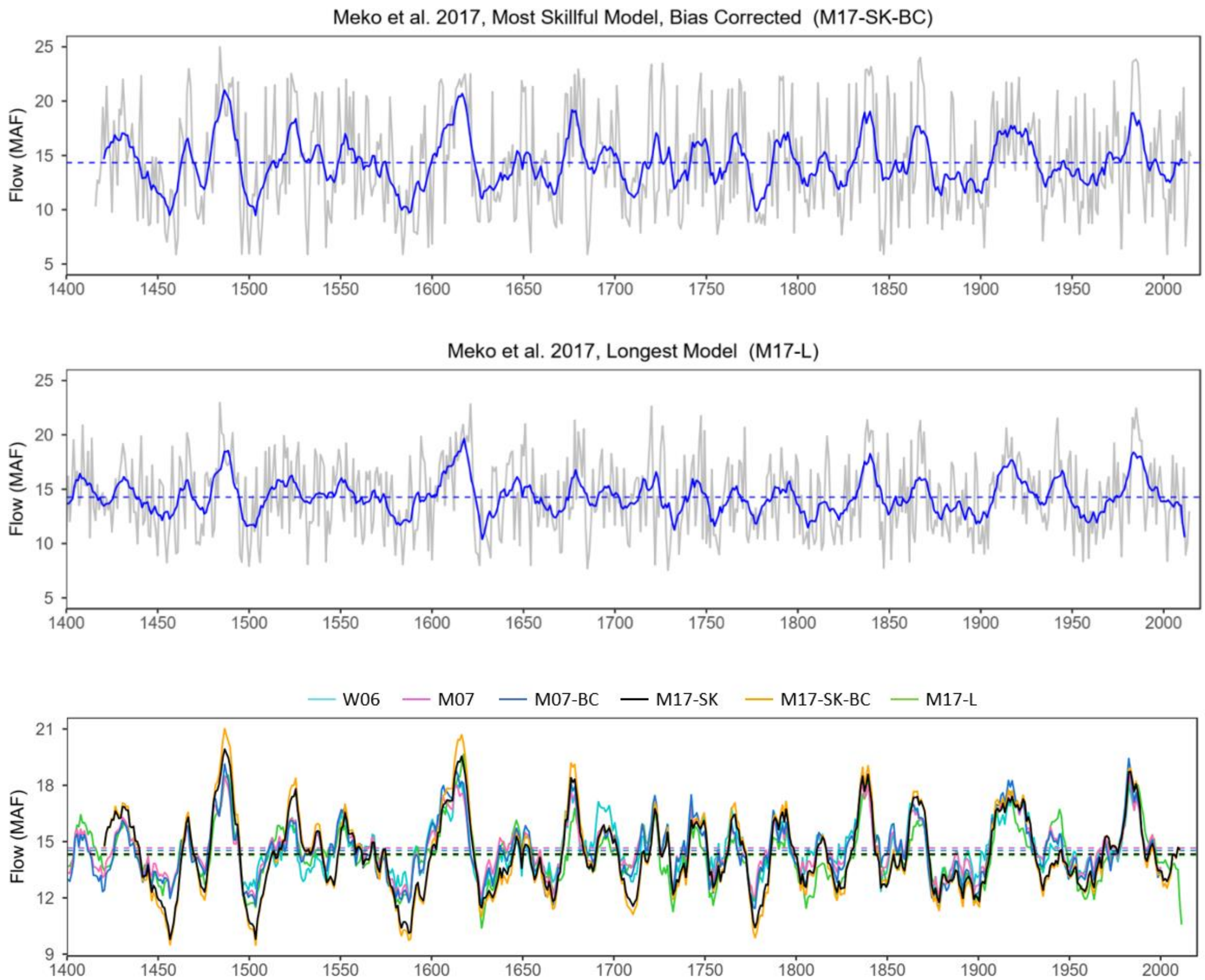


Figure S5-6. Time series of reconstructions (gray lines) along with 10-year moving average (blue lines).

All the reconstructions discussed above are the most recent ones that used a longer calibration period (91, 99, and 109 years in W06, M07, and M17, respectively) than earlier reconstruction studies. From this, we infer that these recent studies are likely to be more reliable and each one may have some useful information about the past. For example, Meko et al. (2012) showed that events similar to the severe and sustained mid-1100s drought estimated in the M07 reconstruction (Figure S5-7) may occur once in every 400-600 years (Meko et al., 2012). On the other hand, M17-SK shows more severe droughts than the W06 and M07.

These tree ring reconstructions all appear to be plausible estimates of the past streamflow with varying levels of uncertainty, but in our assessment, based on the statistics above, M17-SK is best. In the current study, based on the above analyses, the M17-SK reconstruction (Meko et al., 2017) was used in the analysis below.

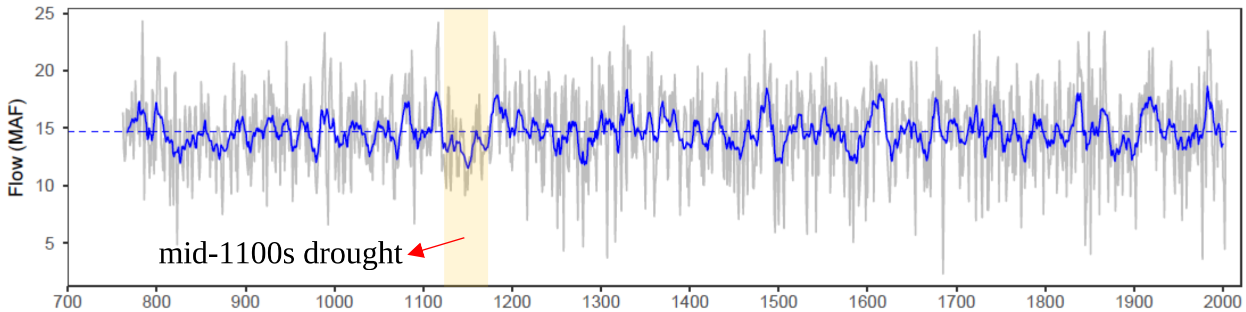


Figure S5-7. M07 tree-ring reconstructed flow (gray line) of the Colorado River at Lees Ferry, 762-2005, and 10-year moving average (blue line).

Sidebar 6: Effects of Climate-related Forest Changes on Runoff

Forests in the Colorado River Basin have changed substantially in this century. A large part of the Colorado River Basin is forested (Figure S6-1.a), most notably in the high elevation regions where much runoff originates (Lukas and Payton, 2020). Forest changes are driven by high tree mortality due to a combination of insects, wildfire, and moisture deficits (van Mantgem et al., 2009). Recent research in headwater catchments shows that forest disturbance and recovery may impact streamflow, and data from the US Forest Service's Forest Inventory and Analysis (FIA) program allows us to quantify the extent of forest change throughout the Colorado River Basin. This sidebar describes how forests have changed in the Colorado River Basin and summarizes the implications for streamflow, based on FIA data and a review of the literature. Our principal finding is that forests have changed substantially in the past two decades, particularly in high-elevation headwater catchments that contribute most of the basin-wide streamflow. Contrary to the common assumption that reductions in forest cover result in reduced evapotranspiration and increased streamflow, recent research demonstrates that this is not always true in the semi-arid western US, where forest cover loss sometimes results in decreased runoff.

The interaction between precipitation and forests affects the proportion of precipitation that runs off versus is lost to evapotranspiration. Direct effects of tree cover include interception of precipitation and transpiration of soil moisture. Tree cover indirectly affects hydrologic partitioning by altering energy balances, specifically by shading the soil and snowpack. Most of the existing knowledge about the relationship between forest cover and streamflow arose from experiments where watersheds were subjected to clearcut timber harvests, and streamflow subsequently increased due to decreased evapotranspiration (e.g., Troendle and King, 1985). However, naturally occurring disturbances throughout the western US have exhibited different post-disturbance vegetation patterns and streamflow responses than those observed following experimental clearcuts (Goeking and Tarboton, 2020).

Recent observations within the Colorado River Basin provide evidence that forest disturbances can affect streamflow via effects on snow accumulation as well as evapotranspiration from trees, surviving vegetation, snowpack, and soil. Following tree mortality in study areas in the Upper Basin, transpiration from trees decreased and maximum snow accumulation increased, as expected (Biederman et al., 2014). However, a reduced forest canopy has also allowed more sunlight to reach the snowpack and soil, driving increased snowpack sublimation, soil evaporation, and transpiration from post-disturbance vegetation, which collectively can offset or even overcompensate for decreased canopy transpiration and increased snow accumulation, leading to a net decrease in available runoff (Biederman et al., 2014; Biederman et al., 2015; Guardiola-Claramonte et al., 2011; Penn et al., 2016). These studies confirm that forest disturbances not only affect runoff, but also can decrease water yield.

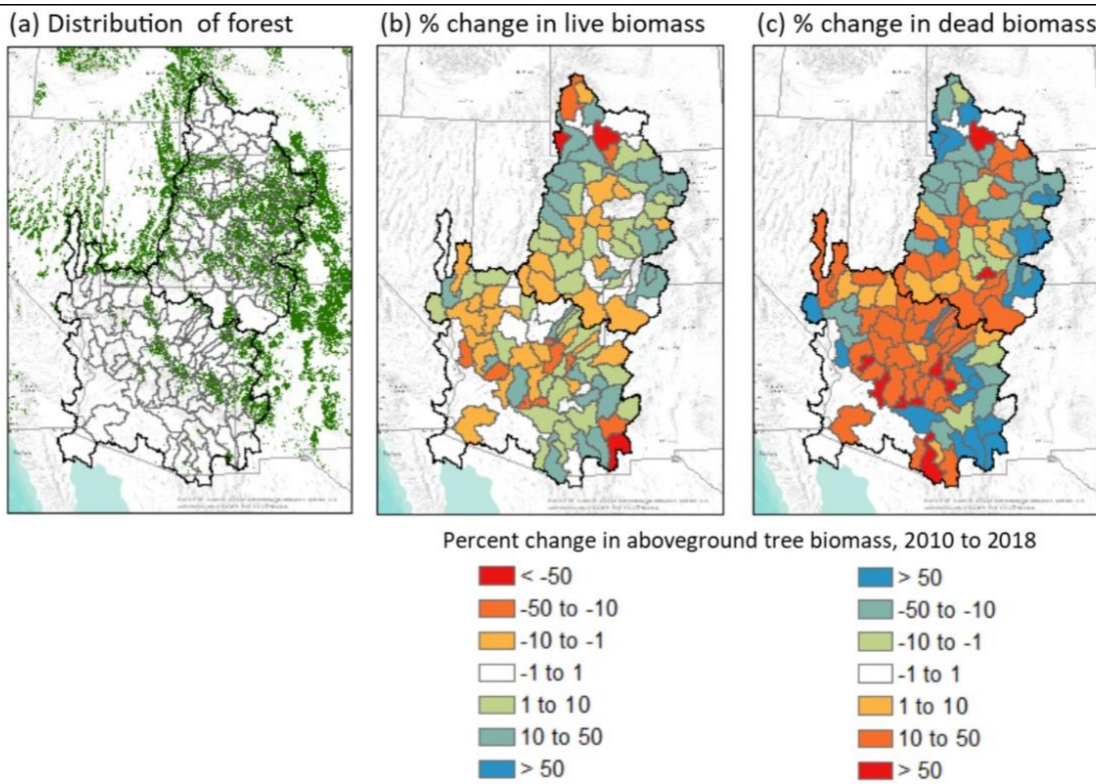


Figure S6-1. Forest extent and density in the Colorado River Basin. (a) Distribution of forests (green areas), defined as areas with at least 10% cover of trees as delineated in the 2016 National Land Cover Dataset's tree canopy cover layer (Yang et al., 2018). (b and c) Percent change in aboveground tree biomass between the 2018 and 2010 analysis periods summarized at the level of 8-digit Hydrologic Unit Codes (USDA, 2020). (b) Percent change in aboveground live tree biomass. (c) Percent change in aboveground dead tree biomass. Colors in (b) and (c) are scaled so that tree mortality (decreasing live tree biomass and increasing dead tree biomass) are both shown in warm tones, while blue indicates increasing live tree biomass and decreasing dead tree biomass.

Warmer temperatures in the future are expected to continue causing vegetation changes in the Colorado Basin both directly, via increased temperatures and drought stress (McDowell et al., 2016), and indirectly, via increased likelihood of insect epidemics (McDowell et al., 2011) and severe wildfire (Sankey et al., 2017). These changes are expected to include altered forest structure due to shifting species' distributions (Buma and Livneh, 2015) and, in severely disturbed areas, conversion from forest to nonforest land cover (i.e., shrublands or grasslands, Parks et al., 2019). In the San Juan River basin, failing to account for indirect effects of climate on forest vegetation could lead to overestimation of basin-wide runoff by as much as 10% by the end of the century (Bennett et al., 2018). Although future forest disturbances will decrease canopy transpiration (Buma and Livneh, 2015), increased transpiration by surviving vegetation may offset any gains in available water (Livneh et al., 2015b; Bennett et al., 2018). Future forest disturbances will affect not only water but also sediment yield. Sedimentation rates based on wildfire projections are expected to increase by at least 10%, and by as much as 100% in many watersheds, by 2050 (Sankey et al., 2017). Such simulations underscore the importance of accounting for dynamic vegetation and land cover in simulation models in order to paint a more accurate picture of future streamflow (Bennett et al., 2018).

The studies cited above focus on small subsections of the Colorado River Basin. Forest change throughout the entire watershed can be summarized using data collected by the US Forest Service's (USFS's) Forest Inventory and Analysis (FIA) program (see fia.fs.fed.us). FIA serves as the strategic forest monitoring program for US forests; is mandated by multiple legislative acts as an ongoing, permanent monitoring program; and provides ground-truth data for maps based on remote sensing datasets (e.g., Figure S6-1.a). The earliest incarnations of the program began with the passage of its initial enabling legislation, the McSweeney-McNary Forest Research Act of 1928. After several decades of forest monitoring conducted by disparate USFS entities, the Agriculture Research, Extension, and Education Reform Act of 1998 (i.e., the 1998 Farm Bill) mandated a nationally consistent, probabilistic sample, with a standardized set of measurements across all forest types and land ownership categories, and publicly available data via online datasets, analytical tools, and regularly published reports. The FIA sample design is optimized for broad-scale estimation of land cover characteristics based on its nationwide network of permanent monitoring plots, with a mean grid spacing of 5 km; each plot in the western US is measured every 10 years (Bechtold and Patterson, 2005).

The Colorado watershed includes approximately 11,000 FIA plots. Because the Upper and Lower Basins have different extents and densities of forest cover types, the two basins are characterized separately here using data from the online estimation tool EVALIDator (USDA, 2020), which allows summaries by Hydrologic Unit Code (HUCs). The data in Table S6-1 and

Figure S6-1 are based on FIA data collected between 2001 and 2018 (USDA, 2020). Nominal years (2010 and 2018) represent published FIA estimates of forest characteristics across multiple measurement years (Bechtold and Patterson, 2005). Data reported in 2010 represent measurements from 2001 to 2010, and 2018 data represent measurements collect between 2009 and 2018 (USDA, 2020).

Table S6-1. Changes in forest structure in the Upper and Lower Colorado River Basins during 2018 compared to 2010.

	Percentage change	
	Upper Basin	Lower Basin
Total forest area	1.0%	-0.9%
Tree growth, by volume[1]	-15.2%	-5.4%
Aboveground biomass of live trees	-7.4%	-2.8%
Aboveground biomass of dead trees	27.0%	-5.7%

[1]Growth is mean annual volume of new growth on live trees, averaged over the preceding 10-year period.

Vegetation changes throughout the Colorado River Basin during the past two decades have been characterized mainly by changes in forest density rather than area of forest. While the extent of forests has barely changed between 2010 and 2018, the structure of those forests has changed, demonstrated by declines in live tree biomass and rates of tree growth (Table S6-1, indicated by negative values; Figure S6-1.b). Dead tree biomass in the Lower Basin has decreased, while it has increased in the Upper Basin due to ongoing tree mortality since 2010 (Table S6-1; Figure S6-1.c). Forests in both basins experienced high tree mortality due to a combination of drought, insects, and disease since the turn of the century, and this mortality peaked in the Lower Basin prior to 2010 (Ganey and Vojta, 2011; Shaw et al., 2005). Increases in mortality and dead tree biomass, and declines in growth and live tree biomass, have hydrologic ramifications. First, decreased growth corresponds to decreased transpiration from the canopy, although subcanopy evapotranspiration may have increased to offset the decreased canopy transpiration. Second, increasing dead tree biomass in the Upper Basin contributes fuel that may influence the severity of future wildfires, which in turn are linked to runoff and sedimentation.

FIA data illustrate that the forests of the Colorado River watershed have changed in ways that may be obscured by thematic land cover maps, and recent research summarized above suggests that such changes are already affecting streamflow. Given changes in forest density in the Colorado watershed, the ways in which forests influence the partitioning of precipitation into runoff versus evapotranspiration may be better explained by forest density metrics such as biomass and growth than by the metric of forest extent. Substantial changes in forest density influence the partitioning of precipitation into runoff versus evapotranspiration. Contrary to the conventional wisdom that decreased forest cover leads to increased streamflow, which was developed in small, relatively wet watersheds with experimental clear-cut timber harvests, forest disturbance in the semi-arid southwest may lead to decreased streamflow (Goeking and Tarboton, 2020). In the Upper Basin, the observed decreases in live forest biomass are consistent with post-disturbance decreases in streamflow in the literature examined by Goeking and Tarboton (2020). Thus, these forest biomass changes may be responsible, at least in part, for diminished streamflow originating in the Upper Basin over the last two decades. Although the studies cited here pertain to natural disturbances, they suggest that intentional management to reduce the density of upland vegetation, with the intent of increasing streamflow, may be ineffective or even counterproductive.

Simulations of future water supply will likely be more realistic if those simulations account for the substantial effects of ongoing forest disturbances on streamflow. Physically-based models are capable of representing the potentially counteracting indirect effects of forest disturbance and recovery on streamflow, but empirical models have not demonstrated the capability to reproduce observations of decreased streamflow following disturbance (Goeking and Tarboton, 2020). Examples of such physically-based models include the Distributed Hydrology-Soil-Vegetation Model, or DHSVM (e.g., Livneh et al., 2015b); the Regional Hydrologic Eco-Simulation System, or RHESSys (e.g., Bart et al., 2016); ParFlow (e.g., Penn et al., 2016); and the Variable Infiltration Capacity model, or VIC (e.g., Bennett et al., 2018). Bennett et al. (2018) provide an excellent example of the additional datasets and modeling decisions required to account for future forest disturbances when making streamflow projections within the Colorado River Basin.

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