Exploring drought vulnerability in the Gunnison basin

Thesis presented for the degree of Master of Science

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Abstract

A steady streamflow of the Colorado River is critically important for the water supply of the American Southwest. The recent megadrought has depleted reservoir storages while the imbalance between water supply and demand is further increasing. Runoff from the West Slope Basins, which are alpine headwaters of the Colorado River, is affected by climate change. This worsens the region's downstream susceptibility to water shortages that cause economic and ecological damage. However, which factors drive agricultural shortages on a detailed scale have remained not entirely clear. Based on the water accounting model StateMod, we present a shortage analysis of the Gunnison Basin using the observed historical streamflow record, augmented with two synthetic ensemble datasets. One ensemble is used to contextualize the historical record in a multitude of similar streamflow samples, while the other adjusts the streamflow data to account for plausible climate-change scenarios. Our results indicate that water rights drive shortage vulnerability and that drought vulnerability is increases in climate-change scenarios.

Content

Introduction

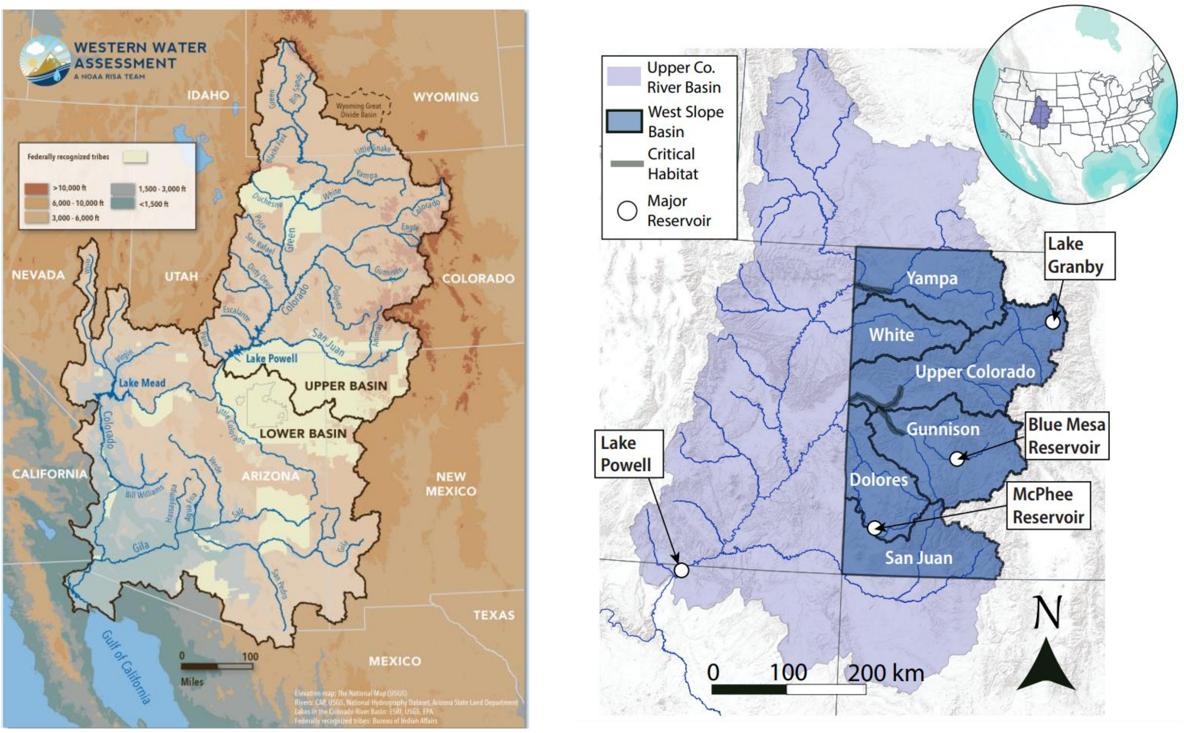

Figure 1 (a) Overview of the Colorado River Basin, highlighting the division into the Upper Basin and Lower Basin (reprinted from Lukas & Payton, 2020); (b) Geography of the Upper Basin, with the West Slope subbasins highlighted (reprinted from Gold et al., 2024).

The Colorado River is the critical water supply of the arid Southwestern United States and northern Mexico, providing water for 40 million people in the area (Bureau of Reclamation, 2012; Schmidt et al., 2022). It serves as the main water source for agricultural, hydroelectric and touristic purposes in the region. Periods of drought lead to water shortages across these sectors and cause economic as well as ecological damage.

In recent decades, the increasing imbalance between supply and demand has significantly decreased water storage reservoir levels (Lukas & Payton, 2020). However, the main rules and regulations that govern the complex water system date back to 1922 and 1944, when future streamflow volumes were overestimated (Wheeler et al., 2022). The complex hierarchy between water users, combined with uncertainties around future hydrologic conditions, motivates exploratory studies into the drought vulnerability of the river basin.

The Colorado River Basin is divided into the Upper Colorado River Basin and Lower Colorado River Basin as shown in Figure 1a (Lukas & Payton, 2020). The Upper Basin contributes to a much larger share of runoff compared to the Lower basin. The West Slope subbasins, located within the Upper Basin as highlighted in Figure 1b, contribute more than 60% of annual inflow to Lake Powell, the largest water storage reservoir in the Upper Basin (Gold et al., 2024; Salehabadi et al., 2020). The relative share of the West Slope basins in the total water supply of the Colorado River Basin make them critically important for the whole water system and therefore especially relevant to research.

Precipitation in the Colorado River Basin is governed by the region's elevation profile. Mountainous areas collect the vast majority of annual precipitation as snowfall during the winter. The warming temperatures of spring cause snowmelt that provide the basin with large volumes of runoff. The mountainous headwaters are primarily located in the West Slope basins, of which the Upper Colorado has the largest contribution to Lake Powell inflow, followed by the Gunnison basin (see Figure 2a) (Gold et al., 2024).

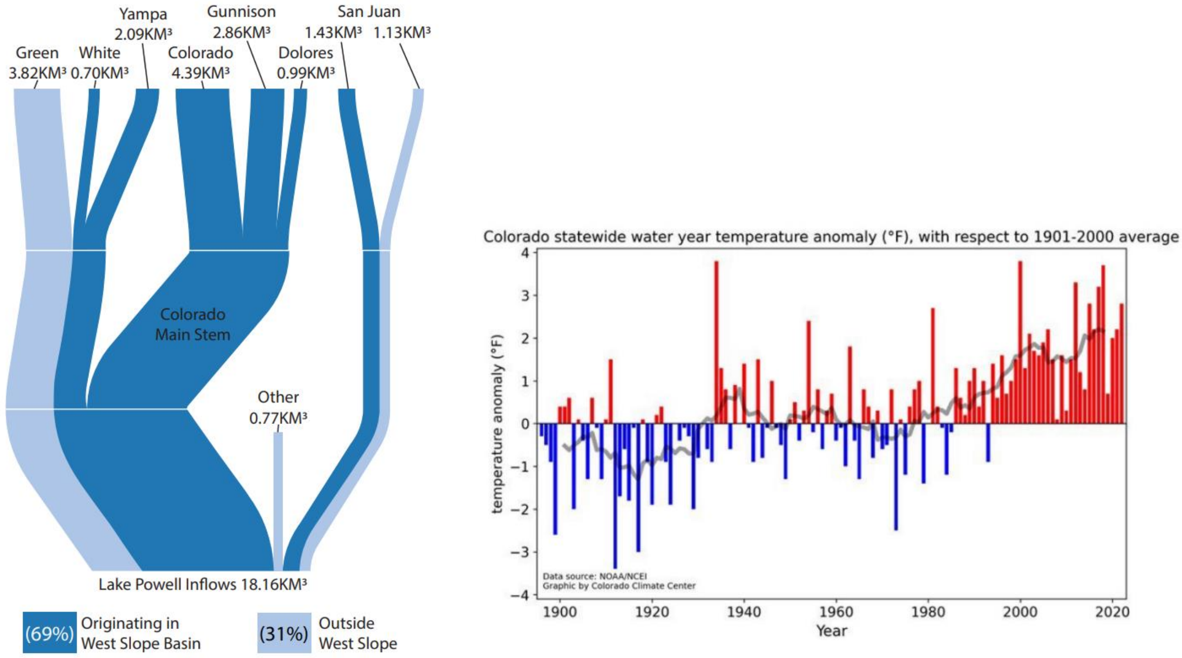

Figure 1 (a) Diagram of average annual Lake Powell inflow, separated by source region, shows that West Slope basins account for circa 69 percent (reprinted from Gold et al., 2024); (b) Historical temperature deviation from the long-term average shows recent warming trend (reprinted from CWCB, 2023).

Persistent drought conditions in the 21st century, combined with effects of climate change, have led to increasing concerns about the future stability of the Colorado River streamflow (Lukas & Payton, 2020; Salehabadi et al., 2020). Severe drought conditions have occurred in the historical record before, but warming temperatures (see Figure 2b) and increased water demand exacerbate drought impact (MacDonald, 2010; Tillman et al., 2020; Udall & Overpeck, 2017). Because there are irreducible uncertainties in the future of the water basin, originating for instance from hydroclimatic variability or unpredictable policy changes, research approaches must deal with these “deep uncertainties” (Gupta et al., 2024; Kwakkel et al., 2016). One such methodology is to use an ensemble of scenarios to inform about possible future states of the system, based on the framework of exploratory modelling (Bankes, 1993; Kwakkel & Pruyt, 2013).

Salehabadi et al. (2022) investigated drought vulnerability in the Colorado River Basin by resampling historical droughts. These simulated future scenarios inform about possible future hydrologic conditions. They report scenarios where Lake Powell reservoir levels drop below the minimum required for hydropower generation.

A recent study by Hadjimichael et al. (2023) introduced a scenario discovery framework and applied it to the Upper Colorado basin, one of the West Slope basins. The authors presented methods to explore the historic drought vulnerability of the Upper Colorado basin, which are well-suited for application in the context of the Gunnison subbasin.

This contribution will explore what factors drive water shortages and drought vulnerability in the Gunnison basin. The impact of historical hydrologic conditions on water users is examined with regard to streamflow, water demand, shortages and diversion rights. Complementary to the historical streamflow data, two sets of synthetic streamflow ensembles are used. A baseline ensemble expands the historical record with alternate realizations that have similar hydrologic properties. A second ensemble is used to evaluate the effects of possible future climate scenarios on the basin's drought vulnerability and to assess the basin's susceptibility to climate change. Understanding of the Gunnison basin helps water resource managers to plan for future hydrologic conditions, to manage water supply and demand, and to assess the governing rules and regulations.

Methodology and Data

Water allocation model

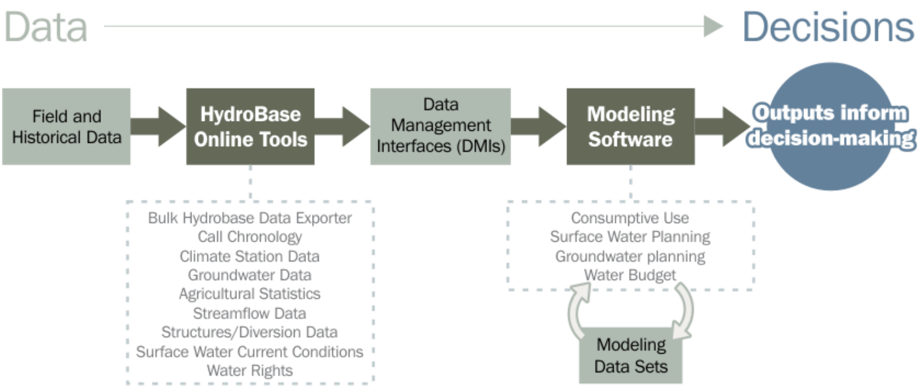

Figure 3 Flow-chart of modelling process (reprinted from CDSS).

In this study, a modelling toolset from the State of Colorado is used. Streamflow data, along with water rights, operating rules and basin structures are the input features to model the Gunnison's water supply, demand and shortage. The model output is then used to visually analyze what factors influence drought vulnerability and explore the impact of climate-change scenarios on the basin. The general flow of data input to output is schematically shown in Figure 3 (reprinted from CDSS).

The observed historical record of natural streamflow ranges from 1909 to 2013. This dataset covers annual streamflow of five outlet nodes of all West-Slope basins: Upper Colorado, Gunnison, Yampa, White and Southwest (the combination of San Juan and Dolores). The here presented work focusses on the Gunnison subbasin.

Water management in Colorado is informed by Colorado's Decision Support Systems (CDSS), which are developed by the Colorado Water Conservation Board (CWCB) and the Colorado Division of Water Resources (DWR). CDSS is a collection of databases, software and models, such as HydroBase, StateCU and StateMod, to study river basins and inform policymaking.

HydroBase is Colorado's database containing relevant river basin properties, including water rights, structures and diversions. Agricultural statistics, irrigation areas and surface water conditions are also collected in this database. The State of Colorado's Stream Simulation Model (StateMod) is a water allocation and accounting model that is used to asses management policies. On daily or monthly timescale, the model can simulate water supply, demand and shortage, based on streamflow data, user's water right and the river basin's structures and operating rights. StateCU is the model that accounts for agricultural irrigation and other consumptive water use.

Direct Diversion Rights

A water right allows a user to divert a certain volume of water (decree in cubic feet/second) with a specified priority (Admin number). “First in time, first in right” is the original water right policy under the Law of the River, the basin’s guiding legal framework. This means that seniority is based on “the earliest date of diversion or storage for beneficial use” (Lukas & Payton, 2020). Water rights can be sold and inherited. Senior water rights holders are last to be shorted during drought, while junior rights holder are first to be cut off from water supply.

Within CDSS, a ‘direct diversion rights’ table contains the current state of water rights and relates decree and administration number to a specific user ID. A user can have multiple water rights of varying decree and administration number, resulting in a complex hierarchy of diversion rights.

CDSS provide several geographical attributes of the Gunnison subbasin (CDSS). Each subbasin is divided into multiple water districts for management purposes. These districts can be utilized to spatially group water users and obtain more detailed spatial aggregations. Irrigated land polygon data is available with several attributes, among which are crop type and user ID specification. This is a relevant data, since the majority of consumptive water usage is attributed to agriculture (CWCB, 2023).

Synthetic ensemble data

Gold et al. (2024) presented a novel method of generating synthetic streamflow data using a hidden Markov model (HMM). In their workflow, the generated streamflow data is fed to StateMod to model drought vulnerability of the West Slope basins. By repeating the data generating process, an ensemble of streamflow data is produced that aims to better represent the basin’s hydroclimate. The ensemble consists of 1000 streamflow records over a 105-year range.

Figure 4, reprinted from Gold et al. (2024), shows a comparison of the historical streamflow data with the synthetic data, across the West Slope basins. The synthetic data includes more extreme values, as indicated by the larger range between the 10^{th} and 90^{th} percentiles. Simultaneously, it retains the original trend of monthly streamflow, as indicated by the similar historical and synthetic mean values. In this study on the Gunnison subbasin, water shortage is further investigated using a 10% subset of the original ensemble data. The size of the ensemble was reduced to limit computational demands.

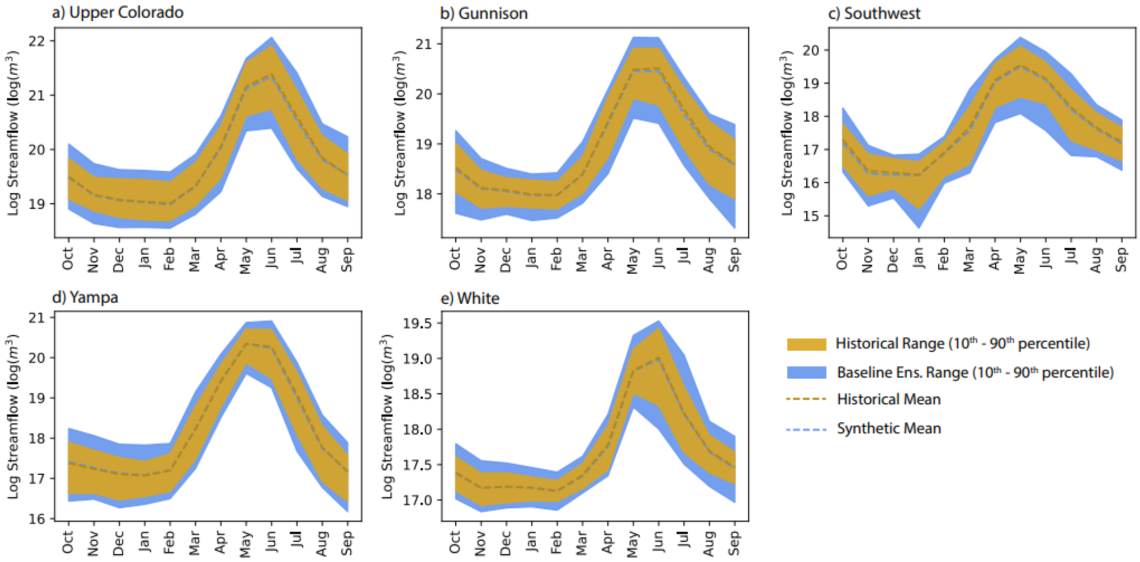

Figure 4 Monthly streamflows of each West Slope Basin of the historical data (orange) compared to the synthetic baseline ensemble data (blue). Mean values are shown as dashed lines. The shading indicate the 10th-90th percentiles (reprinted from Gold et al., 2024).

The ensemble as described above is the baseline ensemble, since it retains the mean values as observed in the historical record. The historical data does not represent the full hydrologic variability, because it is a sample of 105 years (Hadjimichael et al., 2023; Woodhouse & Overpeck, 1998). This ensemble aims to fully capture the internal variability of the hydrological system.

The baseline ensemble is one of two synthetic datasets that were generated. Besides this baseline, a climate adjusted ensemble was presented. By changing the parameters of the data generating process, the climate adjusted dataset accounts for plausible climate change scenarios on the region's hydrology. In a climate change scenario, annual streamflow is reduced and timing of snowmelt is altered due to warmer average temperatures. The climate adjusted ensemble informs about the possible future state of water supply and shortage.

Both ensemble sets can be used as drop-in replacement for the historical data in the StateMod workflow.

Data preparation for analysis

For the visual and spatial analyses, there was no need for extensive data preparation, since the StateMod model provides the main data. The model output is ready to use as-is.

Direct Diversion Rights data was filtered to exclude specific outliers. These are rights holders that have access to large volumes of water whenever there is excess supply. These outliers are identifiable by having the lowest possible water priority. These water rights are not informative when investigating shortages but skew the overall distribution of water rights.

Basic geometric transformations were applied to geographical data sources to obtain the desired regions of interest. These operations include clipping and spatial joins using QGIS 3.36.2-Maidenhead.

Selected data exploration results

Droughts in the historical record

Data exploration began by defining drought periods within the historical streamflow records of all West Slope subbasins. The employed drought definition categorizes a dry year when annual streamflow is half a standard deviation lower than the historical average. This follows the approach of Hadjimichael et al. (2023) and Gold et al. (2024), that is based on multiple examples from the literature (Ault et al., 2014, 2016; Diffenbaugh et al., 2015; Naumann et al., 2018). To be selective towards longer-term hydrologic trends, the streamflow data was transformed using an 11-year rolling mean. The resulting drought periods of the West Slope basins are on a decadal-scale, as visualized in Figure 5. The streamflows of each West Slope Basin are correlated, but differences are noticeable using this drought definition. The Gunnison and Upper Colorado River basins roughly share two decadal-scale drought periods, around the 1960's and more recently from circa 1999-2010.

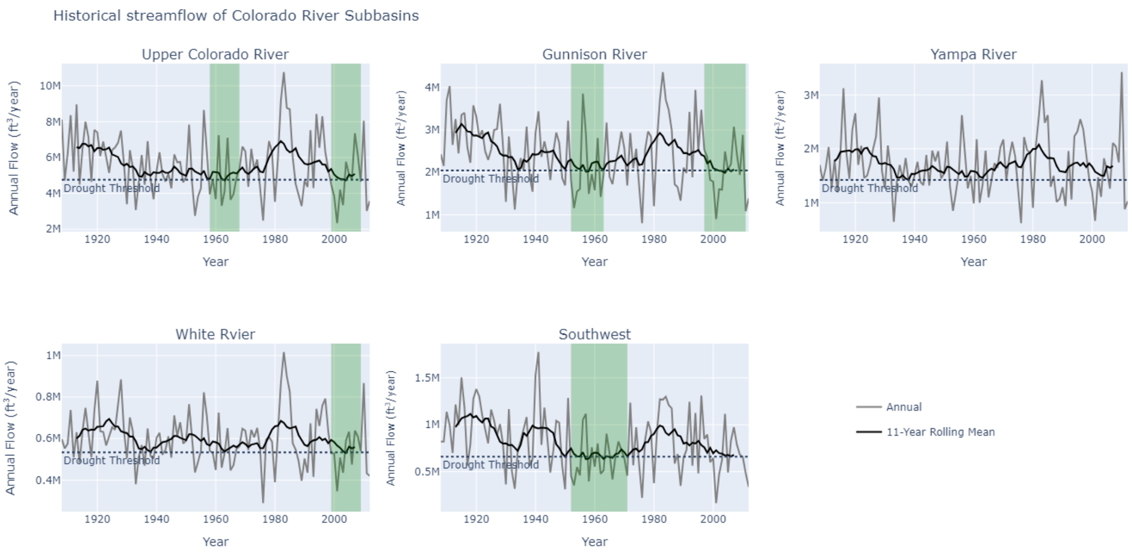

Figure 5 Historical streamflow records of the West Slope Basins (gray solid line), with the 11-year rolling-mean shown in black. The horizontal dotted line indicates the drought threshold for each subbasin. Sustained drought periods are highlighted in green.

Consumptive use shortage and streamflow

Historical streamflow and consumptive use shortage have a strong negative correlation. Figure 6 shows that high annual shortages coincide with years of low streamflow. The figure also illustrates that high annual shortages occur outside of drought periods when a long-term drought definition is applied.

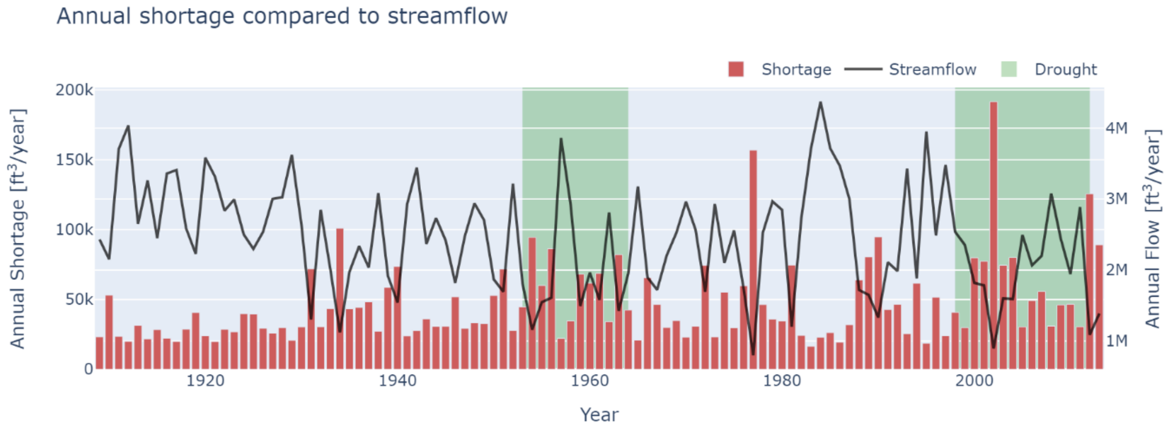

Figure 6 Historical streamflow (black) compared to consumptive use shortage (red) in the Gunnison basin, with drought periods highlighted in green.

Shortage and demand per water district

After grouping the consumptive use shortage and demand by water district (Figure 7), it becomes clear that there are notable discrepancies between the different districts. The North Fork Tribs district accounts for 74% of all historical shortage, while the next highest, Tomichi Creek, accounts for only 10%. Although historical water demand is also unevenly distributed among the districts, the differences are smaller. The clear outlier in this visualization is the Lower Uncompahgre River district, which has the highest water demand but the lowest historical shortage.

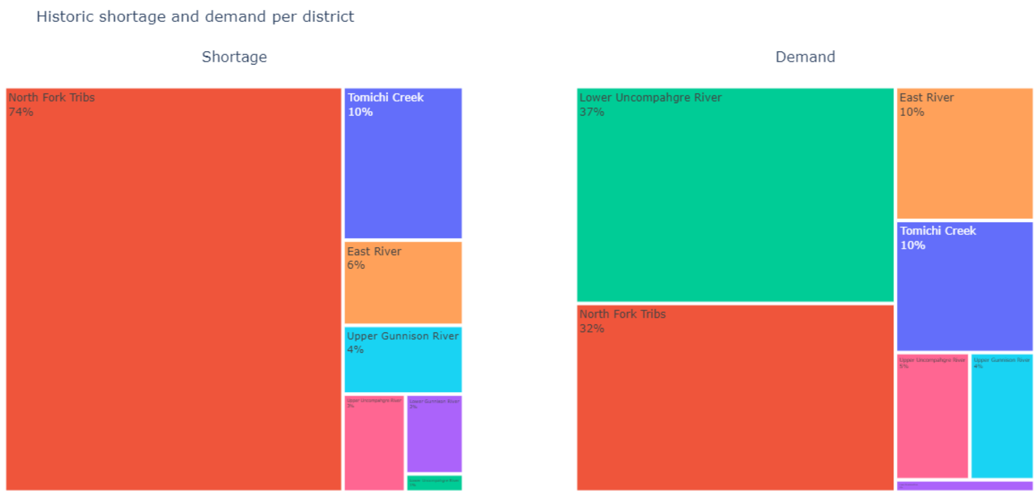

Figure 7 Mosaic plots of the relative share of shortage (left) and demand (right) per water district show large differences between districts.

Results and Analysis

Grouping by water district

Figure 8 shows the historical total relative share of water demand and shortage per water districts. Two notable districts stand out: North Fork Tribs and Lower Uncompahgre River. North Fork Tribs has historically experienced the most water shortages by a substantial margin.

Conversely, the Lower Uncompahgre River district has had the lowest volume of water shortages, while its water demand has been the highest. This result indicates that the raw volume of water use does not predict the volume of water shortages, but that other factors drive shortages.

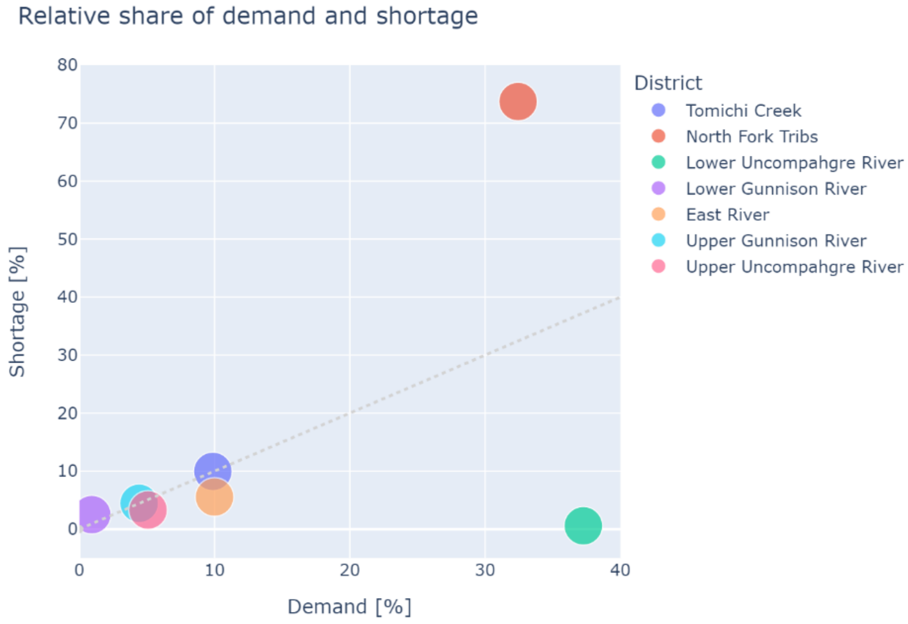

Figure 8 Scatter plot of relative water demand versus relative water shortage per district. North Fork Tribs and Lower Uncompahgre River districts are two clear outliers. The plot diagonal is shown as a dotted gray line.

Spatial analysis

Figure 9 visualizes the spatial distribution of water users and irrigated land in the Gunnison basin. Water districts are colored according to their mean annual shortage. This aggregation illustrates that susceptibility to shortage is concentrated in the Northwestern region of the Gunnison basin. Since approximately 70% of consumptive water use is attributed to agriculture, irrigated land is an important feature of the spatial analysis. However, historical water shortage does not appear to be predicted by irrigation. North Fork Tribs and Lower Uncompahgre River are the most densely irrigated districts, but their historical shortages are contrasting.

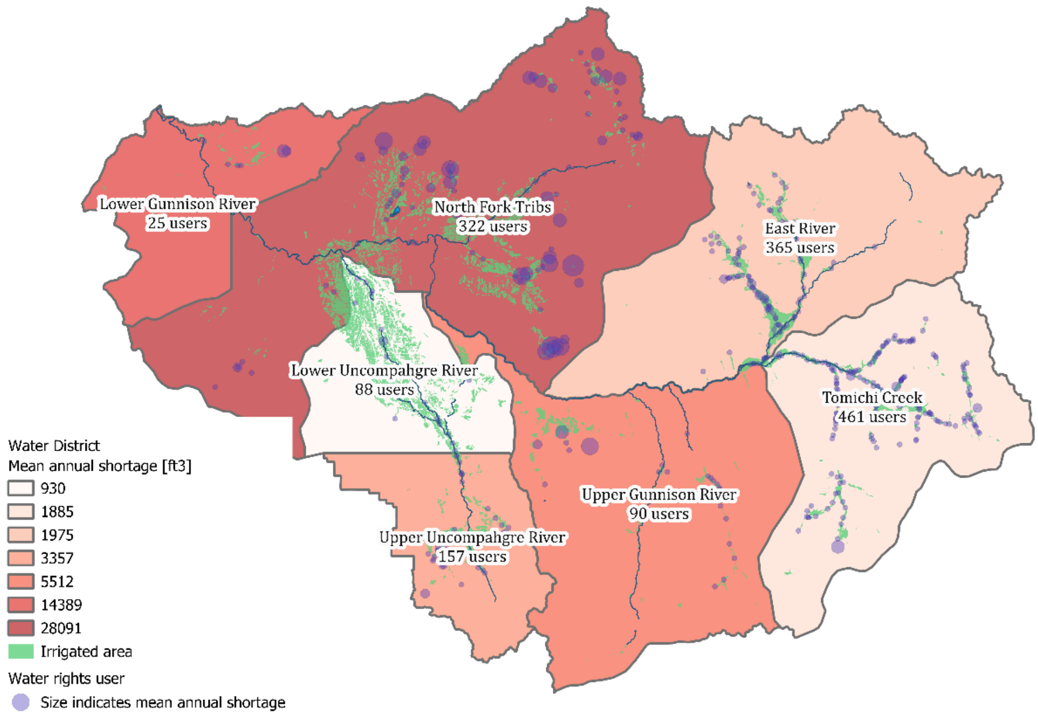

Figure 9 Spatial visualization of the Gunnison, with each water district colored according to its mean annual shortage and irrigated land overlayed in green. Individual water users are shown as purple circles with a size corresponding to their mean annual shortage. Shortage is concentrated in the Northwestern area of the Gunnison

Water rights

Figure 10 shows the allocation of water rights across the districts in terms of decree volume and Admin number. Water priority is represented by the Admin number, with lower values indicating senior water rights and higher values indicating junior water rights.

The differences in shortage vulnerability previously seen between North Fork Tribs and Lower Uncompahgre River districts correlate with their allocation of water rights. North Fork Tribs holds high-volume water rights that have medium to low priority, making these users susceptible to high-volume shortages. In contrast, the Lower Uncompahgre River district features high-volume high-seniority water rights. The quality of water rights appear to be an important factor driving drought vulnerability in the Gunnison basin.

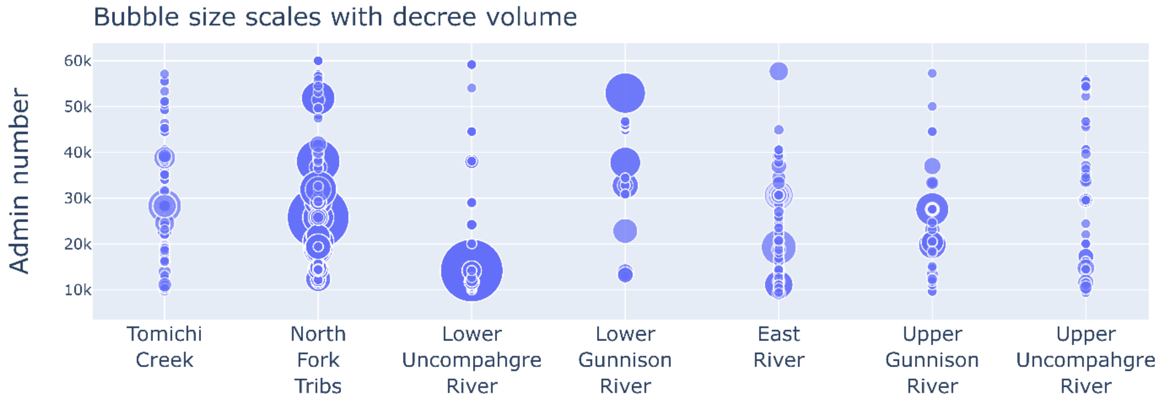

Figure 10 Water rights per district, with a low Admin number indicating high seniority. Bubble size increases with decree. The Lower Uncompahgre River stands out with its high-volume high-priority water rights. North Fork Tribs shows notable high-volume medium-to-low-priority water rights.

Synthetic ensemble data

The generated ensemble data was used for two purposes: (1) to contextualize the historical record within an ensemble of synthetic baseline realizations of the same hydroclimatic distribution, and (2) to evaluate drought vulnerability in the Gunnison basin under future climate change scenarios, using climate-adjusted simulated streamflow data. Drought vulnerability per district was assessed using quantiles of annual consumptive use shortage over a 105-year period, as illustrated in Figure 11. The median shortage indicates the level of shortage experienced in a typical year, while the 0.9 and 0.99 quantiles show shortage levels under more severe drought conditions.

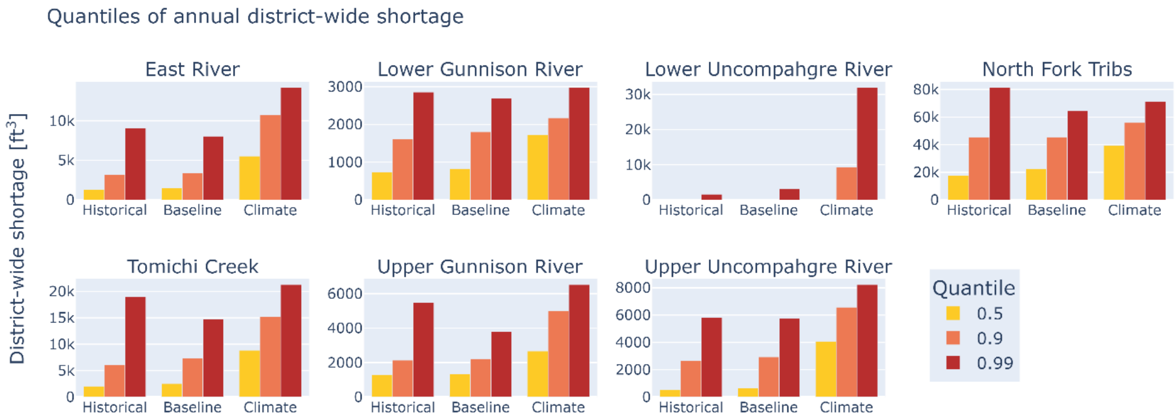

Figure 11 For each district, annual shortage quantiles are shown for historical, baseline and climate-adjusted datasets. The 0.5, 0.9 and 0.99 quantiles are respectively shown yellow, orange and red bars.

The Lower Uncompahgre River district again stands out in this analysis for its robustness against water shortages, even in multiple baseline realizations. Interestingly, the climate ensemble shows that the district will become more vulnerable to drought conditions in modest climate change scenarios, as indicated by the increase of 0.9 and 0.99 shortage quantiles in the climate ensemble. Even though this district did not experience severe shortages historically, its vulnerability increases in future scenarios.

For most other water districts, the increase of the median annual shortage is the most notable change in the climate scenarios. This means that water shortages will be greater in a typical year in the adjusted hydroclimate scenario. The historical and baseline median shortages are very similar across the districts, which is as expected due to the similarity between the historical and baseline mean streamflow (see Figure 4).

The historical and baseline 0.9 quantile annual shortages are comparable in volume for each district. This indicates that the severity of the historical 0.9 quantile shortage aligns with the severity of the expected 0.9 quantile shortage based on multiple baseline streamflow realizations.

For all districts except the Lower Uncompahgre River, the 0.99 quantile is higher in the historical record than in the baseline ensemble. This may indicate that the driest years in the observed historical record are outliers within the hydroclimate. However, this result might also be attributable to the synthetic data generation process, that has difficulty dealing with extreme values.

In the Lower Gunnison River and North Fork Tribs districts, the 0.9 and 0.99 quantile shortages are similar in both the baseline and climate ensembles. These districts may have reached a shortage limit, whereby a drier hydroclimate not further worsens their drought vulnerability, because they are already maximally shorted.

Conclusion and Discussion

In this work, drought vulnerability of the Gunnison basin was analyzed using the historical streamflow record, which was supplemented with two synthetic streamflow ensembles. Consumptive use shortages were assessed using StateMod, the State of Colorado's water accounting and allocation model.

This study finds that the magnitude of district-wide water shortages is not driven by the magnitude of water demand. The district with the highest-volume water demand, the Lower Uncompahgre River, historically experienced the least shortage in our analysis.

Although agriculture accounts for the large majority of consumptive water use, irrigation appears to not drive water shortages. The two most irrigated water districts, North Fork Tribs and Lower Uncompahgre River, are opposites in terms of drought vulnerability. North Fork Tribs has historically experienced the most extensive shortages, while the Lower Uncompahgre Riber has shown to be robust against drought conditions.

Water rights appear to be significant drivers of drought vulnerability. On the district level, there appears to be a correlation between low-priority high-volume rights and large shortages, and conversely, a correlation between high-priority high-volume water rights and drought robustness.

The results of the climate-adjusted ensemble modelling indicate that the Gunnison basin is susceptible to more frequent and more intense water shortages in future climate-change scenarios.

It should be noted that model results of future scenarios rely on the current regulations and practices of the water basin, while there is no guarantee that these will remain stationary over time. Results should therefore be interpreted in context of exploratory modelling. Moreover, the historical results were obtained by applying historical streamflow data to a model of the current state of the basin. This informs about the characteristics of the basin, but it does not give a representation of true historic events.

In future work, a similar workflow as here presented for the Gunnison basin could be applied to different West Slope basins. Additionally, the water rights have been identified as an avenue for further investigation, since this factor seems to be an important driver of drought vulnerability in the Gunnison basin.

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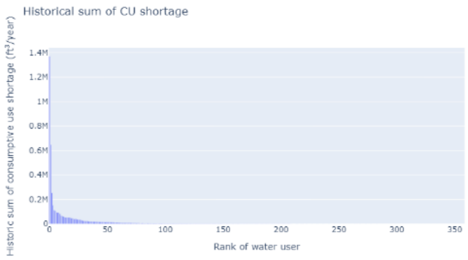
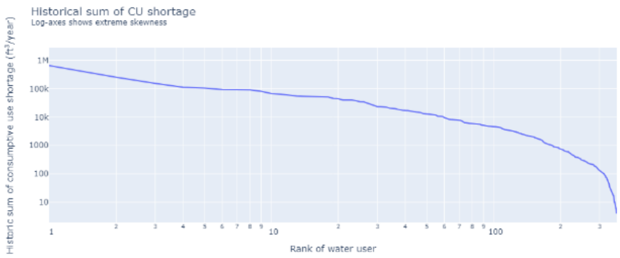
Appendix

Distribution of shortage across users

Inspection of the historical total consumptive use shortage shows that the burden of drought is very unequally distributed across the users within the Gunnison basin. A relatively small percentage large volume users account for the vast majority of water shortage volume. Users that do not experience shortage are excluded from this visualization.





Historical demand and shortage

An overview of the historical demand and shortage, both total and consumptive, in the Gunnison subbasin shows that there is high variability in the consumptive use shortage. The other shown metrics, consumptive use demand, total use demand and total use shortage, are notably more stable over time. During the two drought periods that are highlighted, there is more consumptive use shortage on average than outside of these drought periods. However, prominent dry years also occur outside of the defined drought periods.