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# Water Woes Worsen: Middle Rio Grande Reservoir Modeling Projects Declining Water Availability Under Climate Change Simulations

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# WATER WOES WORSEN: MIDDLE RIO GRANDE RESERVOIR MODELING PROJECTS DECLINING WATER AVAILABILITY UNDER CLIMATE CHANGE SIMULATIONS

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# List of Abbreviations

| | |
|---|---|
| BCCA | Bias Correction Constructed Analogs |
| BCSD | Bias Corrected, Spatially Downscaled |
| IPCC | Intergovernmental Panel on Climate Change |
| IQR | Interquartile Range |
| CMIP3 | Coupled Modeling Intercomparison Project Phase 3 |
| CMIP5 | Coupled Modeling Intercomparison Project Phase 5 |
| GCM | Global Climate Model |
| GHG | Greenhouse Gas |
| kAF | Kilo Acre Feet |
| RCP | Representative Concentration Pathway |
| Reclamation | U.S. Bureau of Reclamation |
| VIC | Variable Infiltration Capacity |

## Abstract

The Middle Rio Grande is a vital source of water for over 2M people. Climate change is impacting regional hydrology and is likely to put additional stress on a water supply that is already stretched thin. To gain insight on future water availability, a simple water balance model was used to simulate the Elephant Butte-Caballo reservoir system (Southern New Mexico, USA). The water balance model was run under 97 climate simulations derived from Global Climate Models (GCMs) developed under the Intergovernmental Panel on Climate Change's (IPCC) 5$^{th}$ generation Coupled Modeling Intercomparison Project (CMIP5). Results suggest that the percentage of years that water rights allocations are fulfilled over the next 50 years (2021-2070) will decrease compared to the past 50 years (1971-2020). The modeling also projects an increase in multi-year drought events. In most cases, headwaters flow from snowmelt is projected to have a greater influence on water availability downstream of Elephant Butte and Caballo reservoirs than local evaporation and precipitation from the reservoir surfaces.

# 1 Introduction

Increasing temperatures due to climate change are contributing to an increased risk of drought in the Southwestern United States. (Garfin et al., 2018) As one of the main sources of water in the region, decreased water availability in the Rio Grande would have a direct effect on the agriculture, industry, and municipalities that depend on it. (Hurd and Coonrood, 2012) Elephant Butte and Caballo Reservoirs, located along the Rio Grande in Southern New Mexico, supply water to users in parts of New Mexico, Texas, and Mexico. With regional water resources already completely allocated to holders of legal water rights and inadequate water available to support in-stream flows to maintain natural habitats, changes to regional hydrology will provide significant challenges for water managers and users. (Llewellyn, 2013)

Running hydrologic models under future climate change scenarios is a common approach used to increase our understanding of how climate change will affect water resources, enabling water managers and users to be more prepared by informing more robust and resilient policy. Global climate models (GCMs) generate future climate change scenarios by simulating earth processes worldwide. In contrast with forecasting, climate projections have more sources of uncertainty and make predictions further out into the future. Climate projections can be looked at as a tool to explore a range of plausible outcomes based on reasonable assumptions rather than year-to-year predictions. (Shepherd et al., 2018) A common source of climate projections is the Coupled Modeling Intercomparison Project (CMIP) framework laid out by the World Climate Research Programme. The CMIP framework offers standardization of certain aspects of GCMs, such as output formatting, allowing simulations from multiple GCMs to be looked at as an ensemble. There have been multiple generations of CMIP, with the most recent release being CMIP6.

Recent CMIP phases have accounted for uncertainty in human response to climate change by defining sets of parameters to cover a range of scenarios. CMIP5 uses four representative concentration pathways (RCPs): RCP2.6, RCP4.5, RCP6.0, and RCP8.5. The number associated with each RCP corresponds with a different set of atmospheric greenhouse gas (GHG) concentrations leading to different levels of effective radiative forcing in the year 2100. (van Vuuren et al., 2010) GCMs can be run under multiple RCPs, which allows for comparison of how different emissions scenarios affect the climate projections.

GCMs provide projections on climate parameters such as temperature, wind speed, and rainfall; however, they do not directly model surface hydrology. To develop hydrologic projections, hydrologic models (i.e., SWAT, Arnold et al., 1998, VIC, Liang et al., 1994) are run using inputs derived from Global Climate Model (GCM) scenarios. Since GCMs are run at a global scale, projections are output on a coarse grid (typically on the order of a degree latitude and longitude for CMIP5) and contain regional biases. Each projection must undergo bias correction and spatial downscaling before variables can be used as climate inputs to hydrologic models. Two commonly used statistical procedures used to adjust climate projections for water resources assessments are Bias-Correction and Spatial Dissagregation (BCSD) and Bias Correction Constructed Analogs (BCCA). (Gutmann et al., 2014)

A significant concern for storage reservoirs in arid regions is that the warming climate will increase evaporative losses. Modeling future evaporation rates must be estimated based on available parameters from downscaled GCMs, which can limit the options for equations used to estimate evaporation. Zhu et al. (2005) used a linear relationship that relates temperature and precipitation to evaporation while modeling reservoirs in California. While this approach neglects known factors that influence evaporation rates, such as solar radiation, wind speed, and water temperature, studies evaluating surface water evaporation methods have found calibrated temperature-based models to be adequate for estimating evaporation when additional data was unavailable. (Majidi et al. 2015; Xu et al. 2001)

An early study that modeled evaporative losses under climate change compared a reservoir in England with a reservoir in Iran and found that depending on the reservoir's location, climate change could cause a net positive or net negative effect on water availability. (Adeloye et al. 1999) This study also concludes that net reservoir surface fluxes (evaporation and precipitation) can significantly affect reservoir mass balances. Evaporative losses from reservoirs have shown to be a significant portion of the water balance in semi-arid climates. (Martínez Alvarez et al., 2008; Maestre-Valero et al., 2013)

Many other studies have shown climate change causes increasing evaporation rates. A study on agricultural reservoirs in the Brazilian savannah found that increased evaporative losses due to climate change will cause dry season water availability to decrease by around 5-10% by 2100. (Althoff et al., 2020) Helfer et al. (2012) looked at the evaporation rate for a reservoir in Australia. This study used a 1-D dynamic reservoir model (DYR-ESM) to model reservoir temperature under an ensemble of climate projections from nine CMIP3 GCMs. The evaporation rate increased by 8% in 2030-2050 and 15% in 2070-2090 compared to the baseline period of 1990-2010. The increasing evaporation rate was primarily driven by an increase in air temperature though wind speed was also found to play an important role in the evaporation rate. This was a relatively in-depth study on evaporation rate, but it did not consider evaporation in volumetric terms.

The Upper Colorado Basin has been the subject of many studies projecting future streamflow under climate simulations. (Christiensen et al., 2004; Dettinger et al., 2015; Ficklin et al., 2013) While the Colorado basin is geographically distanced enough from the Rio Grande to have differences in climate and hydrology, they both experience a semi-arid climate and are primarily fed by snowmelt runoff. Christensen et al. (2004) ran a VIC hydrologic model along with a reservoir/water resources operating model under three future climate simulations. Results projected future streamflow to peak earlier in the season and future average reservoir storage to decrease. The evaporation *rate* is projected to increase; however, lower average reservoir storage and therefore less surface area limited the *volume* of water lost through surface evaporation. Nevertheless, there was a net decrease in water availability, leading the authors to question whether changes to reservoir management would be able to mitigate the effects of climate change.

Ficklin et al. (2013) modeled the Upper Colorado Basin using a subbasin-scale SWAT hydrologic model under 16 climate scenarios. By 2100, peak streamflow occurred

1-2 months earlier, and Spring and Summer flow declined by 36% and 46%, respectively. These flow decreases were driven by increased evapotranspiration (+23%), changes in precipitation type, and declining snowmelt runoff. Cayan et al. (2010) found that higher temperatures have increased the severity of recent droughts in the Upper Colorado basin by reducing soil moisture. The risk of severe drought is projected to increase during the second half of the 21st century.

Climate change is expected to have significant effects on Rio Grande hydrology. In 2015, Dettinger et al. compared the Colorado, Klamath, Sacramento-San Joaquin Bay-Delta, and Rio Grande basins and argued that among these, climate change is expected to cause the greatest reduction in water availability along the Rio Grande. Hurd and Coonrod (2012) developed a hydro-economic model of the Middle Rio Grande to simultaneously look at future water availability and the resulting economic impacts. Their modeling projected that by the 2030s, regional economic losses due to changes in water availability will range from $15M to $114M per year. By 2080, the economic cost has the potential to increase to $302M per year; however, this was likely an underestimate due to modeling assumptions that ignore many social and ecological costs. Agriculture is expected to be hardest hit by declines in water availability because agriculture uses the most surface water.

It is estimated that 50 to 75 percent of the water flowing through the Rio Grande in Southern New Mexico originates as melt runoff from the Rocky Mountains in Southern Colorado and Northern New Mexico. (Rango 2006) Chavarria and Gutzler (2018) found April 1st snow water equivalent had decreased around 25% between 1958-

2015, which is significant because April 1st has historically been around peak snowpack. Future snowmelt runoff modeling of the Upper Rio Grande basin done by Elias et al. in 2015 projected that peak flows would occur 14-24 days earlier and snowmelt runoff volume was projected to change between +7% to -18% by the end of the 21st century.

The U.S. Department of Interior, Bureau of Reclamation (henceforth Reclamation) has done multiple hydrologic modeling projects regarding future water availability in the Middle Rio Grande. As part of their West Wide Climate assessment, Reclamation used the CRLE evaporation model and BCSD CMIP3 climate projections to estimate future evaporation rates from many reservoirs in the Western U.S., including Elephant Butte. (Lewellyn, 2013) The evaporation rate for Elephant Butte was projected to increase by 4.1 inches/year (7.7%) between the baseline period and 2080. Reclamation has also contributed streamflow projections for the Rio Grande. Streamflow time series were constructed using the VIC hydrologic routing model driven by BCSD CMIP5 climate projections. (Reclamation, 2014) The resulting streamflow projections represent streamflow as if it were a natural system without human interference.

Townsend and Gutzler (2020) used a statistical procedure to normalize Reclamation's naturalized streamflow projections at San Marcial (a gauging location above Elephant Butte Reservoir). [Figure 1] Normalization adjusts for the human alterations to natural streamflow. Dams change the timing of flow while consumptive use reduces the volume of streamflow by over 50%. Normalized streamflow varies between projections but the majority of project declining streamflow as the 21$^{st}$ century progresses.

Bennett et al. (2020) modeled 2050s hydrologic components on the Pajarito plateau (a tributary to the Upper Rio Grande) under five earth systems models. Their work suggests increasing aridity due to higher evapotranspiration was driven by increasing temperatures and changing precipitation type but did not make projections on streamflow of Rio Grande tributaries in the subbasin.

Previous studies have shown the Middle Rio Grande's dependence on snowmelt in the mountainous headwaters region, documented decreasing snowpack and earlier peak snowmelt, and produced naturalized and normalized streamflow upstream of Elephant Butte Reservoir. Previous research has also shown climate change is likely to increase the rate of evaporation from Elephant Butte and Caballo Reservoirs.

This research builds on that by exploring how releases from the Elephant Butte-Caballo reservoir system are projected to change under climate change by using a reservoir water balance model to make release projections under a large ensemble of climate simulations. The reservoir model accounts for streamflow, reservoir surface fluxes, and local runoff, allowing the comparative examination of the effects of climate change on water availability locally and in the headwaters region.

This paper extends previous results by projecting yearly release time series from the Caballo-Elephant Butte reservoir system that accounts for reservoir surface evaporation, surface precipitation, and runoff from the surrounding sub-watersheds. Modeling the reservoir water balance is useful because evaporation is a significant part of the water balance and will be affected by climate change. This also allows comparison of changes in water availability due to snowmelt runoff in the headwaters with change in water availability due to local climate. Increased information on how the reservoir system is affected by climate change also has direct implications on water management planning and decision making. The paper begins by outlining the study area and methods used to model Elephant Butte and Caballo reservoirs. It then presents results, including reservoir releases under future climate scenarios and the relative influence of climate change locally compared to in the headwaters. Finally, there will be discussion followed by concluding points.

# 2 Methods

## 2.1 Study Area

The study area is located in Southern New Mexico along a section of the Middle Rio Grande between the San Marcial gauges (USGS 08358400 and USGS 08358300) and the Caballo Reservoir gauge (USGS 08362500). [Figure 1] The study area is split into two sub-watersheds defined by Elephant Butte and Caballo reservoirs. Elephant Butte Reservoir has a storage capacity of 2,024,586 AF. (Ferrari, 2008b) Caballo Reservoir is much smaller at 324,934 AF and is mainly used for short-term attenuation to allow finer control of the timing and volume of deliveries to downstream users. (Ferrari, 2008a) The two reservoirs are managed conjunctively, meaning releases are coordinated to fulfill a common policy agreement. Releases flow downstream to irrigated agricultural areas and to municipalities including El Paso and Juarez.

Elephant Butte and Caballo releases are determined by a 2008 operating agreement between Texas, New Mexico, and Mexico that details how much water will be released each year. (Reclamation, 2008) The operating agreement is defined on a calendar year basis based on the previous year's storage and the amount of water that flows into Elephant Butte at the San Marcial Gauges. When water availability allows, water rights holders receive the full allocation of water, referred to in hereafter as "Full Allocation". Full Allocation of all downstream water rights holders totals 790,000 AF. During years with low surface water availability, water allocations are scaled back proportionately for all water rights holders. When water allocations are cut back, some water users may turn to groundwater to close the gap. Supplementing with groundwater can blunt the effect of drought but it will be unable to provide a long term to water shortages. Groundwater use already exceeds the rate of recharge so increased dependence on groundwater is unsustainable. (Sheng, 2013)

Average annual historic precipitation for the subwatersheds is 12.2 inches of precipitation per year. The evaporation rate from surface water often exceeds 4 feet per year. (Llewellyn, 2013) Evaporative losses from Elephant Butte are estimated to be between 8 and 20% of the volume of water released from the dam each year. (Eichenger, 2003)

## 2.2 Water Mass Balance

A simple water balance model was used to simulate reservoir operation under an ensemble of 97 climate scenarios. Reservoir storage is modeled as shown in equation 1.

$$\frac{dS}{dt} = Q_{in} + P - E + RO - R \quad (1)$$

Where dS/dt is the change in reservoir storage (Elephant Butte and Caballo, combined) per change in time, $Q_{in}$ is the volume of streamflow into the reservoir (San Marcial gauge), P is the volume of precipitation that falls on the reservoirs' surfaces, E is the volume of water that evaporates from the reservoirs' surfaces, R.O. is runoff from the surrounding sub-watersheds, and R is the volume of water released from the reservoir system. Any exchange of water between groundwater and the reservoirs is assumed to be negligible.

The reservoir system was modeled at an annual timestep because the operating agreement specifies releases on a yearly basis. The reservoir water balance model requires yearly time series inputs for temperature, precipitation, and upstream flows. The model was run from 1971 to 2070. Caballo reservoir is assumed to have a constant volume because the annual average storage is very similar year-to-year (storage mainly fluctuates on a finer time scale than we are modeling). This effectively considers the two reservoirs as a single bucket by only determining releases and storage for Elephant Butte.

## 2.3 Climate Simulations

The term “simulation” will henceforth be used to rerefer to the combination of a specific GCM and RCP. This study used IPCC's CMIP5 climate projections. The climate projections were adjusted using the Bias Correction, Spatial Disaggregation (BCSD) method which outputs monthly projections at a 1/8$^{th}$ degree resolution. (Reclamation, 2013) BCSD CMIP5 was chosen to match data availability for normalized streamflow projections. BCSD climate simulations were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive. We included all available BCSD CMIP5 simulations with "r1i1p1" initial conditions for a total of 97 climate simulations spanning 31 GCMs. (rNiNpN labels differentiate multiple runs of the same model and RCP, r is realization, i is initialization method, p is parameterization) Some GCMs were not run under all four RCPs. We looked at all 97 simulations as an ensemble and did not attempt to choose favorites among the simulations or select representative scenarios.

Temperature and precipitation timeseries were constructed by spatially averaging monthly 1/8-degree gridded BCSD values across the Elephant Butte and Caballo sub-watersheds. [Figure 1] The annual precipitation depth and annual mean temperature were used as input to the reservoir model.

## 2.4 Streamflow

Reclamation had previously produced San Marcial streamflow projections using the Variable Infiltration Capacity (VIC) hydrologic routing model driven by each of the 97 BCSD CMIP5 climate simulations described above. (Reclamation, 2014) The VIC streamflow modeling produced "naturalized streamflow" projections that did not account for human retention and diversion. Townsend and Gutzler (2020) developed and applied a statistical normalization procedure to account for human interference upstream of Elephant Butte Reservoir. The resulting "normalized streamflow" time series were used as flow into Elephant Butte Reservoir.

## 2.5 Precipitation

Reservoir surface precipitation is calculated by multiplying the subwatershed-averaged depth of precipitation by the reservoir surface area. Reservoir surface area is derived from a $4^{th}$ order polynomial regression between surface area and volume.

$$SA = a + b * V + c * V^2 + d * V^3 + e * V^4 \qquad (2)$$

Where S.A. is surface area in acres, V is the volume in acre-feet, and a, b, c, d, and e are coefficients. (The values are listed in Table 1 in Appendix C. EBA0-EBA4 are a-e for Elephant Butte and CabA0-CabA4 are a-e for Caballo.) The constants a-d that define the relationship between S.A. and V expressed in (2) are based on sediment surveys done on Elephant Butte and Caballo reservoirs in 2007. (Ferrari, 2008a; Ferrari, 2008b) The relationship between volume and surface area is assumed to be constant during the study period.

## 2.6 Evaporation

The relationship between temperature and evaporation was established through a linear regression of climate simulation temperatures and modeled evaporation. Modeled evaporation values came from 112 CMIP3 climate simulations calculated using the CRLE method as part of Reclamation's West Wide Climate Assessment. (Llewellyn, 2013) Differences between CMIP3 and CMIP5 prevented the direct use of the modeled evaporation as input to the water balance model so a linear regression was done between modeled temperature and modeled evaporation resulting in equation 3.

$$E_i = E_{avg} + \alpha * \left(T_i - T_{avg}\right) + \beta \tag{3}$$

Where $E_i$ is surface water evaporation depth (mm) at time i, $E_{avg}$ is the average annual evaporation depth during the historic period (mm), α is the slope constant, β is the intercept, T is the temperature (deg C), and T avg is the historic average temperature. The evaporation parameters were estimated using modeled data spanning from 2021-2070. (Values are listed as “EvapCoeff” (α) and “EvapInt” (β) in Appendix C, Table 1.) The volume of evaporation is calculated by multiplying evaporation depth by reservoir surface area derived from (2). This method was chosen over more complex methods of evaporation estimation due to the limitations in BCSD parameter availability, specifically the lack of solar radiation.

## 2.7 Runoff

Runoff is calculated as a fraction of the precipitation that falls on the Elephant Butte and Caballo sub-watersheds.

$$RO = A * P * c \tag{4}$$

Where R.O. is runoff, A is the sub-watershed area, P is the average precipitation depth in a given year, and c is a constant (value is listed as “RunoffCoeff” in Appendix C, Table 1). The coefficient was calibrated by running the model with historical observations as inputs. Since all other terms in the water balance had been measured (precipitation, streamflow, releases) or otherwise calibrated (evaporation), the runoff was assumed to be the remainder of the water balance.

## 2.8 Releases

Reservoir releases are based on an equation provided by Reclamation that approximates reservoir management per the 2008 Rio Grande Project Operating Agreement. (Reclamation, 2008) Releases are a function of San Marcial flow and the previous year's storage in Elephant Butte.

$$R = min(a, b * Q_{SM} + c * S_{i-1}) \tag{5}$$

Where R is the "desired" release, $Q_{SM}$ is flow at San Marcial, and $S_{i-1}$ is the previous year's storage in Elephant Butte, and a-c are constants (values are listed as OpConst1-OpConst3 in Appendix C, Table 1). The release is referred to as "desired" because under certain circumstances, reservoir storage may be too low to fulfill the "desired" release (as defined in the 2008 Operating Agreement) or so full that additional water must be released to keep the reservoir from overtopping. R is only adjusted if it is necessary to keep Elephant Butte storage within its operating limits. Iteration is applied during each time step to resolve the interdependencies between reservoir storage, evaporation, precipitation, and release volume to ensure that the model conserves total water volume. Caballo releases are assumed to be the same as Elephant Butte releases because storage in Caballo is assumed to be constant.

# 3 Results

## 3.1 Precipitation, Temperature, and Streamflow

The time series that were developed for precipitation, temperature, and streamflow indicate the ensemble's projections for these parameters over time. To evaluate change, each climate simulation was averaged across two periods: 1971-2020 and 2021-2070. The resulting yearly averages for each simulation are plotted in Figure 2. The ensemble projects precipitation to remain roughly the same, although increased model spread indicates some uncertainty. All simulations project increased temperature. The median simulation for streamflow indicates a slight decline is most likely, but as with precipitation the spread between models indicates there is a range of streamflow values that would be reasonable to expect.

The median simulation projects the local (Elephant Butte and Caballo subwatersheds) average precipitation to be 1.01 ft/yr from 2021-2070, a decrease of 0.6% from the median simulation over the previous 50 years. [Figure 2] The 2021-2070 inter-quartile range (IQR) extends from 0.95 to 1.08 ft/yr, compared to 1.00 to 1.05 ft/yr in 1971-2020.

Averaged over 2021-2070, the median simulation's average temperature was 13.99 degrees C. This was a 1.68 degree increase from the median average temperature of 12.30 degrees C during the previous 50-year period. [Figure 2] The IQR for 1971-2020 was 12.2 to 12.4 degrees C. The IQR for 2021-2070 was 13.6 to 14.4 degrees C. The magnitude of change for individual simulations between the two averaging periods ranged from 0.56 degrees C to.12 degrees C.

Averaged over 2021-2070, the median simulation's streamflow at San Marcial was projected to be 728 kAF/yr. [Figure 2] That was a decrease of 97.6 kAF/year (11.8%) compared to the median simulation in 1971-2020. The IQR for 1971-2020 was 780 to 875 kAF/yr. The IQR for the 2021-2070 was 615 to 953 kAF/year. For further analysis of the streamflow projections at San Marcial, refer to Townsend et al. 2020.

## 3.2 Water Availability

Water availability was considered in terms of modeled releases from the Elephant Butte-Caballo Reservoir system. "Full Allocation" is the release volume that would satisfy users' legal water rights. Benchmark thresholds were established at 50% and 25% percent of Full Allocation to represent a moderate and severe drought, respectively. Twenty-five percent of full allocation is approximately equivalent to the volume released during a recent severe drought that occurred between 2012-2013.

Figure 3 shows release reliability across the ensemble of simulations. The three plotted lines correspond with the three theshold release volumes. The y-axis is the percent of simulations failing to meet each threshold. The x-axis is time. As we move out into the future, the percent of simulations failing to meet each threshold benchmark increases. This translates to an increasing occurance of water deliveries that fall below full allocation of water rights for those receiving water from the Elephant Butte-Caballo reservoir system.

Figure 4 shows the same data as Figure 3 but slices it by climate simulation over averaging periods to show variability between models within the ensemble. The y-axis is the fraction of years the simulation fails to release the desired threshold volume. The x-axis is split into the two averaging periods. Each vertical cluster shows the ensemble under a set of threshold volume (indicated by color) and averaging period ("year range") criteria. Within a "strip" each dot represents a climate simulation.

The fraction of years with releases falling below the threshold volume increases for the median simulation across all threshold volumes. From 1971-2020 the median simulation projected 50% of years would be below 100% allocation which rose to 62% of years from 2021-2070. From 1971-2020 the median simulation projected 10% of years would be below 50% allocation which rose to 20% of years from 2021-2070. This suggests a similar conclusion to Figure 2; that it is likely release reliability (fraction of years a threshold is met) will decline in future years.

Figure 4 also illustrates an increase in variability between the simulations in the future. For 100% allocation, the IQR was 0.12 for 1971-2020 and 0.26 for 2021-2070. For 50% allocation, the IQR was 0.02 for 1971-2020 and 0.24 in 2021-2070. This tells us there is a range of uncertainty and the region will need to be prepared to handle a range of situations.

Figure 5 is set up similar to Figure 4, except the y-axis shows the number of consecutive years each simulation failed to release at or above the three benchmark volumes over each 50-year period. From 1971-2020, the median simulations projected 10 consecutive years below 100% allocation and 3 consecutive years below 50% allocation. From 2021-2070, the median simulation for each value rose to 14 consecutive years below 100% allocation and 4 consecutive years below 50% allocation. The shift towards longer consecutive periods below each threshold indicates it is likely that multi-year droughts will become more common in the future.

For 1971-2020 the 25th to 75th percentile simulations ranged from 7 to 12 consecutive years below full allocation. The IQR expanded to cover 9 to 18 consecutive years below full allocation for 2021-2070. For 50% of full allocation, the 25th and 75th percentile simulations projected 2 and 4 consecutive years for 1971-2020 and 3 to 6 for 2021-2070. As with Figure 4, the increased variability between simulations translates to uncertainty which complicates water resources planning. While the median points to the most likely situation, higher and lower projections cannot be ignored.

Figure 6 maps upstream and local change for each climate simulation. The x-axis is the net change in water contributed to the reservoir from local sources (Elephant Butte and Caballo subwatersheds) through surface precipitation, runoff, and surface evaporation. The y-axis shows the change in streamflow at San Marcial. Change is calculated by subtracting the 1971-2020 average from the 2021-2070 average for each simulation. The solid grey lines perpendicular to each axis indicate zero change between 1971-2020 and 2021-2070. The dashed lines indicate the median simulation change for each axis.

Local influence increased water availability by 4.5 kAF/yr for the median simulation. The average streamflow at San Marcial for the median simulation decreased by 58.8 kAF/yr for the median simulation. The magnitude of change in streamflow is 13 times larger than that of local change meaning streamflow at San Marcial is a far bigger driver of water availability than local precipitation, evaporation, and runoff. While lower volumetric evaporation can slightly offset declines in streamflow, local change only fully offsets upstream losses in one scenario. Locally, the magnitude of surface precipitation and runoff are on a similar scale (~20kAF/yr) and evaporation is around five times larger at around 100kAF/yr. Releases are on the order of 770kAF/yr while streamflow at San Marcial averages around 825kAF/year. Precipitation, runoff, streamflow, evaporation, and releases all decreased when averaged across all simulations.

The negative correlation between upstream and local change seen in Figure 6 was found to be driven by the decrease in streamflow. In low streamflow years, the reservoir storage volume is low which in turn means there is less surface area and therefore less evaporation. Since evaporation is a negative term for local contributions, a decrease in the volume of evaporation occurring shows up as a positive change in local reservoir contributions.

Figure 7 also plots change in two variables 1971-2020 to 2021-2070, this time looking at San Marcial Streamflow and local (Elephant Butte and Caballo subwatershed) average temperature. There is a lack of defined correlation between the change in local temperature and the change in streamflow. Figure 8 looks at change in streamflow at San Marcial against change in local precipitation (1971-2020 to 2021-2070). There is a clear trend that simulations that are wetter locally also tend to have more water availability by means of streamflow.

Figure 9 compares the relative magnitude of each term in the reservoir water balance (streamflow, precipitation, runoff, evaporation, and releases), averaged across all simulations 1971-2070. Streamflow is the primary flux in and releases are the primary flux out. Evaporation is around 6.5% larger than runoff and direct precipitation combined which causes the amount of water released to be smaller than what came in. The relative proportions of the water balance terms are approximately the same between the two periods, despite a decrease in overall water availability.

# 4 Discussion

The ensemble projects a decrease in water availability across all metrics. The average yearly release volume of the median simulation declines by 11.4% between 1971-2020 and 2021-2070. Between the same time periods, the probability that the system will release at or above 50% and 100% of full allocation under the median scenario decreases by 10% and 6%, respectively. The median number of consecutive years with releases below full allocation increased from 10 to 14 for the median simulation between the 1971-2020 and 2021-2070 averaging periods.

This overall decline in water availability was primarily due to decreased streamflow. Change in water availability was far more dependent on upstream (headwaters) climate change than on climate change in the immediate Caballo and Elephant Butte subwatersheds. Diminished snowpack in the high-elevation headwaters is projected with very high confidence, but there is still a huge range in model-projected streamflow (associated with uncertain headwaters precipitation projections). Even considering these uncertainties, the heavy reliance on Rio Grande inflows for surface water availability in our study area increases the future risk of water shortages.

The increased risk of low flow years calls for adaptations to current water management. The feasible space of management options will be further constrained by climate change. Increased risk of low flow years will make it more desirable to maintain a higher storage volume to act as a buffer during low flow years. Simultaneously, increasing temperature will increase evaporative losses making it more costly to maintain a high storage volume. Since evaporation is such a big part of the local water balance, changing policy to purposely operate the reservoir at a low volume could reduce losses however that would limit the capacity of the reservoir to act as a buffer during dry periods. Ultimately there will be less water available for users and users will also need to adapt to decreased water availability.

While the projections described here indicate that the Rio Grande surface water supply in the study region is likely to be less reliable, it is important to point out that water users in region, including agricultural irrigators, also have access to groundwater supplies. These users have compensated for poor surface water years with groundwater for at least 50 years. However, aquifers in the region are already at risk because pumping substantially exceeds recharge (Sheng, 2013; Fuchs et al., 2018). Less surface water in the region due to climate change in the headwaters means that local groundwater supplies will be depleted sooner (Mayer et al., 2021).

While this research provides valuable insight into the future of releases from Elephant Butte/Caballo, it does face some limitations relating to both the hydrologic and management aspects of the system. Evaporation was estimated based solely off temperature, ignoring solar radiation, relative humidity, and windspeed. Since solar radiation was not an available variable from the BCSD dataset, using temperature as a proxy was our best option. The operating equation used in the model also presents limitations because there is no way to account for users choosing to "bank" water in the reservoir for future years. Additionally, the yearly timestep used in the release equations limits the rest of the model. This becomes most problematic because reservoir storage is highest during the summer while the evaporation rate is also highest, so using yearly averages of each potentially underestimates evaporation. The operating equation was used because we did not have a better option for the operating rules. Evaporation ended up being a relatively small term in the water balance compared to streamflow so even if it were underestimated, streamflow would still be the biggest driver of the system.

This study assumed constant management practices upstream of and within the study area by applying the same equations to represent management practices during the whole study period (1971-2070). This allowed us to isolate climate effects on water availability. Realistically, the system was operated differently prior to 2008 and operation strategies will likely change before 2070. Our results should be interpreted as a starting point for discussion of how reservoir management might be changed as an adaptation strategy to minimize water supply risks in a changing climate.

# 5 Conclusion

This study modeled a reservoir water balance in the Middle Rio Grande under 97 future climate scenarios. Future projections show a decline in water availability across all parameters explored. Temperature increased across all simulations. Streamflow and precipitation varied between simulations, but the majority of simulations project these variables to decrease. The reservoir release volume of the median simulation was 10% lower in 2021-2070 than it was in 1971-2020. The longest consecutive drought of releases below full allocation for 2021-2070 was 14 years compared to the median simulation for 1971-2020 of 10 years.

Despite the increasing evaporation rate, there was little change in the volume lost to reservoir surface evaporation between the two time periods. This is because decreased streamflow under the current operation policy keeps reservoir storage low, limiting the surface area that evaporation can occur from. While this means there is less water lost to evaporation, it also means the reservoir has extremely limited capacity to buffer a drought since water is not being held back in case it is needed the next year. This is risky, given projections suggest an increased occurrence of extreme and multi-year drought events.

Decreasing water availability will need to be addressed in the through policy and use changes. For this project, management practices are assumed to be constant throughout the whole study period which is unrealistic (there was a change in operating procedures in 2008, and potential for more changes before 2070) but allowed us to isolate the hydrologic effects of climate change alone on water availability. Future research should investigate the tradeoffs of different management decisions such as minimizing evaporation versus banking more water year-to-year since the value of water to users depends on both the amount and the timing.

That said, the magnitude of change in reservoir input from streamflow was far greater than change of magnitude in local precipitation and evaporation. Any local gains can easily be overshadowed by decreased streamflow, producing a new decrease in water availability. An implication of this is that while local policy changes could reduce extreme low flows compared to current policy, there is ultimately a very limited ability to increase the amount of water available under a longer averaging period. Water users will also have to adjust their expectations on how much water will be available and their water use practices, including finding ways to decrease water use, in order to adapt to changing conditions.

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# A Figures

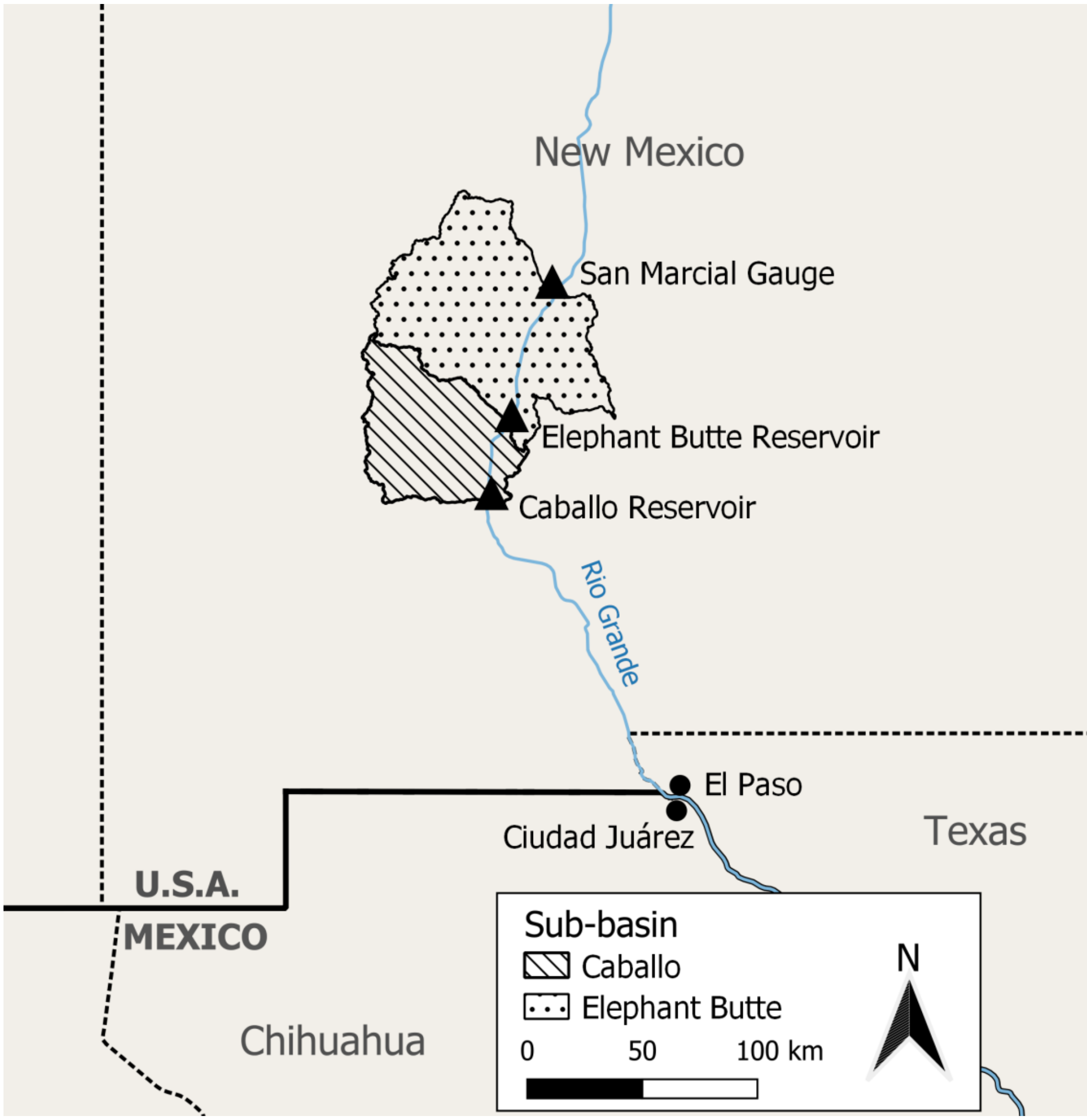



*Figure 1: Map of study area. Elephant Butte Reservoir, Caballo Reservoir and the San Marcial Gauges are represented by black triangles.*

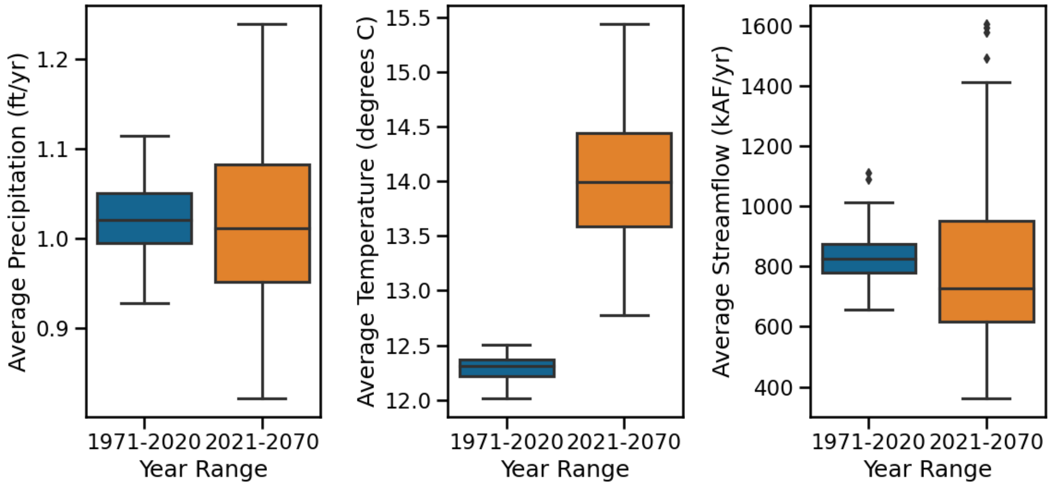



*Figure 2: Box and whisker plots of the average yearly precipitation, temperature, and streamflow for each climate simulation. Each climate simulation is averaged across two periods: 1971-2020 and 2021-2070. Colored boxes cover the 25th-75th percentile with the center line being the median. The whiskers span the remainder of the data with a maximum length of 1.5 times the inter-quartile range. Values outside of the whiskers are considered outliers and plotted as dots.*

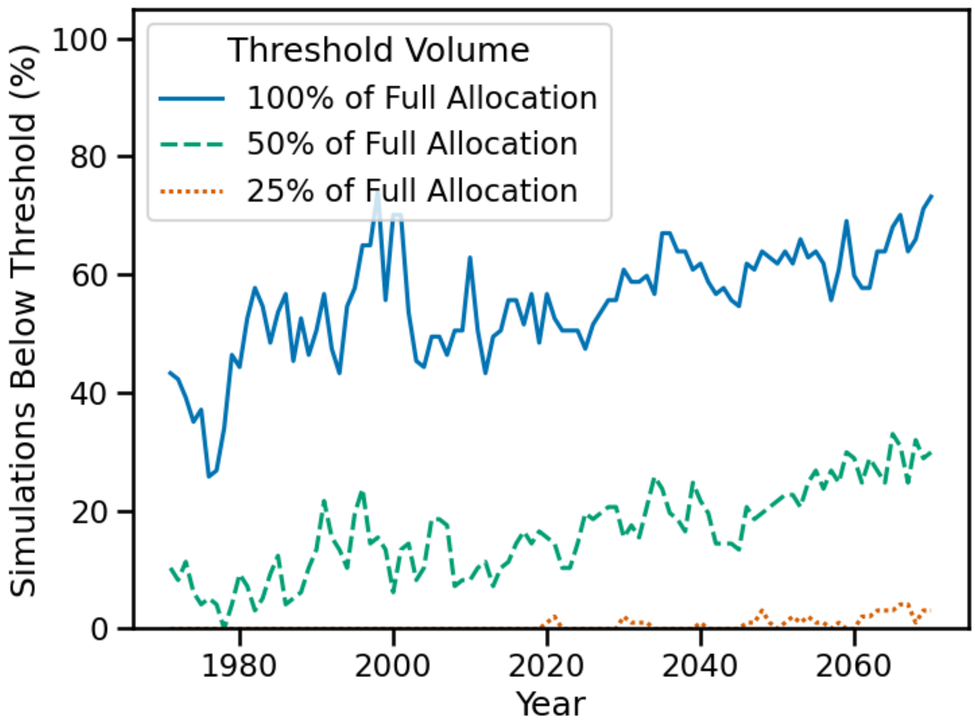



*Figure 3: Percent of climate simulations that fall short of releasing the threshold volumes in each year of the study period (1971 to 2070). Full allocation is the "goal" release volume where water rights allocations can be delivered. 50% of full allocation represents a moderate drought and 25% represents an extreme drought.*

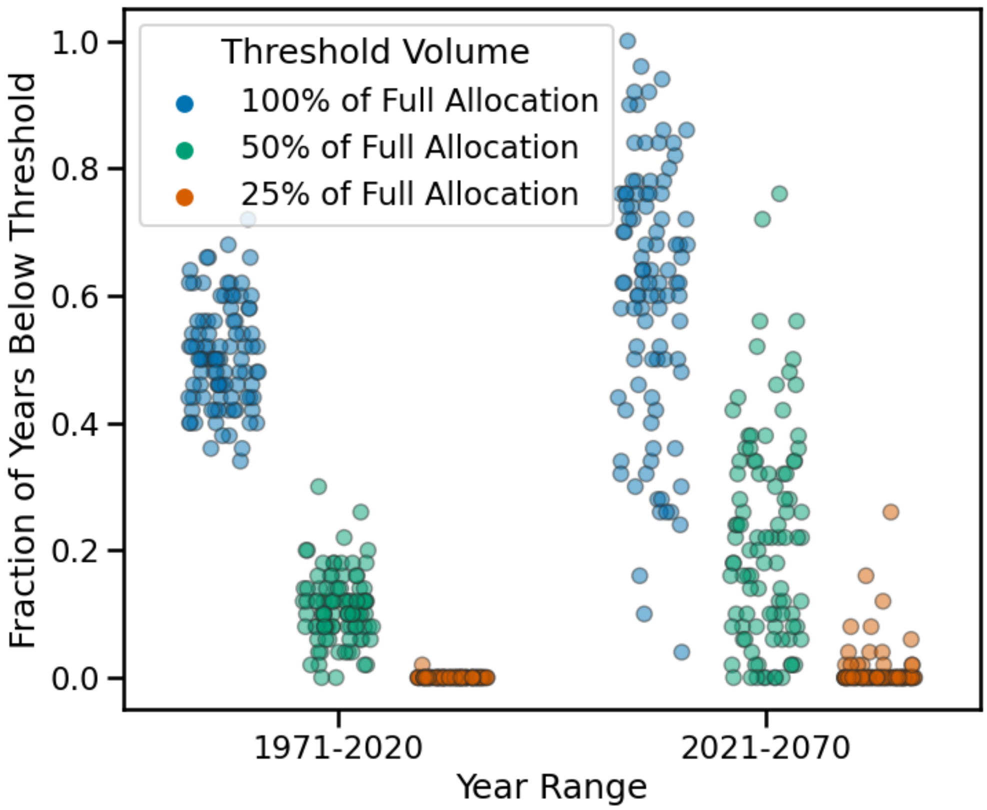



*Figure 4: Reservoir reliability at three threshold volumes (100%, 50%, and 25% of full allocation) during the past (1971-2020) and future (2021-2070) time periods. Each dot represents the fraction of years that one climate simulation projects the reservoir will fail to release above a threshold volume.*

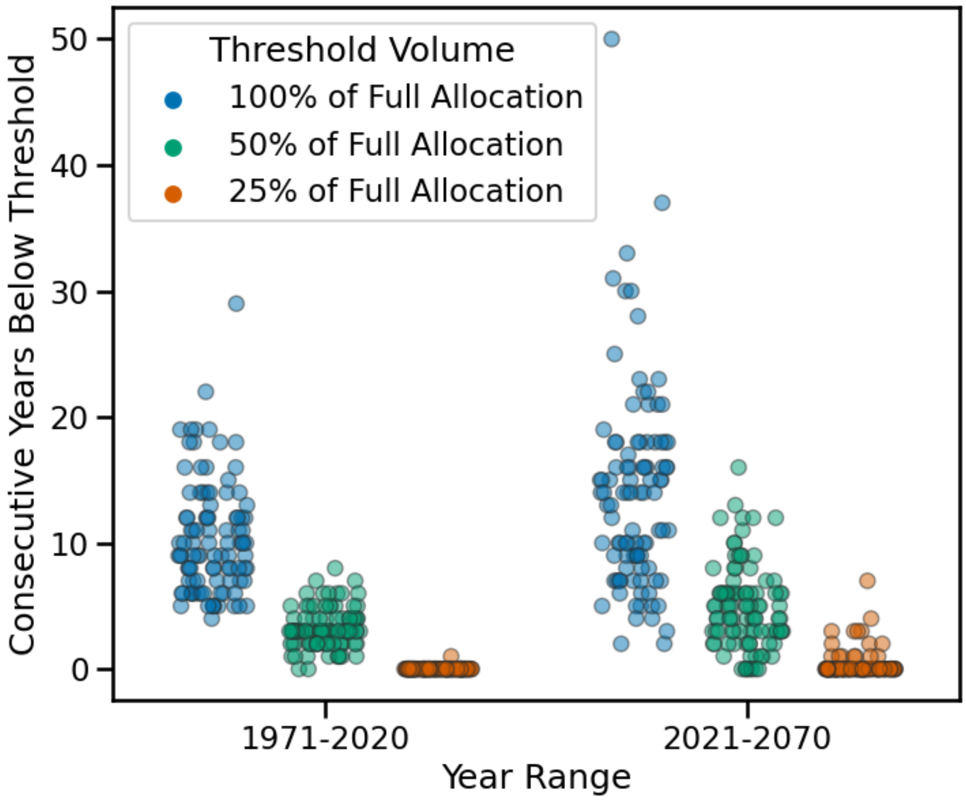



*Figure 5: The longest consecutive-year drought for each simulation at three threshold volumes during the past (1971-2020) and future (2021-2070) time periods. Each dot represents the number of consecutive years a climate simulation fails to release at or above a threshold volume (100%, 50%, or 25% of full allocation).*

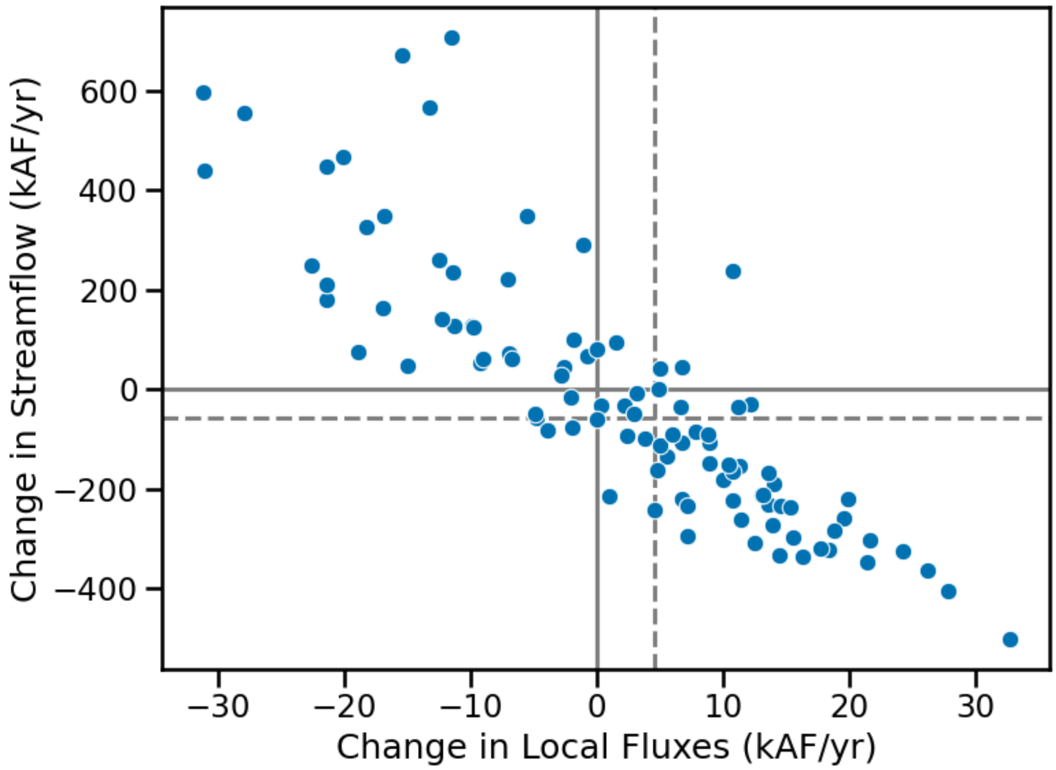



*Figure 6: Change in average streamflow against change in local fluxes between past (1971-2020) and future (2021-2070) periods. Streamflow is the amount of water flowing into the reservoir from upstream (measured at the San Marcial gauge). Local fluxes are the net amount of water entering or leaving the system though reservoir surface evaporation, reservoir surface precipitation, and runoff from the Caballo and Elephant Butte subwatersheds. Each point represents a climate simulation. The solid lines represent no change between the past and future time periods. The dashed lines show the median amount of change for each axis. Median simulations project a decrease in streamflow and an increase in net subwatershed influence.*

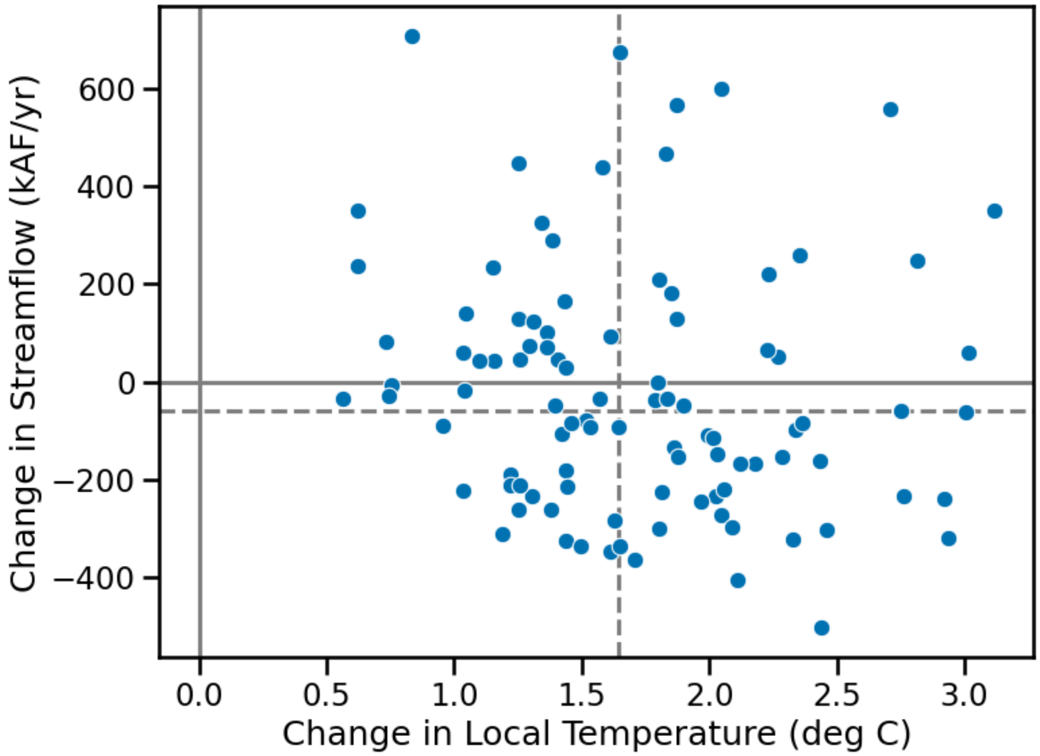



*Figure 7: Change in average streamflow against change in local temperature between past (1971-2020) and future (2021-2070) periods. Streamflow is the amount of water flowing into the reservoir from upstream (measured at the San Marcial gauge). Change in local temperature is the projected temperature, spatially averaged across the Elephant Butte and Caballo subwatersheds. Each point represents a climate simulation. The solid lines represent no change between the past and future time periods. The dashed lines show the median amount of change for each axis. Median simulations project an increase in temperature and*

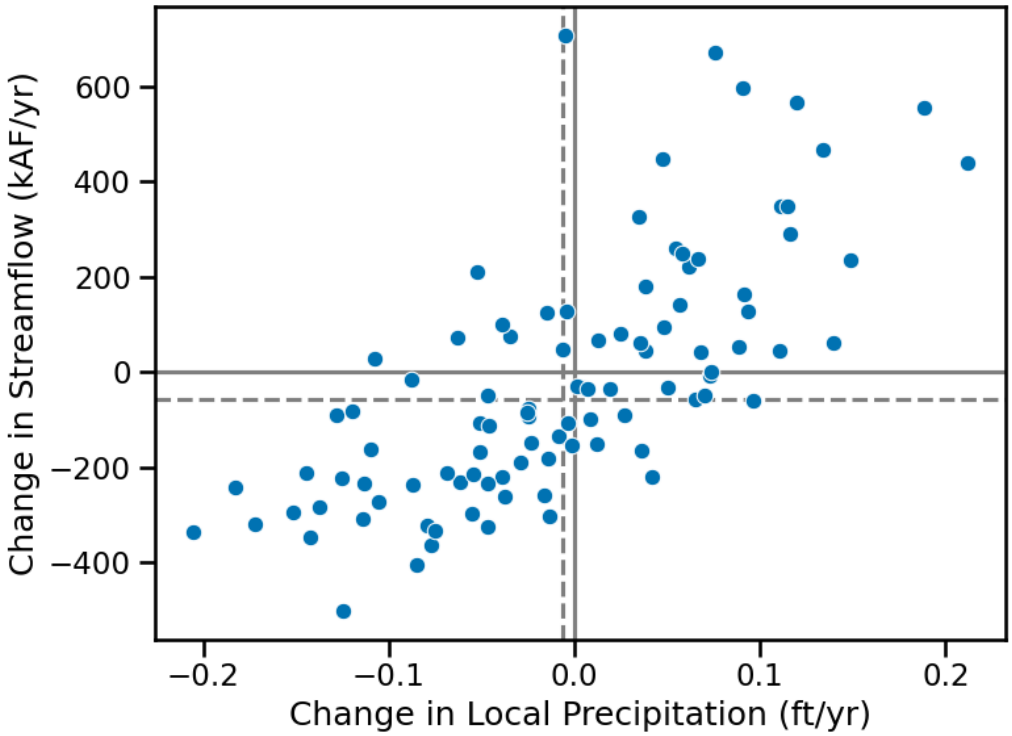
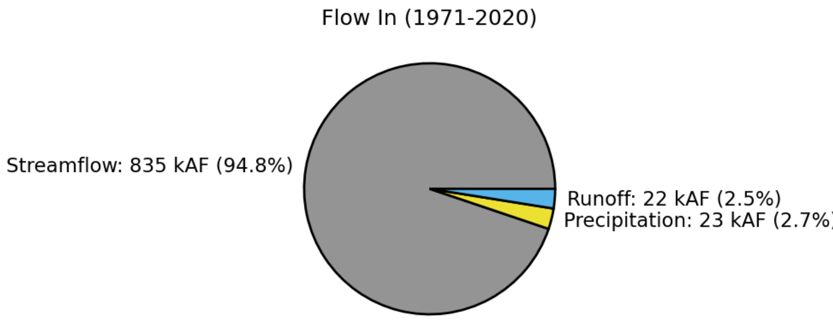
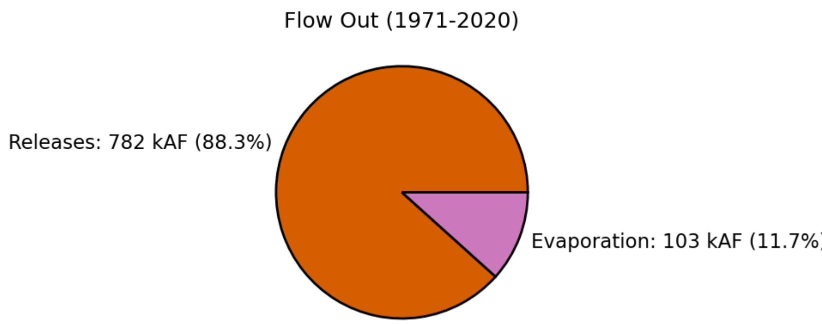
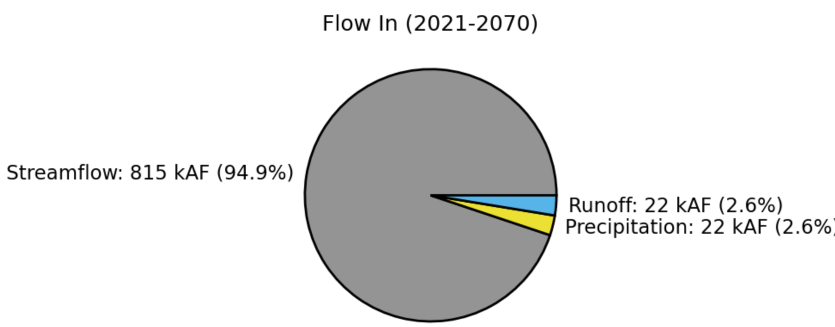



*Figure 8: Change in average streamflow against change in net sub-watershed reservoir contributions between past (1971-2020) and future (2021-2070) periods. Streamflow is the amount of water flowing into the reservoir from upstream (measured at the San Marcial gauge). Net subwatershed influence is the net amount of water entering or leaving the system though reservoir surface evaporation, reservoir surface precipitation, and runoff from the Caballo and Elephant Butte subwatersheds. Each point represents a climate simulation. The solid lines represent no change between the past and future time periods. The dashed lines show the median amount of change for each axis.*


Flow In (1971-2020)
Streamflow: 835 kAF (94.8%)
Runoff: 22 kAF (2.5%)
Precipitation: 23 kAF (2.7%)


Flow Out (1971-2020)
Releases: 782 kAF (88.3%)
Evaporation: 103 kAF (11.7%)


Flow In (2021-2070)
Streamflow: 815 kAF (94.9%)
Runoff: 22 kAF (2.6%)
Precipitation: 22 kAF (2.6%)

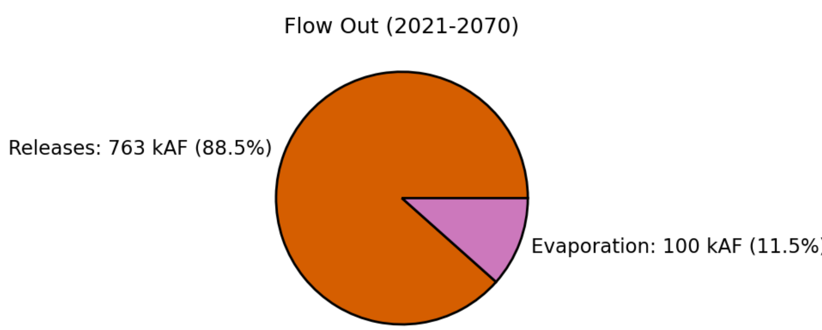

Flow Out (2021-2070)
Releases: 763 kAF (88.5%)
Evaporation: 100 kAF (11.5%)

*Figure 9: This figure shows the relative magnitude of each term in the water balance. Percentages were calculated based on the average across all simulations 1971-2020 and 2021-2070. Flows into the reservoir are approximately equal to the flows out at this time scale allowing comparison between percentages in and out over the same time period. Evaporation is a larger loss than local runoff and precipitation causing the amount of water released by the reservoir to be around 6.5% less than the amount of streamflow coming into the reservoir.*

# B Climate Models

| Climate Model ID | Climate Modeling Group |
|---|---|
| ACCESS1-0 | Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia |
| BCC-CSM1-1 | Beijing Climate Center, China Meteorological Administration |
| BCC-CSM1-1-M | Beijing Climate Center, China Meteorological Administration |
| CanESM2 | Canadian Centre for Climate Modelling and Analysis |
| CCSM4 | National Center for Atmospheric Research |
| CESM1-CAM5 | Community Earth System Model Contributors |
| CESM1-BCG | Community Earth System Model Contributors |
| CMCC-CM | Centro Euro-Mediterraneo per I Cambiamenti Climatici |
| CNRM-CM5 | Centre National de Recherches Meteorologiques/Centre for Europeen de Recherche et Formation Cancee en Calcul Scientifique |
| CSIRO-Mk3-6-0 | Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence |
| FGOALS-g2 | Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth Systems Science, Tsinghua University |
| FIO-ESM | The First Institute of Oceanography, State Oceanic Administration, China |
| GFDL-CM3 | NOAA Geophysical Fluid Dynamics Laboratory |
| GFDL-ESM2G | NOAA Geophysical Fluid Dynamics Laboratory |
| GFDL-ESM2M | NOAA Geophysical Fluid Dynamics Laboratory |
| GISS-E2-H-CC | NASA Goddard Institute for Space Studies |
| GISS-E2-R | NASA Goddard Institute for Space Studies |
| GISS-E2-R-CC | NASA Goddard Institute for Space Studies |
| HadGEM2-AO | Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) |
| HadGEM2-CC | Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) |
| HadGEM2-ES | Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) |
| INM-CM4 | Institute for Numerical Mathematics |
| IPSL-CM5A-MR | Intitut Pierre-Simon Laplace |
| IPSL-CM5B-LR | Intitut Pierre-Simon Laplace |
| MIROC-ESM | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (the University of Tokyo), and National Institute for Environmental Studies |
| MIROC-ESM-CHEM | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (the University of Tokyo), and National Institute for Environmental Studies |
| MIROC5 | Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (the University of Tokyo), and National Institute for Environmental Studies |

| | |
|---|---|
| MPI-ESM-LR | Pax-Planck-Institut fur Meteorologie (Max Planck Institute for Meteorology) |
| MPI-ESM-MR | Pax-Planck-Institut fur Meteorologie (Max Planck Intitute for Meteorology) |
| MRI-CGCM3 | Meteorological Research Institute |
| NorESM1-M | Norwegian Climate Centre |

# C Supplemental Information

Reservoir Model: https://doi.org/10.5281/zenodo.5822674

NetCDF Spatial Averaging: https://doi.org/10.5281/zenodo.5819343

Table 1: Model Inputs

| Name | Value | Description | Units |
|---|---|---|---|
| StartYear | 1950 | Simulation start year | year |
| EndYear | 2099 | Simulation end year | year |
| InitDataYear | 1950 | Initial data year | year |
| EBInitStorage_af | 415000 | Elephant Butte Storage on Starting Year | acre-feet |
| CabInitStorage_af | 57420 | Caballo Reservoir Storage on Starting Year | acre-feet |
| FullAllocation | 790000 | Static Demand | acre-feet |
| RunoffCoeff | 0.01 | Runoff coefficient | n/a |
| EBMin | 17300 | Elephant Butte Minimum storage volume | acre-feet |
| EBMax | 1990000 | Elephant Butte Maximum storage volume | acre-feet |
| EBA0 | 0.00E+00 | EB area-storage a0 | n/a |
| EBA1 | 4.30E-02 | EB area-storage a1 | n/a |
| EBA2 | -4.09E-08 | EB area-storage a2 | n/a |
| EBA3 | 2.42E-14 | EB area-storage a3 | n/a |
| EBA4 | -4.99E-21 | EB area-storage a4 | n/a |
| CabA0 | 0.00E+00 | Caballo area-storage a0 hypsometric | n/a |
| CabA1 | 9.99E-02 | Caballo area-storage a1 hypsometric | n/a |
| CabA2 | -5.92E-07 | Caballo area-storage a2 hypsometric | n/a |
| CabA3 | 2.02E-12 | Caballo area-storage a3 hypsometric | n/a |
| CabA4 | -2.50E-18 | Caballo area-storage a4 hypsometric | n/a |
| OPConst1 | 875000 | Maximum | n/a |
| OPConst2 | 0.56708 | Operating Agreement Coefficient | n/a |
| OPConst3 | 0.46873 | Operating Agreement Coefficient | n/a |
| EvapCoeff | 32 | Evaporation coefficient-future | mm/day/deg C |
| EvapInt | 0 | Evaporation intercept | mm/day |
| CabLandArea | 793751 | Caballo watershed area | acres |
| EBLandArea | 1400469 | Elephant Butte watershed area | acres |
| HistoricTas | 11.86212126 | Avg E.B. temp (1950-1999), access avg | deg C |
| HistoricEvap | 1354.6 | Avg EB evaporation (1950-1999) | mm |