TMWA CLIMATE CHANGE ANALYSIS

Contract No. PO-004638

Abstract

This paper discusses the methods that were utilized to develop hydrology for the Truckee River Basin that has been adjusted for a changing climate. This hydrology was developed as part of the Water for the Seasons research project that was funded by NSF and USDA. After the Water for the Seasons project was completed, The Truckee Carson TROA Planning Model RiverWare model was used to evaluate the future water supply of the Truckee Meadows Water Authority (TMWA) based on the Water for the Seasons hydrology. A validation of the Water for the Seasons hydrology was also completed as part of this effort.

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1 INTRODUCTION

This study discusses the methods that were utilized to develop hydrology for the Truckee River Basin that has been adjusted for a changing climate. This hydrology was developed as part of the Water for the Seasons research project that was funded by NSF and USDA from 2014-2018. After the Water for the Seasons project was completed, the Truckee Carson TROA Planning Model RiverWare model was used to evaluate the future water supply of the Truckee Meadows Water Authority (TMWA) based on the Water for the Seasons hydrology. This study utilizes preliminary assumptions for demands and other parameters that are further refined by TMWA in the 2020-2040 Water Resource Plan. (Truckee Meadows Water Authority, 2020) A validation of the Water for the Seasons hydrology was also completed as part of this effort.

Water Supply planning can be affected by many different variables. In areas that depend on surface water flow to meet municipal, industrial and agricultural water demands a thorough understanding of the area's hydrologic regime is necessary. A hydrologic regime can generally be defined by five main components: magnitude, frequency, duration, timing and rate of change (Poff, et al., 1997). While each of these components are important to water supply the magnitude (quantity), timing and frequency are generally the most important. First, the quantity of water needs to be sufficient to meet demands. Second, the water needs to come at a time of year that is in phase with demands and/or during the period when reservoirs are permitted to store water. Third, a sufficient volume must come frequently enough to allow for enough drought storage to meet demands during the following periods when quantity is insufficient.

1.1 WATER SUPPLY PLANNING OVERVIEW

There are many different approaches that can be taken to determine if a portfolio of water rights and resources will be sufficient to meet demand with a desired reliability. The most straightforward method is to use records of observed historical streamflow to develop statistics characterizing the magnitude, timing and frequency of the water supply. These statistics can then be used to: (a) compute the amount of supply that will be available over various periods, (b) compare the supply to anticipated demand, and (c) ensure that additional storage is reserved to satisfy demand through periods of shortage. This technique becomes challenging in complicated river systems which often have multiple reservoirs, many different users, complex water rights, complex operational agreements and additional requirements. These complications can make it difficult to estimate the supply from a particular water source. Also, other attributes of the streamflow beyond quantity, timing, and frequency can have significant and at times poorly understood impacts on the yield of water rights. For example, a junior water right may only receive water when flows are high. If the flows are changing quickly then the water right will only receive water for a short period of time. In contrast, if the flows are changing slowly then the water right may receive water for a longer period of time after they are entitled to divert. Many such relationships exist, some of which can be difficult to understand or account for.

One way to take these complex relationships into account is to use a water supply computer model. Once the water supply model is configured to represent the physical features, water rights, demands, and water agreements of the basin, it can be used to estimate the yield of the water rights in the system based on input streamflow (or hydrology). Such a model can then be altered to estimate how the yields may change as the demands and hydrology in the basin change. A strength of a water supply model is that it can determine how water supply yield will be affected by all the characteristics of hydrology.

1.2 Hydrology Selection

When developing a water supply model, the modeler must decide what hydrology to input into the model for water supply planning. The modeler may have to choose between historical and synthetic hydrologic datasets. If synthetic hydrology is used (produced by statistical methods, or a precipitation runoff model) it can be difficult to ensure that the quantity, timing, and frequency of the hydrologic data is representative of the region and appropriate for use in the water supply model. Furthermore, verification of the other characteristics of hydrology that may impact water supply can be a challenging task. Depending on data availability, planning objectives, and various other variables different hydrology datasets may be appropriate for different studies. Here we will discuss three options for hydrology datasets: historical, adjusted historical and fully synthetic.

1.2.1 Historical Hydrology

Fortunately, streamflow is widely measured and some areas (including the Truckee River Basin) have a historical dataset of observed flows that extends over 100 years. These observed flows can be used as input to the water supply model to determine what the yield of water rights would be if the observed streamflow record were to repeat itself with the anticipated future demands, operational policy, and basin structures (reservoirs, diversions, etc.). The strength of this method is that the historical record accurately captures all the characteristics of hydrology for the basin. In addition, use of historical hydrology reduces the amount of modeling that needs to be done, which always introduces some amount of modeling error and/or bias. Even though it is not anticipated that history will repeat itself precisely, the use of historical streamflow for water supply planning ensures that all the important characteristics of the basin hydrology are considered. A schematic

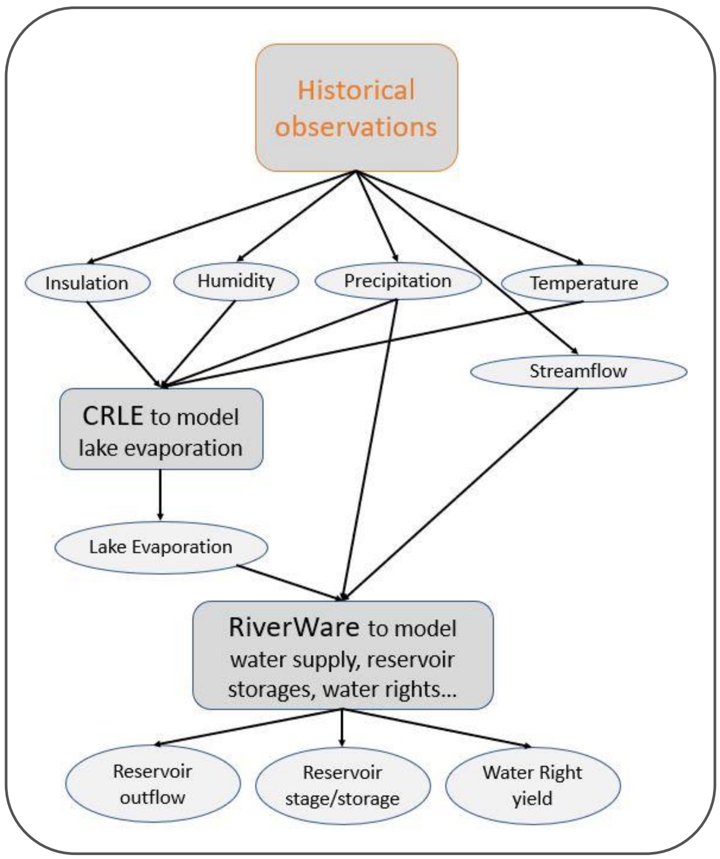


Figure 1: Modeling water supply using historical observations

summarizing this approach is shown in Figure 1. Using observed, historical hydrology to drive a water supply model has been the industry standard for many years to assess future water supply reliability. The methodology is well established and provides a reasonable assessment of the resiliency of a water user's water supply. It does, however, rely on the major assumption that the past climate provides a good representation of the future climate.

1.2.2 Non-Historical Hydrology

But what happens if there is reason to believe that significant characteristics of past climate will be different in the future?

In order to begin to answer this question we must anticipate how the future climate will differ from the past, then evaluate if those anticipated differences are likely to alter the future streamflow characteristics (magnitude, frequency, duration, timing, or rate of change). In a climate which is following a general warming trend, we can expect to see several impacts on hydrology in the future. The natural flow may be impacted as evaporation and transpiration are known to increase with temperature, which both remove water from the system and reduce the overall amount of water supply. In historically snowmelt driven basins like the Truckee River Basin, snow accumulates throughout the winter then melts during the spring and summer months. Snowmelt produces high flows during the spring and summer, while flows are low in the winter when much of the precipitation falls as snow and does not produce immediate runoff. In a warmer future, less snow may accumulate and the snow that accumulates might melt and run off earlier, potentially significantly altering the timing of the streamflow. Many of these processes are well understood, and computer models are often used to relate the climate (generally just the precipitation and temperature, although wind, humidity and other parameters also constitute climate and may be considered by some models) to the streamflow. Computer models of this type are generally referred to as a precipitation-runoff model. These models can be calibrated to reproduce the historical streamflow when provided with historical climate as input. Generally model calibration involves adjusting model parameters so that the model output streamflow matches the historical streamflow when input with historical precipitation and temperatures. Once the model is calibrated a separate validation period step is generally conducted in which the model is input with additional observed climate and the results are compared to observed streamflow data that was not used in the calibration step. If the model matches the streamflow well in the validation period, then the modeler can have confidence that the precipitation runoff model reasonably represents the physical processes that turn climate (temperature and precipitation) into streamflow in the basin.

Once developed a precipitation-runoff model can be used to generate hydrology from any input climate. Two options for estimating future climate will be discussed: adjusted historical climate and fully synthetic climate.

1.2.2.1 Adjusted Historical Climate: Truckee Basin Study

With a calibrated precipitation-runoff model available, we can relate climate to streamflow. One method for developing future hydrology, is to first adjust the observed climate based on the anticipated changes to climate in the future. Next one can use this climate as input to the precipitation-runoff model to produce adjusted hydrology. The adjusted hydrology can then be input into the water supply model to determine how the changes to climate will impact water supply reliability. This process is summarized in Figure 2. This approach was utilized in the Truckee Basin Study (Department of the Interior, Bureau of Reclamation, 2015) in which the historical precipitation and temperatures were adjusted to reflect five potential future climate scenarios. These scenarios were intended to represent the range of possible future change in precipitation and temperature based on the suite of climate projections used for that effort (the CMIP3 ensemble released in 2010).

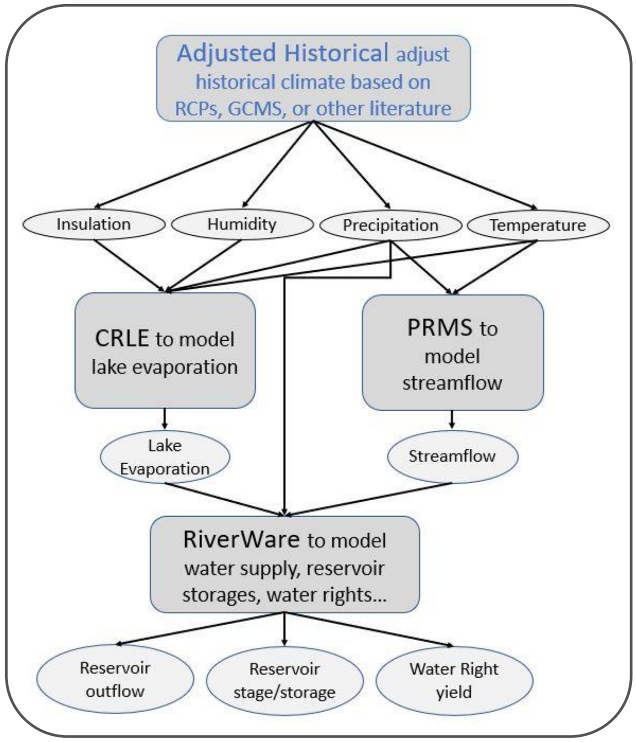


Figure 2: Modeling water supply with adjusted historical climate

1.2.2.2 Fully Synthetic Climate: Water for the Seasons

But what if there is reason to believe that the changes to future climate will not be effectively represented by simple adjustments to the historical precipitation and/or temperature?

The earth's climate is driven by many interconnected processes. For example, melting ice caps could impact the circulation of the jet-stream which may shift the flow of moisture to or from a particular location. In order to thoroughly estimate how the runoff in a region will be impacted by increasing greenhouse gases, it is necessary to simulate the climate of the entire globe as the global climate is certainly interconnected. This adds a significant challenge and requires adding several more layers of models to the process, in comparison to merely adjusting the historical climate. Within this method, all aspects of climate are subject to change and any of these may have impacts to the streamflow regime's magnitude, frequency, duration, timing, and/or rate of change. The modeling process for producing fully synthetic hydrology is summarized in Figure 3.

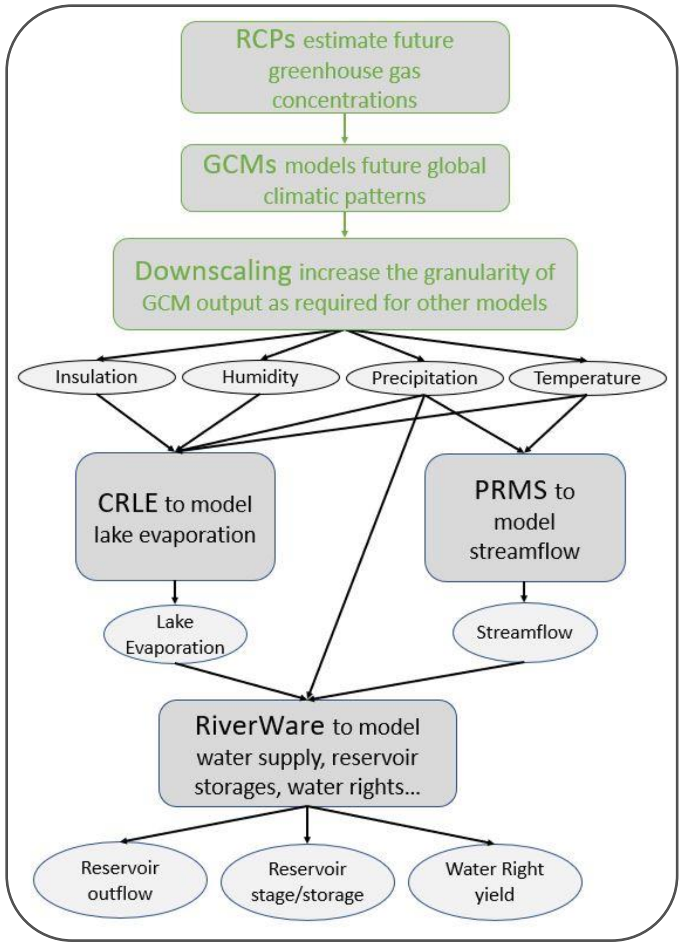


Figure 3: Modeling schematic for producing fully synthetic

The Water for the Seasons project was a four-year research project funded by the National Science Foundation and United States Department of Agriculture to assess the impacts of drought due to changing climate in the Truckee-Carson River System. The project team included scientists, engineers and researchers from the University of Nevada Reno, Desert Research Institute, Precision Water Resources Engineering, United States Geological Survey and Ohio University that integrated climate, hydrology, operations, and groundwater models. A major part of the Water for the Seasons project was the daunting task of holistically projecting how changes to climate may impact future hydrology. The project accomplished that goal by making available state-of-the-art future hydrology datasets that include the effects of climate change that can be used for water supply planning purposes in the Truckee River Basin. These datasets were developed utilizing the 2013 CMIP5 ensemble output from the IPCC, an update from the 2010 CMIP3 ensemble used by the Truckee Basin Study.

1.3 Selected Option: Fully Synthetic Datasets

This paper will summarize the steps taken in the Water for the Seasons project to produce fully synthetic climate and hydrology datasets for the Truckee River Basin, including a summary of the methods that were used to estimate future greenhouse gas concentrations (RCPs), simulate future global climatic patterns (GCMs), downscale and bias correct the GCM results, estimate future evaporation using Complementary Relationship Lake Evaporation (CRLE), and estimate future streamflow using Precipitation-Runoff Modeling System (PRMS). The resultant hydrology will be validated to discuss how well it represents the observed streamflow of the Truckee River Basin. Finally, the assumptions of the water supply model (RiverWare) will be described and results characterizing impacts to water supply will be discussed. Additional water supply results will be discussed in the 2020-2040 Truckee Meadows Water Authority Water Resource Plan.

2 Climate and Hydrology Models

In order to produce fully synthetic future hydrology, several models and processes are necessary. These models and processes have been developed by various groups and made available for public use and planning. A summary of each of the necessary processes (shown in Figure 3) will follow. As part of the CMIP5, model output was provided based on observed greenhouse gas concentrations for the historical validation period of 1951-2005. Compilation and processing of the necessary GCM downscaled data through the PRMS and CLRE models was completed by Seshadri Rajagopal and Justin Huntington of Desert Research Institute as part of the Water for the Seasons project (Rajagopal, 2019). After the Water for the Seasons Project was completed, an additional hydrology validation process was completed by Precision Water Resources Engineering to compare the fully synthetic modeled hydrology to the observed hydrology from 1951-2019 extending the CMIP5 validation period with RCP 4.5 scenario output to compare to all of the available historical data.

2.1 Greenhouse Gas Concentrations: RCP Overview

The key variables in predicting how future global climate trends change are the amount of future greenhouse gas emissions, their concentrations, and land-use trajectories. With the varied amount of science available for these projections, a standard set of scenarios is used to guarantee consistency in the climate science research and study fields. The scenarios, developed as part of the Intergovernmental Panel on Climate Change (IPCC), are known as Representative Concentration Pathways. The IPCC Expert Meeting Report of 2007 defines what the pathways represent:

> *"The name 'representative concentration pathways' was chosen to emphasize the rationale behind their use. RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasize that it is not only a specific long-term concentration or radiative forcing outcome, such as a*

stabilization level, that is of interest, but also the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics" (The Core Writing Team, 2008).

Four Pathways are provided (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) and are intended to "together span the range of year 2100 radiative forcing values found in open literature, i.e. from 2.6 to 8.5 W/m2." (van Vuuren, et al., 2011). Concentrations are used as the primary product of the RCPs and designed as inputs to climate models. The RCPs represent a larger set of scenarios in literature and each of the RCPs covers the 1850 to 2100 period with extensions available that have been formulated for the period thereafter up to 2300 (van Vuuren, et al., 2011)

RCPs should not be interpreted as forecasts, absolute bounds or considered to be policy prescriptive; rather, RCPs represent the general perception of emissions produced in literature.

The general description of each pathway is shown in Table 1.

Table 1: Description of each pathway defined by the IPCC's Meeting Report of 2007.

Pathway	Description
RCP 2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline to 2.6 W/m^2 by 2100; represents the range of lowest scenarios, which require stringent climate policies to limit emissions; representative of the lowest mitigation scenarios currently in literature
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100; comparable to several climate policy scenarios and some low-emissions reference scenarios; low baseline or intermediate mitigation scenario
RCP 6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100; representative of most non-climate policy scenarios; medium baseline or high mitigation scenario
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100; representative of the high range of non-climate policy scenarios; high emission scenario

The Water for the Seasons study utilizes the RCP 4.5, which corresponds to stabilizing greenhouse gas emissions, and RCP 8.5 which is a high emissions scenario. The RCP 8.5 scenarios has high levels of greenhouse gas emissions with lower mitigation efforts of greenhouse gasses.

The greenhouse gas projections and radiative forcing for all four pathways are shown in Figure 4 and Figure 5. The greenhouse gas concentration curves based on the RCP 8.5 scenario show the upper range of emission potential, while the RCP 4.5 shows a more moderate emission scenario.

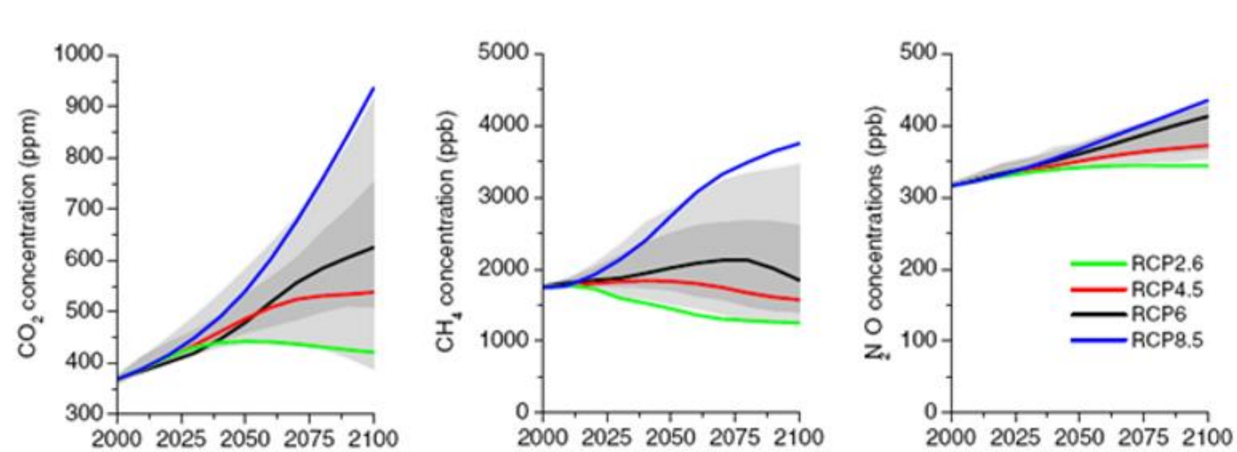


Figure 4: Trends in concentrations of greenhouse gases (van Vuuren, et al., 2011). Grey area indicates the 98th and 90th percentiles (light/dark grey) of the recent EMF-22 study (Clarke, et al., 2009).

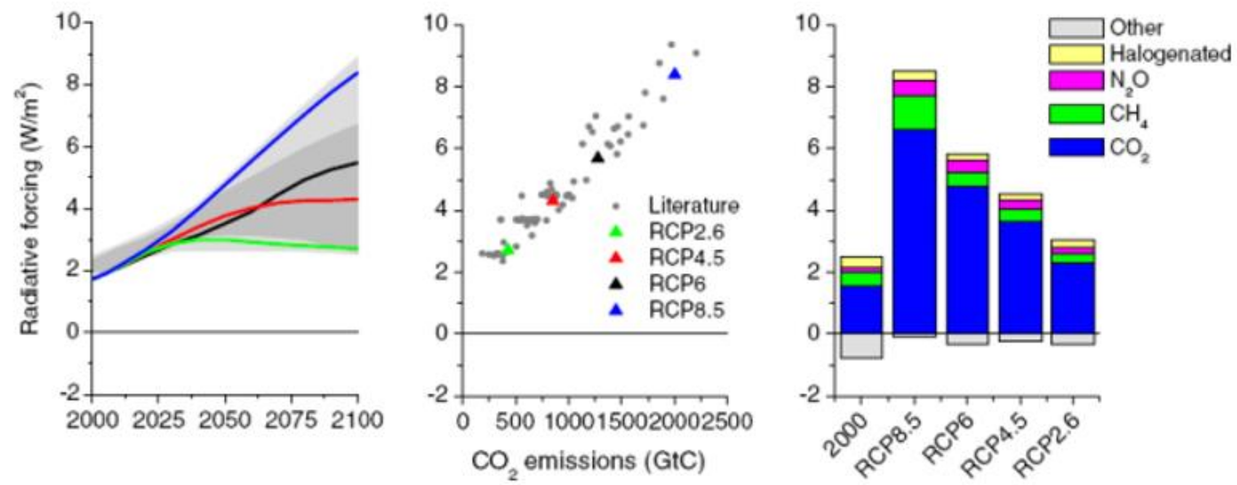


Figure 5: Trends in Radiative Forcing (left), Cumulative 21st Century CO_2 Emissions vs. 2100 Radiative Forcing (middle), and 2100 Forcing Level per Category (right). Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature. The dots in the middle graph also represent many studies. Forcing is relative to pre-industrial values and does not include land use (albedo), dust, or nitrate aerosol forcing (van Vuuren, et al., 2011).

2.2 Simulating Global Climate: GCM Selection Process

There are more than 60 general circulation models (GCMs) currently used by the Intergovernmental Panel on Climate Change (IPCC) in the Fifth Assessment Report produced as part of the *Coupled Model Intercomparison Project Phase 5* (CMIP5). Each of the models has been run with up to all four of the RCPs available as input to GCMs. This suite of simulated climate is too large for the scope of the Water for the Seasons project, so a subset of those GCMs was selected. A GCM provides simulated climate parameters that can be input to hydrology models to generate simulated streamflow for use in water resource models. Climate simulation is an imprecise science and the different GCMs do not always agree. To account for this, the output from several GCMs are used to represent the uncertainty in changes to the climate that will result from the different RCP Greenhouse Gas scenarios.

Six of the eight GCMs used in the Water for the Seasons study were included because they belonged to a group of 10 GCMs that the California Department of Water Resources determined through a commissioned study to be the best representations of the potential climate futures for California (see Table 2). The study, *Perspectives and Guidance for Climate Change Analysis,* by Lynn, et. al., 2005, used a series of methods for comparing GCM model results to climate variables that had resemblance to those that impact the southwestern United States. The analysis started with 31 CMIP5 GCMs that were evaluated over Global Metrics, Regional Metrics, and then California Metrics (see Table 3 below). The global metrics included longwave and shortwave radiation, winds, precipitation, and temperature. The analysis of these metrics removed 12 of the GCMs as their global performance was not rated high enough. The regional round of metric evaluation ranked models based on their "daily and seasonal regional temperature structure, and in the level of anomalous variability of precipitation, along with other measures" (Lynn, Schwarz, Anderson, & Correa, 2015). The regional round of model culling removed four additional models. The remaining 15 GCMs were evaluated on a level that was considered relevant to the California climate and water resources. The evaluation was made on such variables as "ENSO temporal variation and the correlation of the ENSO precipitation teleconnection pattern to that of historical observation" (Lynn, Schwarz, Anderson, & Correa, 2015). Other evaluation metrics included the magnitude of variability of the frequency of dry periods within a 10-year period and variables like the maximum 3-day total precipitation. There was also an effort to not use two models from the same modeling group to increase diversity in the model output. These efforts eliminated five models leaving 10 GCMs that passed the successive screenings.

Table 2: GCMs selected by DWR and for this study.

GCMs	Selected By DWR	Selected for this study
ACCESS-1.0		
CanESM2		
CCSM4		
CESM1-BGC		
CMCC-CMS		
CNRM-CM5		
GFDL-CM3		
HadGEM2-CC		
HadGEM2-ES		
MIROC5		
BCC-CSM1-1		
GFDL-ESM2M		

Table 3: Evaluation metrics used by California DWR for selecting GCMs to use for California water resources (Lynn, Schwarz, Anderson, & Correa, 2015).

Metric	Description
Global Metrics (Gleckler et al. 2008)	
LW CRE, SW CRE	Longwave (LW) or Shortwave (SW) Cloud Radiation Effects
RSUT, RLUT	Top of the Atmosphere Reflected Shortwave & Longwave Radiation
PR	Total Precipitation
TAS	Surface Air Temperature
ZG (500hPa)	Geopotential Height
VA (200hPa), VA (850hPA) UA (200hPa), UA (850hPA)	Meridional (VA, North-South) and Zonal (UA, West-East) wind speeds at two different levels in the atmosphere 200hPa and 850hPA
TA (200hPa), TA (850hPA)	Temperature at two different levels in the atmosphere 200hPa & 850hPA
Western United States Metrics (Rupp et al. 2013)	
Mean-T and Mean-P	Mean Annual Temperature (T) and Precipitation (P), 1960-1999
DTR_MMM	Mean diurnal temperature range, 1950-1999
SeasonAmp-T SeasonAmp-P	Mean amplitude of seasonal cycle, as the difference between warmest and coldest month (T) or between wettest and driest month (P), 1960-1999 Monthly precipitation calculated as percentage of mean annual total
SpaceCor-MMM*-T SpaceCor-MMM-P	Correlation of simulated with observed mean spatial pattern of temperature and precipitation, 1960-1999
SpaceSD-MMM-T SpaceSD-MMM*-P	Standard deviation of the mean spatial pattern of temperature and precipitation, 1960-1999
TimeVar.1-T to TimeVar.8-T	Variance of temperature calculated at frequencies (time periods of aggregation) ranging for N=1 & 8 years, 1901-1999
TimeCV.1-P to TimeCV.8-P	Coefficient of variation (CV) of precipitation calculated at frequencies (time periods of aggregation) ranging for N=1 & 8 water years[ƚ], 1902-1999
Trend-T and Trend-P	Linear trend of annual temperature and precipitation, 1901-1999
ENSO-T and ENSO-P	Correlation of winter temperature and precipitation with Niño 3.4 index, 1901-1999
Hurst-T and Hurst-P	Hurst Exponent using monthly difference anomalies (T) or fractional anomalies (P), 1901-1999.
California Water Resources Metrics	
Std dev # dry years/10-year period	Standard deviation of 10-year totals of the number of dry years
3-day maximum precipitation	Maximum 3-day total precipitation, as a ratio of average water year[ƚ] precipitation 1961-1990 (%)
El Niño Pattern Correlation	Spatial structure of correlation of precipitation to the Niño 3.4 ENSO index derived from a GCM, gauged by patter correlation to that from historical observations
El Niño Temporal Correlation	Niño 3.4, temporal variation, a measure of the El Niño Southern Oscillation
Miscellaneous	
Model Family	No more than two models from the same model family were included in the selected set of models to represent model diversity

Notes:
*MMM is the season designation: DJF (Dec Jan Feb). MAM (Mar Apr May), JJA (jun July Aug), and SON (Sep Oct Nov).
[ƚ]Water years are October to September instead of the calendar year from January to December.
For GCM background information and affiliated research instituation, see CMIP5 Coupled Model Intercomparison Project at http://cmip-pamdi.llnl.gov/cmip5/availability.html.

In choosing GCMs for the Water for the Seasons, only some of the GCMs included all the data that was necessary for the downscaling methods. From the final 10 GCMs chosen by California, four models did not contain the appropriate data. The four models included in the California

Department of Water Resources study and not included in this study include ACCESS-1.0, ECSM1-BGC, CMCC-CMS, and GFDL-CM3.

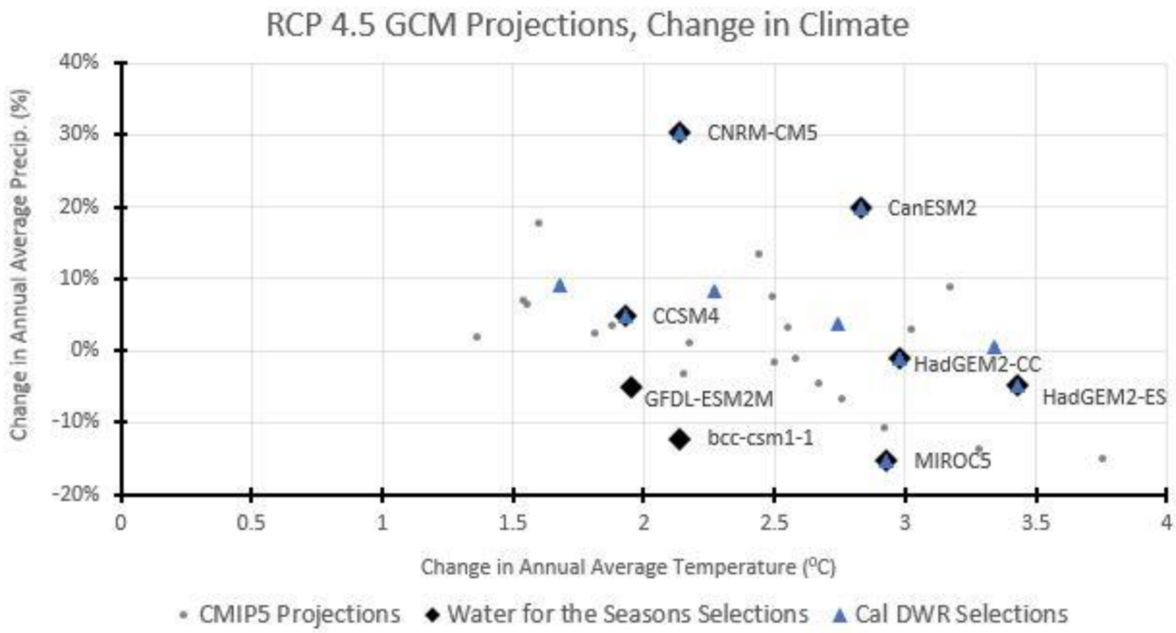
The two additional GCMs were added for development of the Fully Synthetic Climate. These GCMs were chosen because they were two of the five GCMs that were eliminated in the last round of GCM culling by Lynn, et. Al, and they have the data that is necessary for the downscaling effort. This brought the number of GCMs used in the Water for the Seasons project to eight, six from the final recommendation from Lynn, et. al and two that were eliminated in the last round of that study. See Table 2 above for the complete list of selections made in the Water for the Seasons study. A summary of the agencies that produced each of the eight selected GCMs is included in Table 4

Table 4: Summary of GCM agency, locations, and the average normalized deviation (see

Table 11, 0% is a perfect match to the historical validation period) (Intergovernmental Panel on Climate Change, 2020).

GCM	Agency	Location	Public or Private	Average Normalized Deviation
CCSM4	National Center for Atmospheric Research	United States	Public	55.6%
CNRM-CM5	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	France	Public	36.4%
CanESM2	Canadian Centre fo Climate Modeling and Analysis	Canada	Public	54.9%
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	United States	Public	81.6%
HadGEM2-CC	Met Office Hadley Centre	United Kingdom	Public	48.7%
HadGEM2 - ES	Met Office Hadley Centre	United Kingdom	Public	22.3%
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan	Public	74.6%
BCC-CSM1-1	Beijing Climate Center	China	Public	61.9%

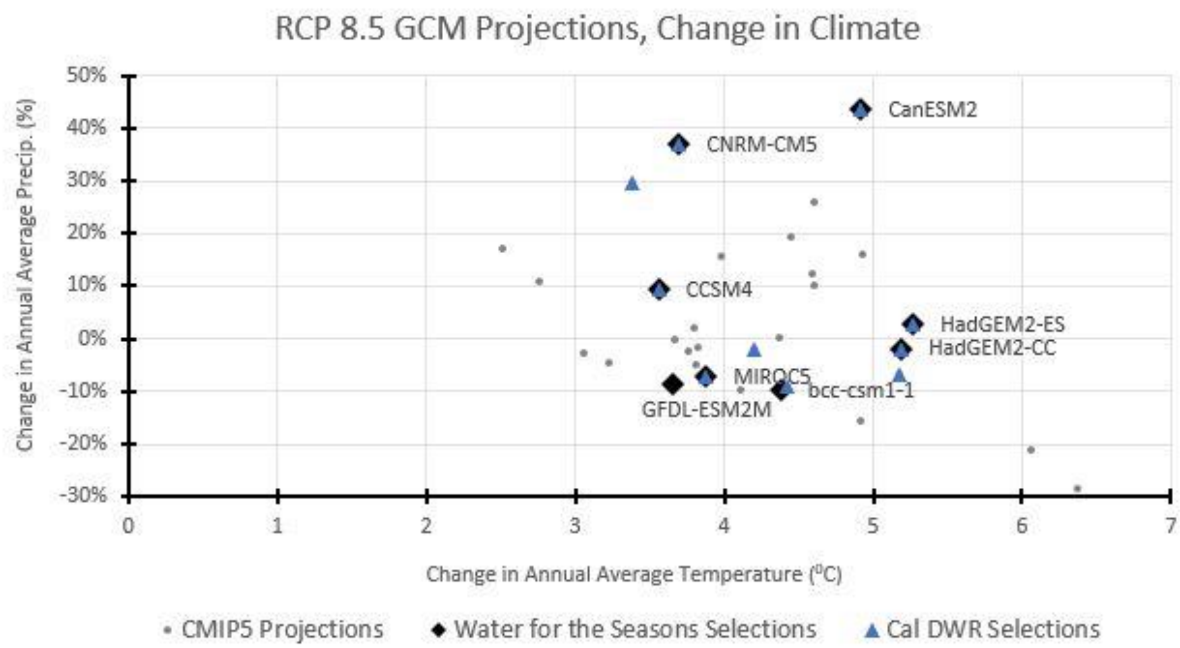
The GCM projections of change in future annual average precipitation and temperature for the RCP 4.5 and RCP 8.5 Scenarios are shown in Figure 6 and Figure 7, respectively. These figures are based on projected averages values for 2070-2099 in comparison to the average from the historical validation period of 1951-2005. Of the initial 31 CMIP5 GCMs (grey dots) the highest and lowest temperature change models were not used, a deviation which is more pronounced in the RCP 8.5 scenario than the RCP 4.5 scenario. For the RCP 4.5 Scenario, the average and median change in temperature are within 0.1°C of the average and median from the CMIP5 GCMs and less than the average and median of the DWR GCMs. For precipitation in the RCP 4.5 Scenario, the average of the Water for the Seasons GCMs again was similar to the CMIP5 GCMs with a 2.1% increase over the validation period which is less than half of the Cal DWR average increase of 5.6%. The median of the Water for the Seasons models showed a decrease in precipitation of 2.9% where the median of the CMIP5 GCMS had an increase of 2.3% and the median the Cal DWR GCM's showed an increase of 4.4%.



	CMIP5 Projections		Cal DWR Selections		Water for the Seasons Selections	
	Temp. Change °C	Precip. Change %	Temp. Change °C	Precip. Change %	Temp. Change °C	Precip. Change %
Average	2.45	1.84%	2.63	5.61%	2.54	2.10%
Median	2.50	2.25%	2.79	4.37%	2.49	-2.91%
Max	3.75	30.26%	3.43	30.26%	3.43	30.26%
Min	1.36	-15.25%	1.68	-15.25%	1.93	-15.25%

Figure 6: "Selection space" of the GCM projections for RCP 4.5.The GCM projections are plotted by their values of "Change in Temperature" from historical and "Percent Change in Precipitation" from historical for the years 2070-2099. The historical comparison period are the years 1976-2005. (Pierce & Cayan, Email Exchange for Data Acquisition for Sacramento/Central Valley Region, 2020)

For the RCP 8.5 scenario, the GCM's selected for this study align more closely with the Cal DWR GCM projections. Most notable is that the potential increase in precipitation is much greater than the RCP 4.5 scenario where the selected Water for the Seasons average change in precipitation is 8.2% in the RCP 8.5 scenario compared to only 2.2% in the RCP 4.5 scenario. These deviations between RCP scenarios are not observed in the median statistic, which is generally lower in the RCP 8.5 scenario. This effect is most pronounced in the CanESM2 and CNRM-CM5 GCMs which show the largest increase in precipitation among all of the GCMs. These two GCM's increase the average for Water for the Seasons and Cal DWR models in a way that does not occur when viewing the larger dataset of the 31 CMIP5 models.



	CMIP5 Projections		Cal DWR Selections		Water for the Seasons Selections	
	Temp. Change °C	Precip. Change %	Temp. Change °C	Precip. Change %	Temp. Change °C	Precip. Change %
Average	4.22	3.66%	4.37	9.59%	4.32	8.18%
Median	4.16	-0.72%	4.31	0.45%	4.13	0.45%
Max	6.37	43.53%	5.27	43.53%	5.27	43.53%
Min	2.51	-28.59%	3.38	-8.90%	3.56	-9.63%

Figure 7: "Selection space" of the GCM projections for RCP 8.5. GCM projections are plotted by their values of "Change in Temperature" from historical and "Percent Change in Precipitation" from historical for the years 2070-2099. The historical comparison period are the years 1976-2005. (Pierce, Kalansky, & Cayan, Climate, Drought, and Sea Level Rise Scenarios for California's Fourth Climate Change Assessment, 2018).

2.3 Downscaling and Bias-Correcting GCMs: LOCA and MACA

Once the eight GCMs were selected, their output needed to be processed to represent the spatial detail required for use in the precipitation-runoff models that produce the hydrology for the Truckee River Basin. This process is known as downscaling. The data that is provided from GCMs is at a relatively coarse spatial resolution, somewhere on the order of 100-mile squares. The downscaling efforts use different statistical methods to generate finer spatial resolution in the GCM output. Downscaling translates GCM signals down to useable hydrologic data. There are many different downscaling methods available, and while some are sufficient for certain applications, more advanced downscaling methods are necessary for applications such as developing hydrology. Two different methods were used to downscale different input variables to the hydrology models. Additionally, both methods apply bias correction to accommodate for differences between the GCM simulations of the validation period and the observed historical period.

The first downscaling method is the Localized Constructed Analogs (LOCA) method. The LOCA method "is a statistical scheme that produces downscaled estimates suitable for hydrological simulations using a multi-scale spatial matching scheme to pick appropriate analog days from observations" (What is LOCA?, 2019). This method uses a pool of potential match days that best represent a variable. A value of the match day that best matches the local areas around a grid scale is used for a finer resolution. This is done using the "systematic historical effects of topography on local weather patterns" (Pierce & Cayan, 2017) that are based on historical relationships. The data provided through the LOCA Method includes temperature and precipitation data at a scale of approximately six-kilometer grids.

The second method is the Multivariate Adaptive Constructed Analogs (MACA) method. The MACA method "is a multi-step process that uses bias correction procedures and a constructed analogs approach for developing the fine-scale spatial pattern using a library of observed patterns" (MACA, 2019). The data resolution is daily at 8-kilometer grid cell size. The products used from MACA include maximum and minimum temperature, maximum and minimum relative humidity, the zonal and meridional wind, and precipitation. Data is available for all the GCMs selected for the Water for the Seasons project.

2.4 Precipitation-Runoff Model: PRMS Overview

The Precipitation-Runoff Modeling System (PRMS) developed for the Truckee Basin was used to convert the precipitation data into streamflow data to be used in the Truckee-Carson RiverWare™ Planning Model. PRMS is a deterministic, distributed-parameter, physical process-based modeling system developed to evaluate the response of various combinations of climate and land use on streamflow and general watershed hydrology (U.S. Department of the Interior, Geologic Survey (USGS), 2019). The PRMS models for the Tahoe and Truckee basins were developed by the Desert Research Institute (DRI) and were used for all GCM projection output available for the Truckee and Carson River Basins. The PRMS models were developed as part of the *Truckee Basin Study, 2015*. These models use the temperature and precipitation data for future climate scenarios to simulate hydrology. The PRMS models take the downscaled output of GCMs and use computational grid cells of approximately 300 m^2, which is considered detailed enough to be appropriate for small sub basins of the Truckee and Carson basins (Department of the Interior, Bureau of Reclamation, 2015). For a detailed description of the development of the Truckee Basin PRMS models, refer to *Appendix C – Future Supply Technical Reports* of the Truckee Basin Study

PRMS simulates the hydrology of the basin above the Truckee River at Farad USGS stream gage near the border between California and Nevada. Approximately 90% of the runoff in the Truckee Basin originates upstream of the Farad gage. For basin inflows in the lower Truckee Basin and in the Carson Basin, future flows were estimated using regression equations (see *Appendix C –*

Future Supply Technical Reports of the Truckee Basin Study). The PRMS models were calibrated using historical periods of data and the output was validated using Truckee and Carson Basin hydrology characteristics. Figure 8 below illustrates how well the output for the 8 GCM simulations of the historical validation period (1951-2005) related to observed historical hydrology in the same period. Raw model output for the Tahoe Basin averaged 73% of the historical volume in the validation period, so each GCM's hydrology output was bias corrected to match the historical volumes. The average of the output from the eight GCMs (Model Avg.) for the Little Truckee and Truckee Abv Farad basins were 98% and 101% of the historical values in the validation period. Given that these values are within two-percent of the historical values and there is some statistical uncertainty that the historical validation period (1951-2005) is representative to the overall basin statistics, no bias correction was performed on the output.

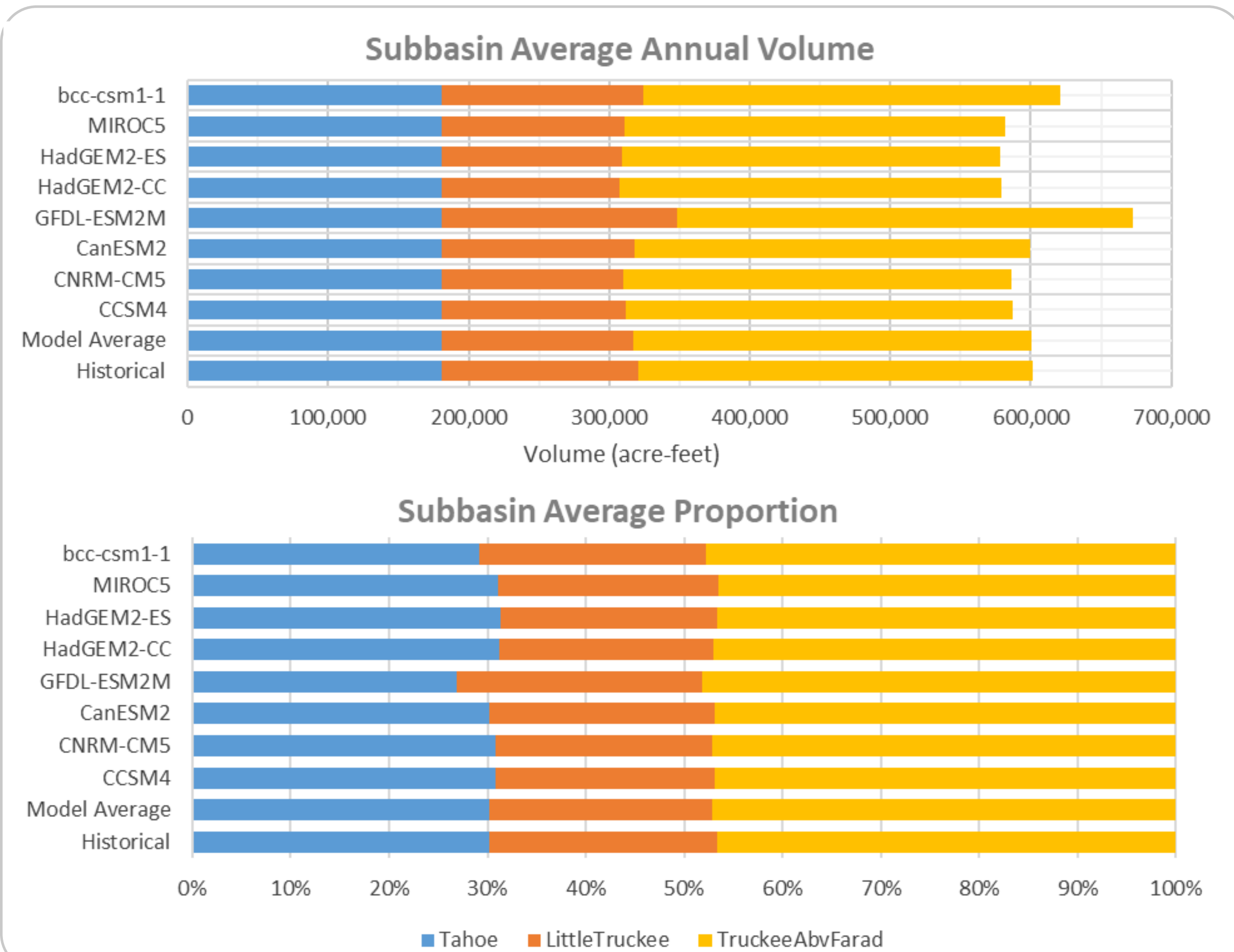


Figure 8: Comparison of the (a) Average Annual Volume by sub basin for the Historical period for each downscaled GCM model output and (b) the Average Proportion of flow for each sub basin for the Historical period for each downscaled GCM model output), for the period of water year 1951 to 2005.

2.5 Evaporation Model: CRLE

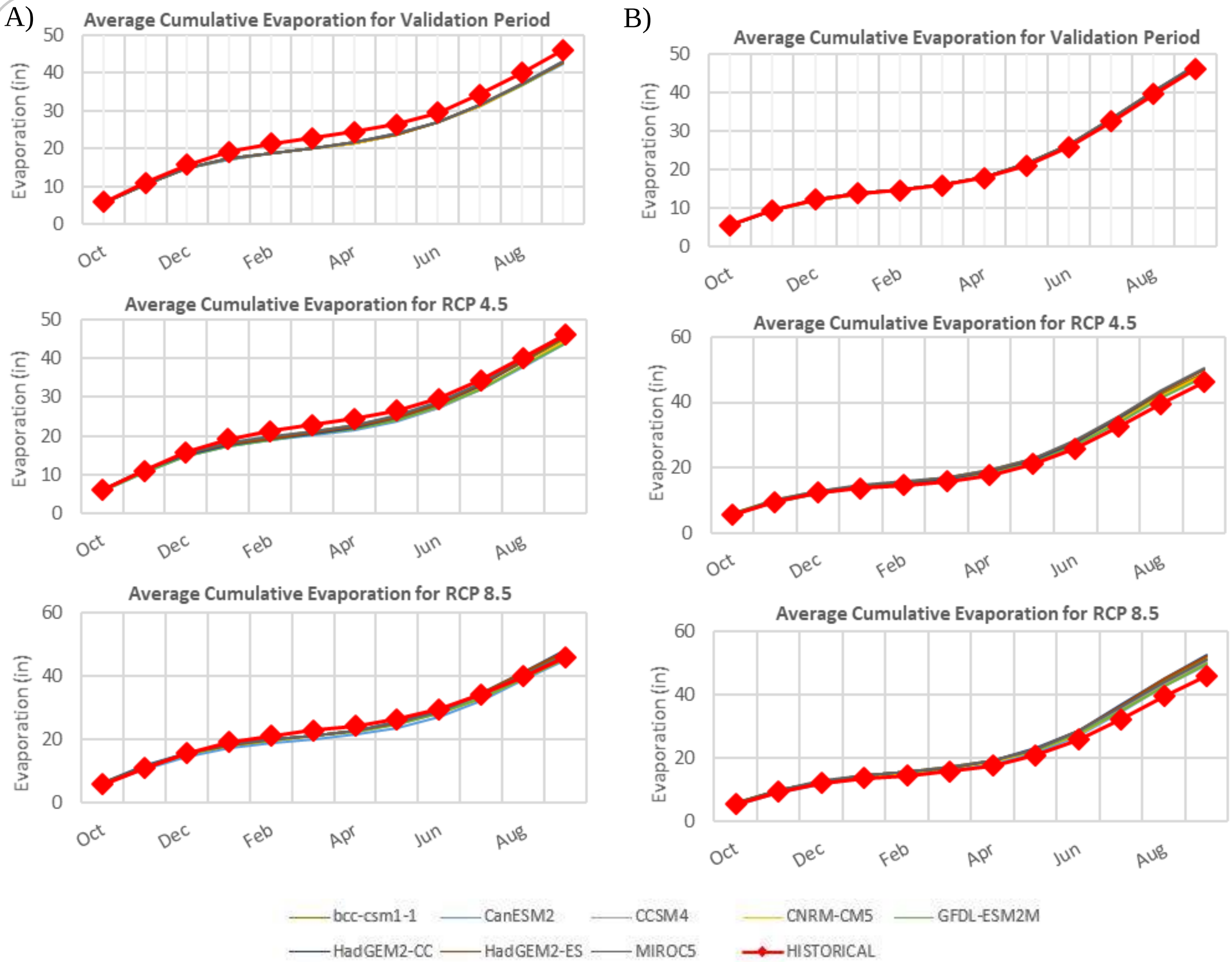
Evaporation rates for the Truckee Basin reservoirs were estimated using a simplified approach that is appropriate for operational purposes and that is based on combined energy and thermodynamic equations with a simple heat storage accounting procedure (Department of the Interior, Bureau of Reclamation, 2015). The Complementary Relationship Lake Evaporation (CRLE) model (Morton, 1986) requires month estimates of solar radiation, air temperature, and dewpoint temperature. It estimates water ‘skin’ temperature, albedo, emissivity, and heat storage impacts. The CRLE has been well tested and extensively applies in operations and modeling of open water evaporation (Huntington & McEvoy, 2011).

The output that the CRLE model gives is the depth evaporation that occurs over a given period. To determine the volume of evaporation, the evaporation depth is multiplied by the surface area of the reservoir at that time. Given that the areas of different reservoirs vary significantly, the same evaporation depth can result is a much different evaporation loss volume on different water bodies. As shown in Table 5, the average surface area of Tahoe is 120,583 acres which is 23 times the average of the sub-total of the surface area on all six other Truckee Basin reservoirs.

Table 5: Reservoir surface area summary for nine prominent lakes and reservoirs in the Truckee-Carson River Basins. Based on daily observed elevations from October 2000 through May 2015. All values are in acres. (TIS, 2019)

Reservoir or Lake	Maximum	Minimum	Average	Standard of Deviation	Coefficent of Variation (CV)
Truckee Reservoirs					
Boca	971	254	636	204	32.1%
Donner	881	778	821	35	4.2%
Independence	715	615	679	17	2.5%
Martis	248	58	62	8	13.5%
Prosser	760	71	400	134	33.4%
Stampede	3,480	1,021	2,591	523	20.2%
Truckee Sub-Total	6,846	3,240	5,189	727	14.0%
Tahoe	121,812	119,820	120,583	480	0.4%
Lahontan	14,953	710	5,480	2,729	49.8%
Pyramid	118,272	109,037	113,042	2,347	2.1%

Downscaled parameters from each of the GCM model’s output were used to run the CRLE model. Figure 9 compares the average cumulative Lake Tahoe and Boca Reservoir Evaporation simulation for the validation period and the RCP 4.5 and RCP 8.5 projections for 2070-2099. The validation period shows some decreases in cumulative monthly evaporation on Lake Tahoe. The historical validation period for the evaporation data is from 2000 to 2009 (Huntington & McEvoy, 2011), where the validation period for the GCMs is from water year 1951 to 2005. If evaporation rates over the GCM validation period have increased from 1951-2005, then the average should be lower than the observed average from 2000-2009. The validation period shows an increase in cumulative evaporation on Boca. The increase is not expected due to the validation period, but the difference is within 2% for each GCM and was determined to be acceptable for this analysis.



C)

	Lahoe Tahoe						Boca Reservoir					
	Validation Period (Hist. 2000-2009, GCMs 1951-2005)		RCP 4.5 (2070 - 2099)		RCP 8.5 (2070 - 2099)		Validation Period (Hist. 2000-2009, GCMs 1951-2005)		RCP 4.5 (2070 - 2099)		RCP 8.5 (2070 - 2099)	
	Evap. (in)	Precent of Reference[1]	Evap. (in)	Precent of Reference[2]	Evap. (in)	Precent of Reference[2]	Evap. (in)	Precent of Reference[1]	Evap. (in)	Precent of Reference[2]	Evap. (in)	Precent of Reference[2]
Historical	46.0	-	-	-	-	-	46.1	-	-	-	-	-
CCSM4	42.7	93%	44.0	103%	46.3	108%	46.6	101%	48.1	103%	50.4	108%
CNRM-CM5	42.5	92%	44.3	104%	45.7	107%	46.5	101%	48.6	104%	50.1	108%
CanESM2	42.7	93%	43.8	103%	45.2	106%	46.6	101%	48.2	103%	49.7	107%
GFDL-ESM2M	42.6	93%	44.0	103%	45.6	107%	46.5	101%	47.9	103%	49.8	107%
HadGEM2-CC	42.7	93%	45.7	107%	48.2	113%	46.6	101%	50.1	107%	52.5	113%
HadGEM2-ES	42.9	93%	45.9	107%	47.9	112%	47.0	102%	50.2	107%	52.5	112%
MIROC5	42.8	93%	46.4	108%	46.8	109%	46.9	102%	50.6	108%	51.2	109%
bcc-csm1-1	42.9	93%	45.2	105%	47.4	111%	46.9	102%	49.1	105%	51.6	110%
Median	42.7	93%	44.7	105%	46.6	109%	46.6	101%	48.9	105%	50.8	109%
Average	42.7	93%	44.9	105%	46.7	109%	46.7	101%	49.1	105%	51.0	109%

Figure 9: Comparison of Average Cumulative Evaporation for (A) Lake Tahoe validation period [2000-2009 for Historical[1], 1950-2005 for GCMs[2]], RCP 4.5 projections of 2070-2099, and RCP 8.5 projections of 2070-2099, (B) Boca Reservoir validation period [2000-2009 for Historical[1], 1950-2005 for GCMs[2]], RCP 4.5 projections of 2070-2099, and RCP 8.5 projections of 2070-2099, (C) Lake Tahoe and Boca Reservoir.

For the both the RCP 4.5 and RCP 8.5 projections of 2070-2099, the comparison is to the validation period evaporation rate for the same GCM and not to the historical value. This is to show the amount of change a model is predicting for a given RCP. The 2070-2099 annual evaporation increases between 3% and 7% for the RCP 4.5 scenarios compared to the validation evaporation amount with a median increase of 5% on Lake Tahoe. For the RCP 8.5 Scenario, increases in evaporation range from 8% to 13% with a median of 9% at Lake Tahoe.

For Boca Reservoir the difference between GCM validation evaporation amounts and RCP 4.5 2070-2099 projections is an increase of between 3% and 7% with a median of 5% and 8%. For the RCP 8.5 2070-2099 projections the average increase in evaporation is 13% with a median increase of 9%.

Each GCM shows an increase in evaporation compared to the same model's performance in the validation period. At Lake Tahoe, these only show a slight increase over the historical validation period. At Boca Reservoir, the values show an increase in evaporation over the historical validation period that are greater than at Lake Tahoe. Figure 9 shows the comparison of Average Cumulative Evaporation depths for Lake Tahoe and Boca Reservoir and the annual increase in evaporation projected by each GCM for each RCP scenario.

2.6 Hydrology Validation

2.6.1 Introduction

"All models are wrong, but some are useful" – George Box (Box, 1979)

The previous sections have described how several models have been used to generate projections of future hydrology reflecting the potential impacts of climate change. Each model is an imperfect representation of the process that it attempts to model. While each has been bias-corrected and reviewed either here or by the references cited, few models will give accurate results with incorrect inputs. So, it is possible that minor errors in the early models in the process cause larger and more significant errors in the later models (see modeling diagram in Figure 3). How can we determine if the end result is useful? To answer this question a validation process has been conducted to determine how well the fully synthetic hydrology reproduces the important characteristics of historical streamflow when input with historical greenhouse gas concentrations. The following sections will review how characteristics of the "validation period" of the fully synthetic hydrology compare to the observed historical hydrology over the same period. Because the validation period does not include the last 14-years of observed historical data we will extend the CMIP5 validation period of the GCM models using the RCP 4.5 forecast to compare it to the historical hydrology record of 1951-2019 extending the validation period from 55-years to 69-years. Comparison of the GCM validation simulation to historical will be discussed for both precipitation and then for runoff volumes for three periods: Annual Volume, April through July Volume, and Non-April through July Volume. For the runoff volume analysis we will consider the Farad Natural Flow (Farad), which is the naturalized inflow occurring upstream of the Truckee River At Farad USGS stream gage (USGS 10346000, located approximately where the Truckee River intersects the state line between California and Nevada), excluding any inflow to or releases from Lake Tahoe.

2.6.2 Precipitation

The runoff in the Truckee River Basin is predominantly driven by snowmelt. Based on the data from water year 1951-2019 for the Boca CO-OP precipitation gage, an average of 79% of the water year precipitation occurs from October through March (Table 6Figure 10). In contrast only about 40% of the historical average water year runoff occurs in the period from October through March (based on the last 30-year average) (TIS, 2019). This illustrates that the Truckee River Basin runoff is heavily snowmelt driven. Historically, snowmelt has provided a reliable source of water in the summer months, when demands are highest, that is out of phase with the time of year when the precipitation occurs. An anticipated impact of warmer future climate is that less of the precipitation will occur as snow and more will occur as rain, and the snowmelt driven runoff would occur earlier in the year. Reductions in the amount of runoff that occurs during the summer months could have water supply resiliency impacts for water providers and irrigators.

Comparisons of the historical data in the validation period shows that the GCM's showed around 83% of the water year precipitation occurring from October through March, which is only 4% higher than what occurred historically. Review of the GCM projections for 2070-2099 with the RCP 4.5 and RPC 8.5 emissions scenarios show a slight increase in some GCM's and some show a slight decrease in the proportion of precipitation occurring from October through March, all of which are within 10% of the proportion shown by the same model in the validation period and fourteen of sixteen of the scenarios are within 5% of the proportion shown by the same model in the validation period.

Table 6: Average Percentage of total Water Year precipitation that occurred through March for the validation period (2070-2099), RCP 4.5 GCM projections, and RCP 8.5 GCM projections.

Percentage of Total Precip through March for:		Historical	CCSM4	CNRM-CM5	CanESM2	GFDL-ESM2M	HadGEM2-CC	HadGEM2-ES	MIROC5	bcc-csm1-1	Median	Average
	Validation Period (1951-2019)	79%	84%	84%	83%	82%	83%	83%	84%	84%	83%	83%
	RCP 4.5 (2070-2099)	-	83%	85%	80%	83%	82%	85%	88%	85%	84%	84%
	RCP 8.5 (2070-2099)	-	83%	87%	74%	90%	83%	85%	83%	85%	84%	84%

Review of the GCM projections for 2070-2099 of the quantity of precipitation has similarly mixed results. With the RCP 4.5 scenario, four models show a decrease in precipitation while four show an increase. CanESM2 shows an increase of 24% while bcc-csm1-1 shows a decrease of 11%, with the average change over all models +4.8% in comparison to the validation period. In the RCP 8.5 scenario, six models show increased precipitation with only two showing a decrease. For this scenario, the largest increase is 69% with the CanESM2 GCM and the largest decrease is 8% with the GFDL-ESM2M GCM. The average change from all models is +15.8%, significantly more than the increase in precipitation with the RCP 4.5 Scenario, primarily due to large increases in the CanESM2 and CNRM-CM5 GCMs.

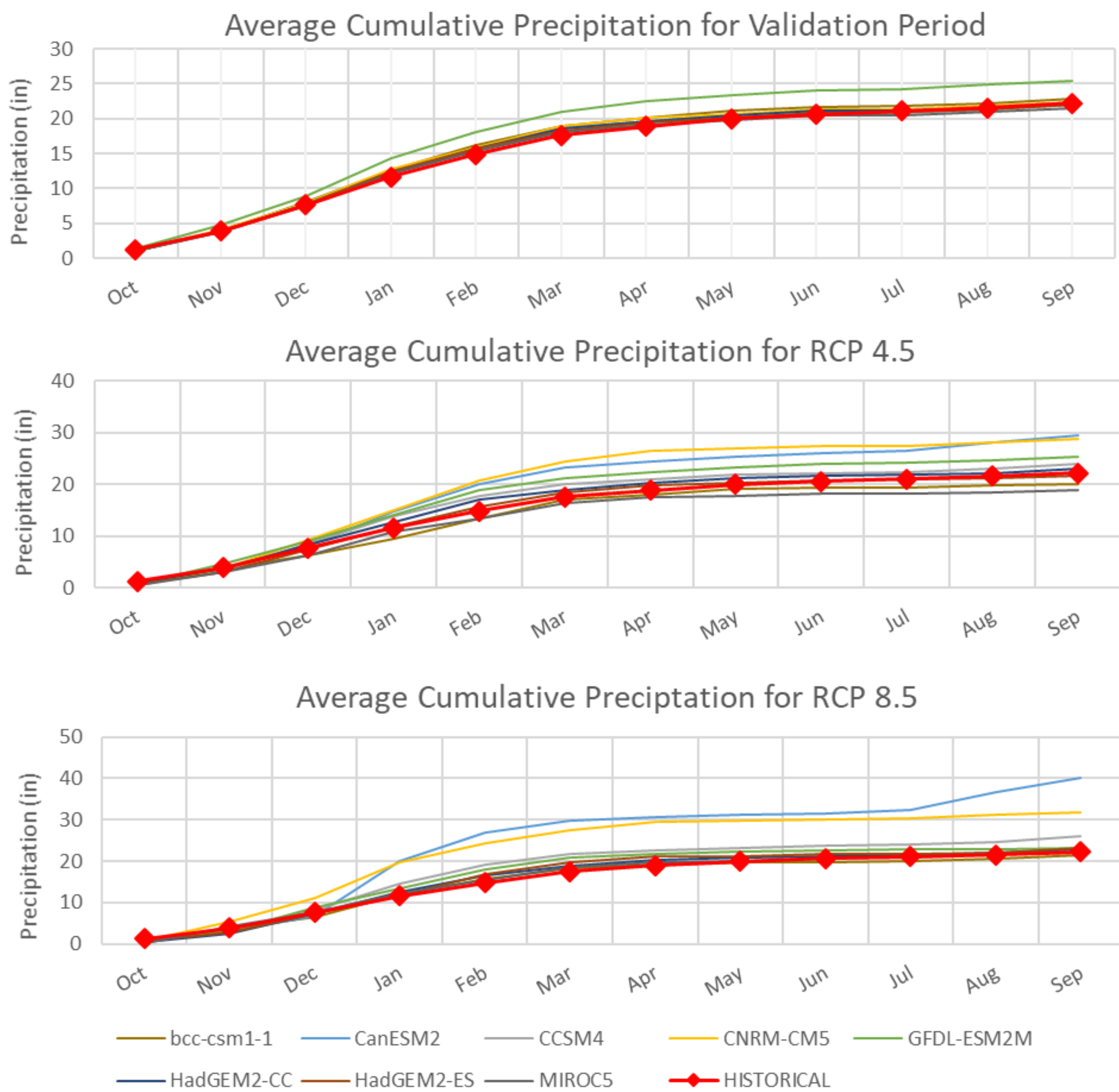


Figure 10 Average Monthly Precipitation for GCMs for the validation period, 2070-2099 (Top), RCP 4.5 GCM projections (Middle), and RCP 8.5 GCM projections (Bottom).

While there is variability between the models and scenarios, most of the GCM models show minor changes in the seasonality and quantity of precipitation in the Truckee River Basin with a few scenarios showing more significant changes.

2.6.3 Annual Volume

The annual runoff volume is the total streamflow available to the basin. If the timing within the year shifts, it may be possible to adjust by storing runoff that occurs outside of the peak demand season in reservoirs; however, changes in the annual volume provides a maximum of the amount of water that will be available for diversions. The period of the year when runoff occurs will be discussed in later sections.

Table 7: Summary of GCM projection average annual volumes in comparison to the historical validation period (water year 1951-2019) in the validation period rows, RCP 4.5 and RCP 8.5 projection rows compare the 2070-2098 volume to the projected historical average for the same period.

		Historical	CCSM4	CNRM-CM5	CanESM2	GFDL-ESM2M	HadGEM2-CC	HadGEM2-ES	MIROC5	bcc-csm1-1	Median	Average
VALIDATION (1951-2019)	Average (acre-feet):	421,688	428,595	415,224	451,777	491,943	373,814	414,039	405,018	441,037	421,909	427,681
	Percent error		2%	-2%	7%	17%	-11%	-2%	-4%	5%	0%	1%
	Slope (acre-feet/year)	-204	1740	-348	632	-2762	-2085	1236	794	-221	206	-127
	Percent error		-951%	70%	-409%	1251%	919%	-704%	-488%	8%	-201%	-38%
RCP 4.5 (2070-'98)	Average (acre-feet):	401,444	468,213	617,569	611,186	482,661	433,925	398,003	338,758	393,837	451,069	468,019
	Percent Change from Validation	-5%	11%	46%	45%	14%	3%	-6%	-20%	-7%	7%	11%
RCP 8.5 (2070-'98)	Average (acre-feet):	401,444	557,141	685,609	796,989	466,232	444,416	452,230	415,770	420,228	459,231	529,827
	Percent Change from Validation	-5%	32%	63%	89%	11%	5%	7%	-1%	0%	9%	26%

Comparison of the 31-year average annual volume produced by each of the GCMs in the validation period is summarized in Figure 11. In the validation period, five of the eight GCMs produced within 5% of the historical volume. The average for all GCM models in the validation period is withing 1% of the historical average. (Table 7).

A linear fit to the historical data in the validation period was extended through the forecast period (2020-2099) to illustrate the current observed trend in Figure 11 A.) and B.). Comparison of the GCM model results to this linear extrapolation shows a general trend toward higher annual volume, with some disagreement between models. Five of the eight GCMS in the RCP 4.5 scenario predict an increase in average volume by the end of the century, by as much as 45% in two cases. Six of eight GCM's in the RCP 8.5 scenario predict an increase, with a maximum change of 89%. The other two GCM's in the RCP 8.5 scenario show minimal change in annual volume by the end of the century, with a difference of 0 and -1%. On average, the RCP 4.5 and

8.5 scenarios show increases of 11 and 26%, respectively in contrast to the 5% decrease obtained by extrapolating the historical 1951-2019 trend (Table 5).

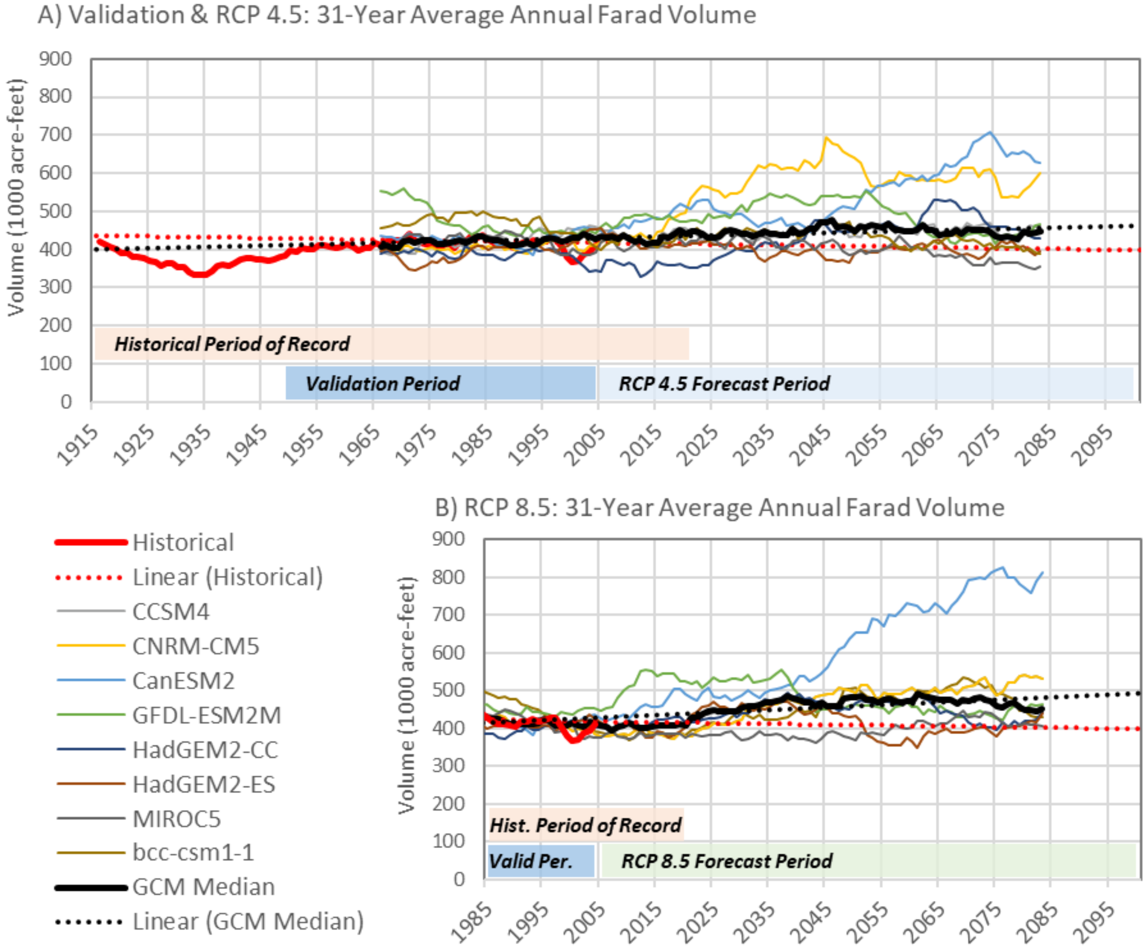


Figure 11: Average Annual Volume Graphs for A) the validation period (1951-2005) and RCP 4.5 projection (2019-2098), and B) RCP 8.5 projection (2019-2098).

2.6.4 April-July Volume

The April through July runoff volume is often an important metric in water resources systems. Changes in the quantity of water that runs off during the April through July period could impact water supply in several ways. If April through July runoff decreases, then additional water will need to be released from reservoirs to augment the lower unregulated inflows. In addition, per United States Army Corp of Engineers' Flood Control Guidelines some reservoirs are not permitted to reach their full storage earlier than May 22nd (for Boca, Stampede and Prosser in the Truckee River Basin). If most of the runoff occurs prior to this date, then reservoirs may be unable to fill. In order to rely on GCM forecasts of changes to this volume, it is important to verify that the GCMs can reproduce the observed trends in April through July runoff.

Table 8: Summary of GCM projection average April through July volumes in comparison to the historical validation period (water year 1951-2005) in the validation period row. The RCP 4.5 and RCP 8.5 projection rows compare the 2070-2098 volume to the projected historical average for the same period.

		Historical	CCSM4	CNRM-CM5	CanESM2	*GFDL-ESM2M*	HadGEM2-CC	HadGEM2-ES	MIROC5	*bcc-csm1-1*	Median	Average
VALIDATION (1951-2019)	Average (acre-feet):	263,769	226,897	247,763	242,668	237,944	244,279	262,797	196,873	226,346	240,306	235,696
	Percent error		-14%	-6%	-8%	-10%	-7%	0%	-25%	-14%	-9%	-11%
	Slope (acre-feet/year)	-61	-79	-1377	-1703	-1741	-2238	76	-53	-319	-848	-929
	Percent error		29%	2149%	2680%	2743%	3554%	-225%	-14%	421%	1285%	1417%
RCP 4.5 (2070-'98)	Average (acre-feet):	257,706	128,513	203,802	146,256	160,736	174,916	127,665	99,578	130,130	138,193	146,450
	Percent Change from Validation	-2%	-51%	-23%	-45%	-39%	-34%	-52%	-62%	-51%	-48%	-44%
RCP 8.5 (2070-'98)	Average (acre-feet):	257,706	93,639	108,322	89,339	91,485	92,743	85,713	92,408	68,801	91,947	90,306
	Percent Change from Validation	-2%	-64%	-59%	-66%	-65%	-65%	-68%	-65%	-74%	-65%	-66%

In a similar analysis to Section 2.6.3, a 31-year moving average was taken of the historical April-July volume and a linear fit was extended through the forecast period (2019-2099). This linear regression shows an annual decrease of 61 acre-feet per year based on observed data from 1951-2019 (Table 8). During the validation period, four of the eight GCM's are decreasing more than 20 times faster than the rate shown in the historical data, with the average of the 8-models decreasing 15-times faster than the historical data. By the end of the century, the average of the eight GCM's predicts a 44% and 66% decrease in annual April through July runoff for the RCP 4.5 and 8.5 scenarios, respectively. While the models appear to be converging later in the century (Figure 12), thirteen of the sixteen scenarios have diverged from the historical data by the end of the observed period with the average of these models underpredicting the 1989-2019 average volume by 23%. Because of this discontinuity the April-July volume shown by these thirteen models is likely too low at least in the near future. Given that the three scenarios that predicted the 1989-2019 April-July volume within 10% of observed converge back to the median of the models around 2050, the median of the models after this date may be more reasonable. It is of note that the historical 31-year average decreased from 1999-2001, then recovered by 2003. This temporary reduction was during a 34-year gap between the wet years 1983 and 2017, during which there were four periods of drought (using the TROA definition discussed in 4.4) 1988-1994, 2002-2004, 2008-2009 and 2014-2016. If recent wet years 2017 and 2019 are not included then it would appear that the historical average April-July volume had reduced to approximately the median of the RCP 4.5 model predictions, however inclusion of this recent data returns the historical 31-year average to approximately the 1951-2019 average.

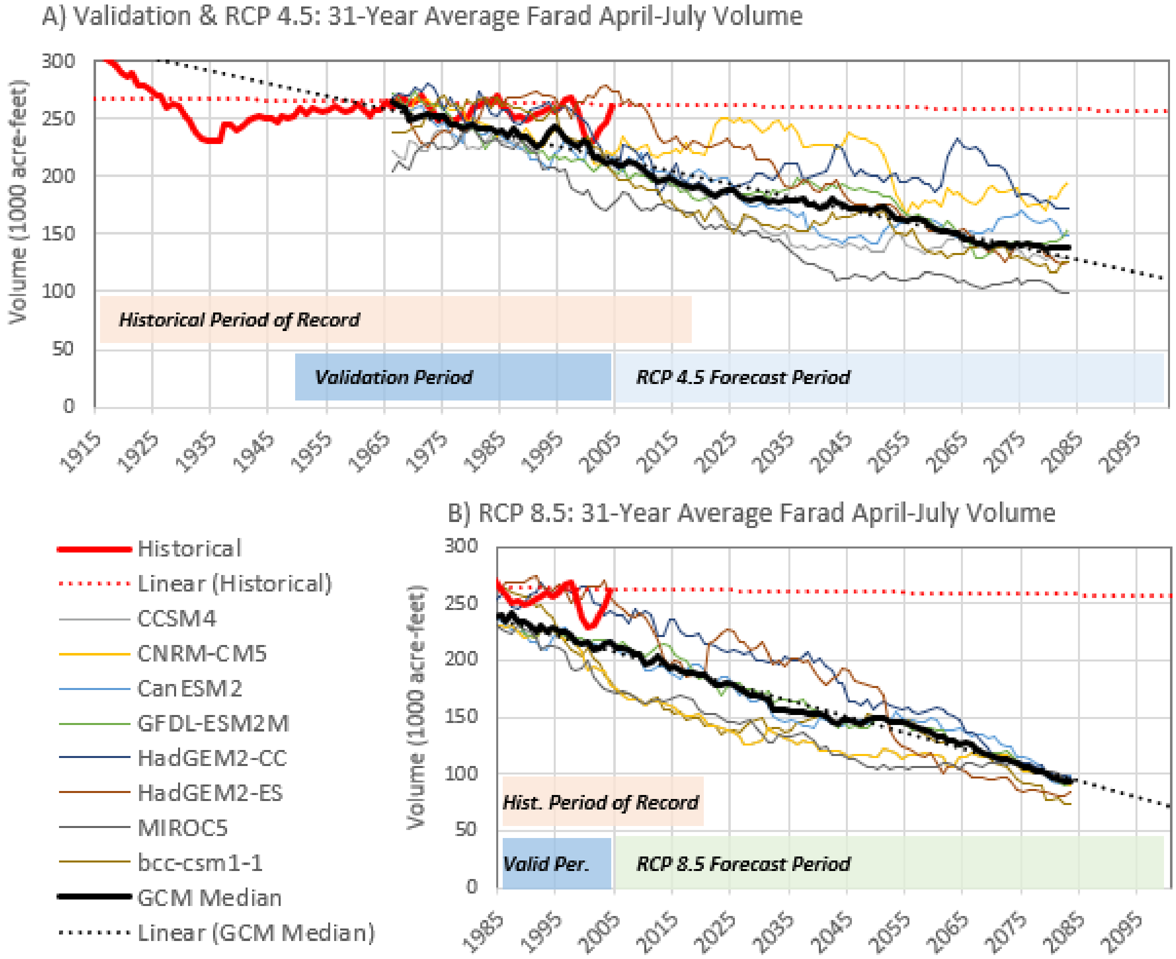


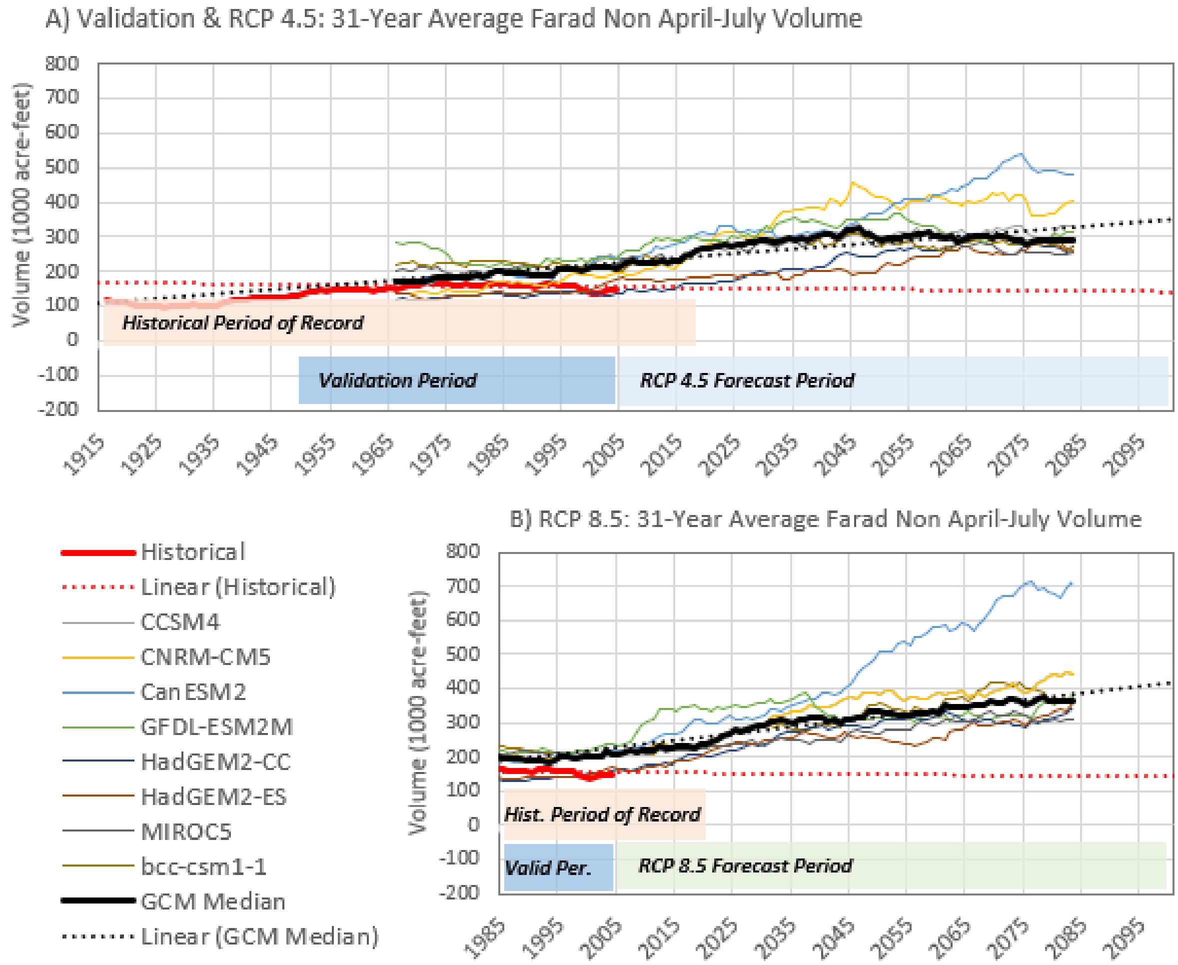
Figure 12: Charts comparing Average April through July Volumes for (A) the validation period (1951-2005) and RCP 4.5 projection for 2019-2098, and (B) RCP 8.5 projection for 2019-2198.

2.6.5 Non-April through July Volume

Runoff outside of the April through July period is generally concentrated between November and March, which is the rainy season in the Truckee River basin (see Figure 10). This period coincides with lower demands, so excess runoff is stored in reservoirs as much as is permissible by relevant dam safety criteria. This is also the most active flood season in the Truckee River Basin which can contribute very large volumes over brief periods. As discussed in Section 2.6.2, the season of precipitation is not expected to change significantly. However, if more precipitation falls as rain instead of snow this will runoff immediately instead of accumulating snow that would not melt and runoff until the summer months thus shifting the runoff from the

April through July period to outside of the April through July period. This effect is compounded by the projected increase in annual runoff discussed in Section 2.6.3.

Figure 13: Average Non-April Through July Volume Graphs for (A) the validation period (1951-2019) and RCP 4.5 projection for 2019-2098, and (B) RCP 8.5 projection for 2019-2098.



Comparison of the validation period for the Non-April through July volume shows inconsistency in the GCMs, similar to disagreement in April through July volume in Section 2.6.4. During the validation period, two of eight GCM's produced an annual Non-April through July volume within 10% of the historical data. Meanwhile, five of the eight have differences greater than 25%. In the validation period, historical data shows a decrease of 143 acre-feet per year, while all but one of the GCMs produces an increasing trend. Five of the eight models show a rate of increase that differs from the historical rate of change by more than six times the decrease observed in the historical data.

GCMs forecast the average Non-April through July volume to exceed the current trend in all scenarios. For the RCP 4.5 scenario, the model average exceeds the historical average by 104%, while individual models exceed historical average by between 51% (MICROC5) to as much as 194% (CanESM2). The RCP 8.5 scenario increases this effect. For the RCP 8.5 scenario all the GCM projections show the Non-April through July accumulation more than double the historical average, and the CanESM2 model shows 3.5 times the historical average (Figure 13 and Table 9 below).

Table 9: Summary of GCM projection average Non- April through July volumes in comparison to the historical validation period (water year 1951-2019) in the validation period rows. The RCP 4.5 and RCP 8.5 projection rows compare the 2070-2098 volume to the projected historical average for the same period.

		Historical	CCSM4	CNRM-CM5	CanESM2	GFDL-ESM2M	HadGEM2-CC	HadGEM2-ES	MIROC5	bcc-csm1-1	Median	Average
VALIDATION (1951-2019)	Average (acre-feet):	157,919	201,697	167,461	209,109	253,999	129,535	151,242	208,145	214,692	204,921	191,985
	Percent error		28%	6%	32%	61%	-18%	-4%	32%	36%	30%	22%
	Slope (acre-feet/year)	-143	1819	1029	2335	-1021	153	1159	847	98	938	802
	Percent error		-1370%	-818%	-1730%	613%	-207%	-909%	-691%	-168%	-755%	-660%
RCP 4.5 (2070-'98)	Average (acre-feet):	143,738	339,701	413,767	464,930	321,925	259,009	270,338	239,180	263,707	296,132	321,569
	Percent Change from Validation	-9%	115%	162%	194%	104%	64%	71%	51%	67%	88%	104%
RCP 8.5 (2070-'98)	Average (acre-feet):	143,738	463,502	577,287	707,650	374,747	351,673	366,517	323,362	351,426	370,632	439,520
	Percent Change from Validation	-9%	194%	266%	348%	137%	123%	132%	105%	123%	135%	178%

2.6.6 Day of 50% Volume

While dividing the volume between what occurs during April through July and the remainder of the year is helpful in regard to current policy considerations and demand distributions, it is a coarse representation of the seasonality of the runoff and may not capture minor changes in the seasonality. A metric that can indicate the period of the year when runoff occurs is the calendar date (month and day) when half (50%) of the Water Year runoff has occurred. This metric can vary significantly from year to year, but the centered 31-year average is relatively consistent (see Figure 14). Historically, this has occurred as early as January 31st (Water Year 1951) and as late as May 27th (Water Year 1975). Figure 14 shows the historical 31-year average of the day of 50% flow, with a linear fit extended through the forecast period. Over the period of record

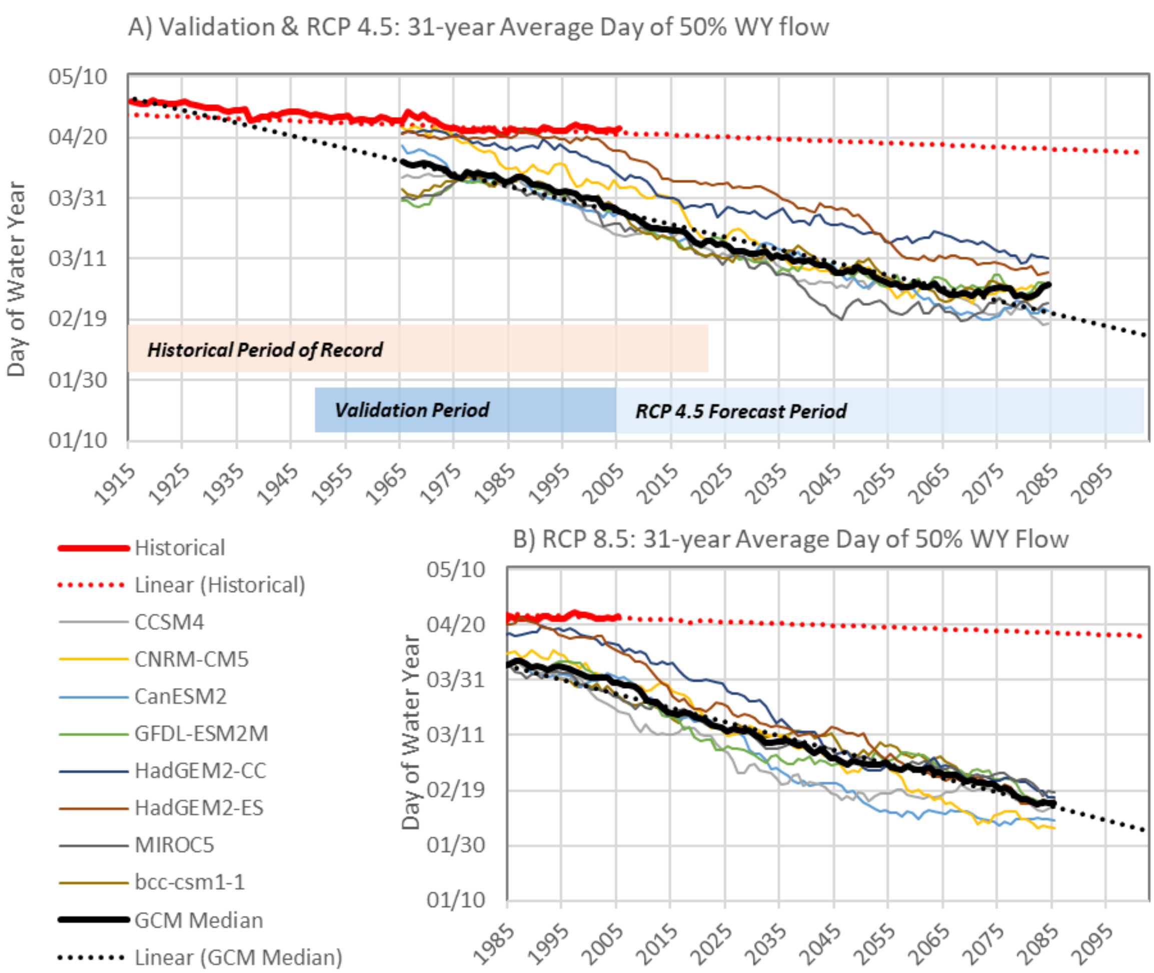
Table 10: Summary of GCM projection average day of the water year when 50% of volume occurs in comparison to the historical validation period (water year 1951-2005) in the validation period row. The RCP 4.5 and RCP 8.5 projection rows compare the 2070-2098 average day of 50% flow to the projected historical date for the same period.

		Historical	CCSM4	CNRM-CM5	CanESM2	GFDL-ESM2M	HadGEM2-CC	HadGEM2-ES	MIROC5	bcc-csm1-1	Median	Average
VALIDATION (1951-2019)	Average (Date):	04/22	03/31	04/12	04/05	03/30	04/15	04/18	03/28	03/29	04/02	04/06
	Error (days/percent of 1951-2019 change)		-22 / 481%	-9.9 / 216%	-17.8 / 389%	-23.6 / 516%	-7.7 / 168%	-4 / 87%	-25.4 / 554%	-23.9 / 523%	-19.9 / 435%	-16.8 / 367%
	Slope (days/year)	-0.07	-0.49	-0.55	-0.65	-0.09	-0.47	-0.19	-0.15	-0.19	-0.33	-0.35
	Percent Error		638%	731%	876%	32%	604%	191%	130%	179%	398%	423%
RCP 4.5 (2070-'98)	Average (Date)	04/16	02/17	03/02	02/22	03/03	03/11	03/06	02/24	02/28	03/01	02/28
	Change from Historical (Days)	-6	-65	-52	-59	-51	-42	-48	-58	-53	-52	-53
RCP 8.5 (2070-'98)	Average (Date)	04/16	02/11	02/06	02/08	02/15	02/18	02/14	02/16	02/15	02/15	02/13
	Change from Historical (Days)	-6	-70	-75	-73	-67	-63	-67	-65	-66	-67	-68

(1901-2019) the 31-Year average day of 50% flow has gradually decreased from May 1st in 1915 to April 23rd in 2005.

The validation period of the GCMs is water year 1951 through 2019. Table 10 summarizes the average day of 50% flow over this 69-year period in the GCMs and for historical data. Comparisons of the GCM results to the accompanying historical period gives an indication of how well certain GCMs replicated the seasonality of runoff in the Truckee River Basin. Table 8 shows that only one of the GCMs have an average day of 50% flow that is within 7 days of the date observed in history (HadGEM2-ES). Fitting a line to the historical data from 1951 through 2019 gives a slope of -0.066 days per year. From this we can summarize that the day of 50% flow has been shifting earlier approximately one day every fifteen years or approximately 4.5 days over the 69-year validation period from water year 1951-2019. The other seven GCMs differ from the historical period by between 8 and 25 days. With the historical rate of change it would take between 100 and 400 years to reach the day of 50% flow that these models have

Figure 14: Average Day of 50% Water Year Flow for (A) the validation period (1900-2005) and RCP 4.5 projection for 2019-2098, and (B) RCP 8.5 projection for 2019-2098.



produced for the validation period.

Review of the forecast from the models that was within 7-days of the historical day of 50% flow in the validation period (HadGEM2-ES) shows that the day of 50% flow shifts to March 6th in the RCP 4.5 scenario for 2069-2098. This would have the runoff occurring 48 days earlier than in the validation period (water year 1951-2019) and 42 days earlier than the observed historical trend. Comparison of the seven models that differed from historical by more than 7 days, show the runoff occurring between 42 and 65 days earlier than in the historical data in the validation period with an average of 45 days.

The RCP 8.5 scenario increases these impacts for all GCMs regardless of their performance in the validation period, moving the average day of 50% flow to February 15th with a range of only 12 days. From Figure 10, we see that historically 50% of the water year precipitation occurs by January 26th, a figure that is not projected to change by more than a few days with the GCM projections. Because the primary reason that the day of 50% runoff occurs later than the day of 50% precipitation is that precipitation falling as snow melts later to produce runoff, the day of 50% precipitation provides a natural boundary to the earliest that the runoff could occur.

Projections from the RCP 8.5 scenarios would likely reach this boundary and level off early in the 22nd century if the projected rate of change continued past the end of the GCM model runs.

2.6.7 Validation Summary

The overall performance of the eight GCM models for the four-hydrology metrics are summarized in

Table 11. The Normalized Deviation for each metric shows how well each GCM replicated the historical hydrology in the validation period. These values are normalized based on the performance of the worst performing GCM, so a Normalized Deviation of 0% indicates that the GCM precisely replicated historical hydrology where 100% indicates that the GCM was the furthest from historical hydrology for that metric. The deviation from each metric is averaged to determine the "Average Normalized Deviation" (or composite score) which is the GCM's overall performance giving equal weight to the five metrics that are discussed in detail in Sections 2.6.2-2.6.6 and are summarized here.

To summarize the overall performance, the two worst performing GCMs were the GDFL-ESM2M and the MIROC5 with composite scores of 82% and 75%, respectively. The middle performance models were bcc-csm1-1, CCSM4, CanESM2 and HadGEM2-CC which scored 62%, 56%, 55% and 49% respectively. The second-best performing model was HadGEM2-ES with the best performance in the annual volume category and a composite score of 36%. Leaving HadGEM2-ES as the best performing model achieving the best performance in Metrics 3, 4 and 5 and the second-best performance in Metrics 1 and 2 and a composite score of 22% (almost half the score of the next best model).

Table 11: Table of values showing the overall performances of each GCM projection at replicating historical hydrology in the validation period (1951-2019). Blue shading (closer to 0%) signifies the best validated model for a given metric and red shading (closer to 100%) signifies the worst validated model for a given metric.

		Historical	CCSM4	CNRM-CM5	CanESM2	GFDL-ESM2M	HadGEM2-CC	HadGEM2-ES	MIROC5	bcc-csm1-1	Median	Average
Metric 1	Percentage of water year precipitation from occurs from Oct.-Mar.	79%	83%	84%	83%	83%	83%	83%	84%	83%	83%	83%
	Normalized Deviation	-	81%	100%	77%	76%	86%	76%	97%	73%	79%	83%
Metric 2	Average annual volume (acre-feet)	421,688	428,595	415,224	451,777	491,943	373,814	414,039	405,018	441,037	421,909	427,681
	Normalized Deviation	-	10%	9%	43%	100%	68%	11%	24%	28%	26%	37%
Metric 3	Average April-July volume (acre-feet)	263,769	226,897	247,763	242,668	237,944	244,279	262,797	196,873	226,346	240,306	235,696
	Normalized Deviation	-	55%	24%	32%	39%	29%	1%	100%	56%	35%	42%
Metric 4	Average Non-April-July volume (acre-feet)	157,919	201,697	167,461	209,109	253,999	129,535	151,242	208,145	214,692	204,921	191,985
	Normalized Deviation	-	46%	10%	53%	100%	30%	7%	52%	59%	49%	45%
Metric 5	Average Day of 50% flow (date)	4/22	3/31	4/12	4/5	3/30	4/15	4/18	3/28	3/29	4/2	4/6
	Normalized Deviation	-	87%	39%	70%	93%	30%	16%	100%	94%	79%	66%
	Average Normalized Deviation	-	56%	36%	55%	82%	49%	22%	75%	62%	55%	54%

3 WATER SUPPLY MODEL: RIVERWARE

3.1 RIVERWARE SOFTWARE DESCRIPTION

RiverWare™ is a general river basin modeling tool that can be used to build and manage river basin models. This modeling software is developed and maintained by the Center for Advanced Decision Support for Water and Environmental Systems (CADWES), a research and development department of the University of Colorado Boulder. RiverWare allows simulation of various river basin features including reservoirs, reaches, confluences, diversions, stream gages, water users, hydropower generation, water quality modeling, and surface water-ground water interaction. Basin policy and objectives can be coded into RiverWare using RiverWare Policy Language (RPL) to simulate how reservoirs, diversions and other control structures would react to various hydrological conditions while following applicable decrees, water rights, agreements and operational objectives. Some of the technical capabilities of RiverWare include water right allocation, reservoir storage accounting, and reach flow accounting. Combination of these river basin features, technical capabilities and RPL allows a model to be constructed that represents even the most complex river basins (CADSWES, 2019). As of 2019, RiverWare is being used by: Bureau of Reclamation, Tennessee Valley Authority, U.S. Army Corps of Engineers, Federal Agencies, Tribes, research labs, State, City and District Agencies, Electric Utilities in the United States and Canada, consulting companies, NGOs, Universities, and 19 Foreign Entities (CADSWES, 2019).

3.2 TRUCKEE-CARSON RIVERWARE MODEL DESCRIPTION

The Truckee Carson TROA Planning Model was developed through a collaborative effort of the TROA signatories, including the Bureau of Reclamation, Truckee Meadows Water Authority (TMWA), the Pyramid Lake Paiute Tribe, and the states of California and Nevada. The Truckee Carson TROA Planning Model is a daily-time step water management simulation model built in the RiverWare modeling environment. The model simulates basin water management operations under TROA, including operations of all major dams and reservoirs in the Truckee and Carson River basins: Lake Tahoe, Donner, Independence, Boca, Prosser Creek, Stampede, Derby Diversion, and Lahontan. The model also includes all the major diversions in the system for municipal and industrial uses, as well as agriculture, including the Truckee Canal, Lahontan Reservoir, and the Newlands Project. Current flow and regulatory standards in the basins are included as constraints in the model, including the 1997 adjusted OCAP, 1935 Truckee River Agreement, 1944 Tahoe Prosser Exchange Agreement, and the 2008 Truckee River Operating Agreement (TROA) (Truckee River Operating Agreement (TROA), 2008). The model receives regular review and refinements from regional stakeholders in anticipation of its use for future planning studies, it has a wider circulation than other available Truckee basin operation models (*e.g.*, Truckee River Operations Model also known as TROM), and it is generally considered the standard planning model in the basin.

In 2017, the Truckee Carson TROA Planning Model was updated to incorporate the RiverWare Water Rights Solver (WRS) utility. This update enabled the model to allocate water by priority to all water right holders downstream of the Farad gage (U.S. Geological Survey (USGS) Gage 10346000) in order of water right priority date. Accounts were added to the water user objects for each water right exercised at that point of diversion. The permitted annual volume for each water right and diversion location are entered for each year of the model run. The model rule logic utilizes this table and user input demand data to set the diversion request for each water right account at the diversion locations. The WRS utility then allocates all of the available water in the river by order of priority date. This means that the diversion request for a downstream water user with a senior priority will be fulfilled ahead of an upstream water right with a junior priority. The holdback of Floriston Rate water to establish credit water storage within upper Truckee River reservoirs, called “Changed Diversion Rights” in TROA, is also allocated in this manner. The water rights can be input to be consistent with a future transient demand scenario that includes transfers of water rights between basin water users.

3.3 MODEL ASSUMPTIONS

In order to model the water supply availability for TMWA, the TROA Planning model was configured to match their most recent system capacities, demands, water rights, and operational strategies. The purpose of this study is to provide a cursory look at TMWA’s future water supply under climate change scenarios. To that end many of the parameters used to configure the model used typical values and first order approximations of TMWA resources and system characteristics. These values were adjusted in more detail in the TMWA 2020-2040 Water Resource Plan (Truckee Meadows Water Authority, 2020).

A preliminary projection of TMWA's demand was used that shows the demand increasing to 110,000 acre-feet per year by 2100 (Figure 15). Demands from the Truckee Basin Study were used to develop relationships between TMWA's future demand and other demands in the system and estimate the water right transfers that will occur to meet TMWA's demands (Department of the Interior, Bureau of Reclamation, 2015).

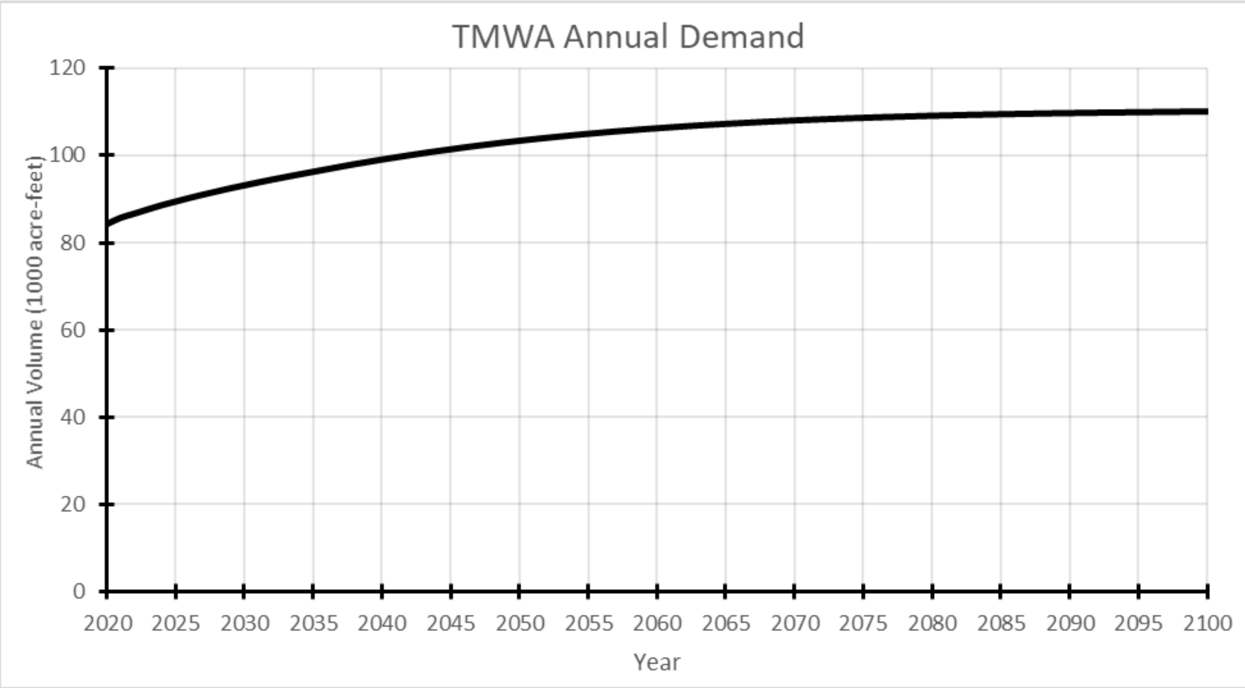


Figure 15: TMWA's Projected Annual Demand that was used for this analysis.

Some additional modeling parameters that are relevant to TMWA's water supply are summarized in Table 12.

Table 12: Additional TMWA model parameters

Parameter	Value	Comment
Ground water pumping capacity	92.8 cfs for all years	Preliminary estimate of the maximum groundwater pumping that could be sustained.
Conservation	10% when reservoir storage is needed to meet demands	Assumed that conservation efforts will result in a 10% reduction in demand at times when TMWA need to draw on drought storage to meet demands.

4 RESULTS

As described in the sections above, three ensembles of hydrology were developed and then run through the RiverWare model as depicted in Figure 3. The three hydrology ensembles are the reference historical ensemble (using observed historical hydrology as described in Section 1.2.1), the RCP 4.5 GCM ensemble, and the RCP 8.5 GCM ensemble. Each GCM ensemble consists of output from the eight GCM models discussed in Section 2.2. The GCM output were each run through the RiverWare model to generate a set of results. The purpose of these runs was primarily to evaluate the GCM models' results and to make some general observations about the impacts of climate change in water supply in the Truckee River Basin. These runs included simplified assumptions about TMWA's system demands and operational criteria that are refined and described in detail in the TMWA Water Resource Plan.

This section consists of a discussion of model results for four different quantities in the basin that are important to TMWA and its customers, and that allow some general observations about the impacts to the Truckee system and to TMWA customers from climate change.

4.1 SEASONAL RUNOFF RESULTS

Through the Water for the Seasons project, DRI developed synthetic hydrology to simulate the future climate. This hydrology represents the cumulative effect of changes in temperature, precipitation quantity, precipitation type (rain or snow) and global climatic patterns resulting from increased Green House Gas emission scenarios. Averaging the seasonal volumes predicted by all eight models by decade gives an indication of the anticipated shifts in timing and quantity of runoff. As shown in Section 2.6, there is significant variability between the model forecasts for some quantities (see the CanESM-2 forecast of Non-April through July volume in Figure 13) such that averaging all of the models may oversimplify the projected result. These projections show dramatic changes to the timing of inflows for both the Truckee and Lake Tahoe basins.

The change in average runoff by quarter for the Truckee River above the Farad Gage is summarized in Figure 16. The Farad natural flow shows a general reduction in the amount of flow that occurs in the months of April through September. The RCP 4.5 scenario projection for the 2090's show 140,000 acre-feet per year less flow in this period than the observed historical reference period (1951-2019), and the RCP 8.5 scenario has 190,000 acre-feet per year less. The decreases in April through September are projected to be more than compensated for by increases in runoff in October through March. The average inflows during these months are expected to increase by 160,000 acre-feet per year in the RCP 4.5 scenario (more than double the 1951-2019 volumes), and by 310,000 acre-feet per year in RCP 8.5 scenario (more than triple the 1951-2019 volumes) by the 2090's. In both scenarios, the January through March quarter is gaining the largest volume and the April through June quarter is losing the largest volume. The July through September period is losing a more modest amount and the October through December is gaining, but not as much as January through March.

While not as significant as the change in the seasonal timing of runoff, the RCP scenarios also show an overall increase in the Annual runoff volume, as discussed in Section 2.6.3. In the RCP 4.5 Scenario, the annual volume generally increases until about the 2050's when volume begins to decrease back to approximately average from the reference historical period by the 2090's. Conversely the RCP 8.5 scenario generally shows a continued increase in the Annual runoff through the end of the 21st century with the 2090's average annual volume approximately 30%

greater than the average from 1951-2019.

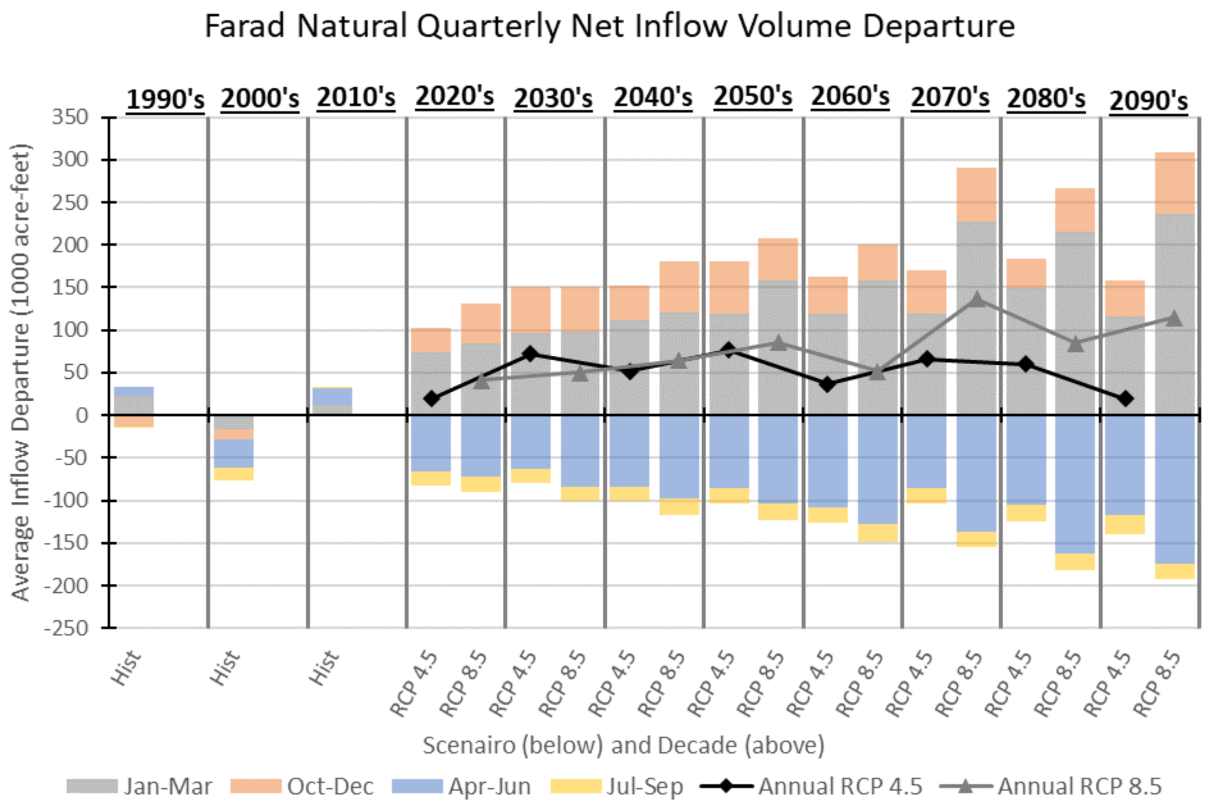


Figure 16: Farad Natural Flow decadal average quarterly volume departure from the 1951-2019 average runoff volumes by quarter.

Given the complexity of approximating evaporation on Lake Tahoe, future trends are characterized by the net inflow (inclusive of evaporation from the Lake and precipitation on the Lake). As shown in Figure 17, the forecasted trends for Lake Tahoe are similar to the trends anticipated for the Farad Natural flow. Overall, there are decreases in the net inflow volume occurring between April and September and increases in the inflow occurring between October and March. For Tahoe, the reduction in volume in the July through September period (losing approximately 60,000 acre-feet per year by 2090 in RCP 4.5 and 8.5 scenarios) is more pronounced than the reduction forecasted for Farad Natural flow in the same period (only losing approximately 20,000 acre-feet per year by 2090). This difference is partially due to comparing the runoff at Farad to the net inflow on Tahoe where lake evaporation is much a more significant term in the water balance (see discussion of Table 5 in Section 2.5).

This increased change in evaporation on Lake Tahoe makes it so that the average annual volume by the end of the decade in the RCP 4.5 scenario shows a 13% reduction from the 1951-2019 historical average by 2090, after exceeding the historical average from the 2030's through the 2080's. The RCP 8.5 scenario shows a 39% net increase in inflow by the end of the 2090 which generally increase from now until then.

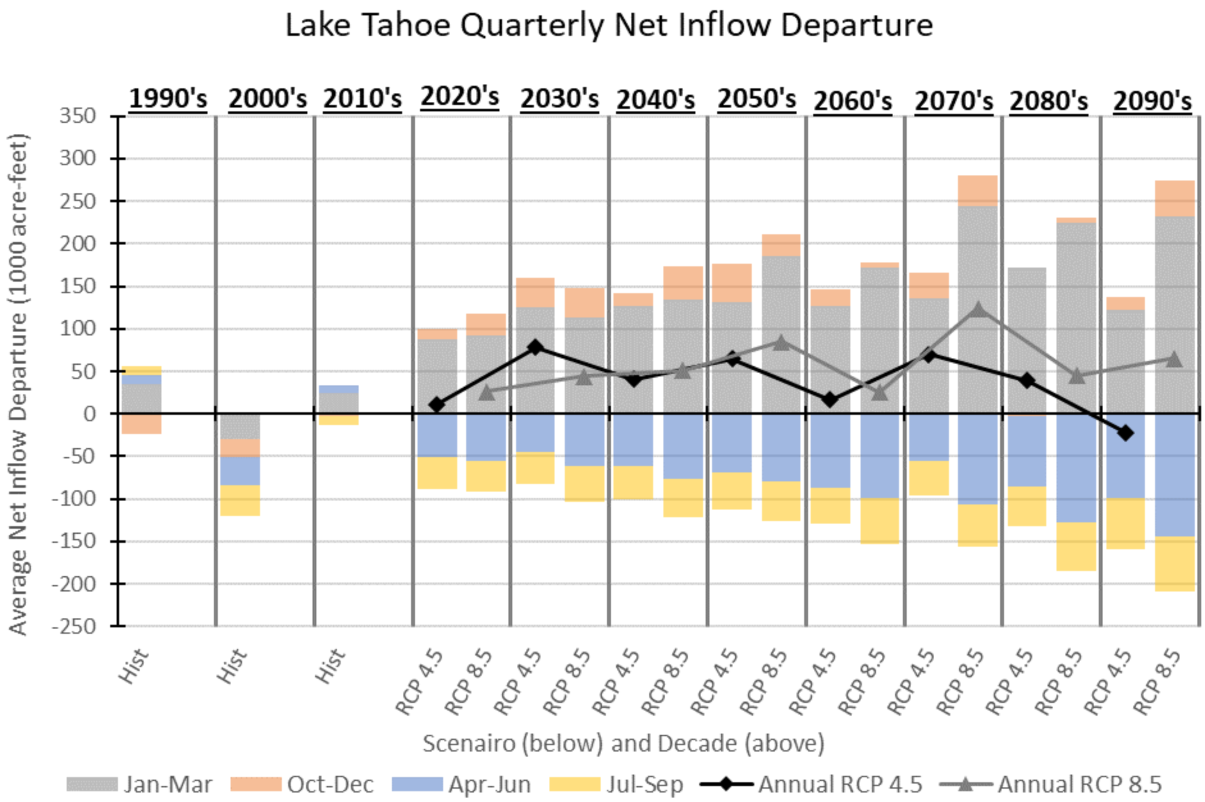


Figure 17: Lake Tahoe average quarterly net inflow volume departure from the 1990-2019 average inflow volumes by quarter.

4.2 Lake Tahoe Elevation Results

In addition to possessing enormous environmental, recreational, and cultural value, Lake Tahoe also serves as an important water supply reservoir for the Tahoe, Truckee, and Carson river basins. Lake Tahoe's relatively small dam impounds up to 6.1 vertical feet of water which amounts to 744,600 acre-feet and approximately 68% of the total reservoir storage capacity in the Tahoe/Truckee system. Lake Tahoe is the single largest water supply source in the Tahoe/Truckee system, accounting for 43% of the total water supplied from all seven Truckee Basin reservoirs.

What makes Lake Tahoe unique among water supply reservoirs is its massive surface area (approximately 120,000 acres) and very shallow depth (6.1 feet). Recent research has determined that, on average, approximately three and a half feet of water evaporate from the surface of Lake Tahoe each year (Huntington & McEvoy, 2011). This amounts to more than 400,000 acre-feet, which though small compared to the total volume in the lake, represents more than half of the total reservoir capacity. Because of the disproportionate influence of evaporation on its water balance, Lake Tahoe is uniquely and acutely susceptible to changes in evaporation, which is one of the primary effects expected in a warming future climate. Relatively small changes in future evaporation rates and average inflow volumes could result in substantial changes to the water supply reliability of Lake Tahoe.

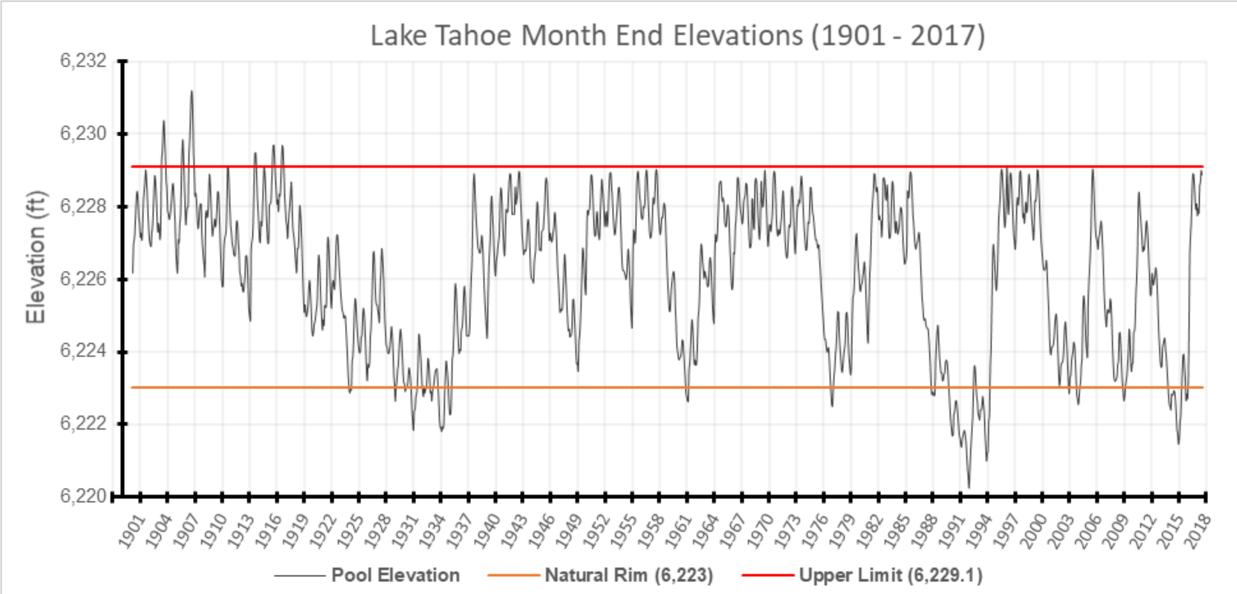


Figure 18: Month End Elevations for Lake Tahoe over the historical period of record (1901-2018).

Lake Tahoe has a natural rim at an elevation of 6,223.0 ft above sea level. When the lake's surface drops below the rim no water can be released through the dam, and the Truckee basin enters drought operations. Furthermore, the lake is operated to, as far as is practicable, prevent the water surface elevation from exceeding 6229.1 ft. As can be seen in Figure 18, the range of the elevation of the water surface is relatively small and stays between these limits the majority of the time. Changing climate, however, may introduce changes to the lake's inflow volume (see Section 2.6.3 for discussion of natural flow in the adjacent basin: Truckee river above Farad) as well as to the volume that evaporates each year (see Section 2.5).

Each year the water surface elevation of the lake fluctuates from its annual minimum, usually occurring in the late fall, and its annual maximum which usually occurs after the runoff peak in the summer. Comparing the average maximum and minimum annual elevations of the lake in the climate change runs to the elevations from historical runs helps illustrate the changes the hydrology generated by the GCM's introduce to the basin.

Table 13 below shows Lake Tahoe's average annual low and high elevations from the historical, RCP 4.5, and RCP 8.5 ensembles of runs. The average annual high elevations are very similar, differing by only one tenth of a foot. The average annual low elevations, however, are substantially lower in the climate change ensembles. Both climate change ensembles show a consistently lower minimum annual elevation than what has been observed historically. This means that the GCM's project that the lake surface will fluctuate more each year than what has been observed historically. This results from the average annual inflow to Lake Tahoe increasing, but the amount of water that evaporates increasing as well. The net effect of the changes introduced by climate change is that annual variability of the elevation of Lake Tahoe will be higher.

Table 13: Average annual low and high elevations of Lake Tahoe for the historical, RCP 4.5, and RCP 8.5 ensembles of runs (2019-2098)

	Annual Average Lake Tahoe Elevations (ft)			
	Summer Max	Change	Fall Min	Change
Historical	6227.29	-	6225.41	-
RCP 4.5	6227.23	-0.06	6224.68	-0.73
RCP 8.5	6227.33	0.05	6224.53	-0.88

4.3 TRUCKEE RIVER FLOW AT FARAD GAGE

The second location in the basin for which results of the climate change runs are discussed is the flow at the Farad Gage near the California/Nevada state line. The most important operational criteria in the basin, the Floriston Rate, is measured here, making this a very important stream gage in the Truckee basin. Each day the upstream reservoirs are operated to maintain a target flow rate at this gage. The target varies between 300 and 500 cfs depending on the time of year and the elevation of Lake Tahoe's water surface.

For the purpose of comparison, three hydrologic year types will be defined: dry, moderate, and wet. These year types will be determined based on the average annual flow rate at the Farad gage in the ensemble of historical runs. A year is considered dry if it is in the lower third of historical years' annual average flow at Farad, with an upper threshold of 569 cfs. A year is considered wet if it is in the upper third of historical years' annual average flow at Farad, with a lower threshold of 732 cfs. Finally, any year with an average annual flow rate that is between these two thresholds is considered moderate.

For the two climate change ensembles, the percentage of years in each run that fall in each of the terciles was determined. These percentages are then compared to quantify the impacts of climate change on the flows at Farad. These tabular results are given in Table 14 and shown graphically in Figure 19.

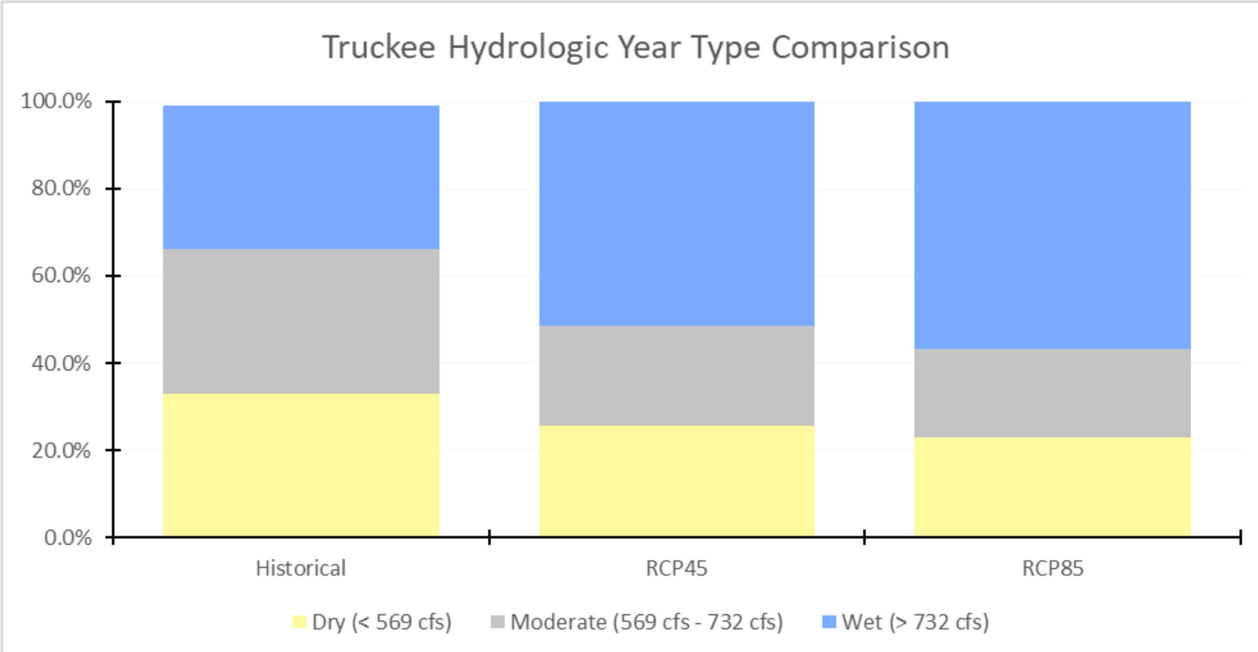


Figure 19: The percentage of years for each ensemble run that were dry, normal, or wet based on the annual average flow in the Truckee River at the Farad gage. The minimum annual average flow in each scenario is shown for reference.

The results show that in the RCP 4.5 ensemble, there is a significant increase in the frequency of wet years going from 33% in the historical ensemble to 51.6% in the RCP 4.5 ensemble. This says that just over half of years are expected to be wet by this definition. The frequency of moderate and dry years decreases from 33% down to 22.7% and 25.7%, respectively. For the RCP 8.5 ensemble, the changes are similar but amplified with the frequency of wet years going up to 56.7% and the frequency of moderate and dry years going down to 20.2% and 23.1%, respectively.

Table 14: Tabular Data of the percentage of years for each ensemble run that were dry, normal, or wet based on the annual average flow in the Truckee River at the Farad gage. The minimum annual average flow in each scenario is shown for reference.

	Farad Annual Flow Year Type Distribution		
	Historical	RCP45	RCP85
Dry (< 569 cfs)	33.3%	25.7%	23.1%
Moderate (569 cfs - 732 cfs)	33.3%	22.7%	20.2%
Wet (> 732 cfs)	33.3%	51.6%	56.7%
Minimum Annual Average (cfs)	203.4	151.6	144.6

Interestingly, however, though the climate change ensembles show a greater frequency of wet years and a decreased frequency of dry years, the driest years in the climate ensemble have a lower flow at Farad than the driest year in the historical ensemble. The driest year in the historical ensemble had an average flow at Farad of 203.4 cfs while the driest year in the RCP 4.5 ensemble was 151.6 cfs. In the RCP 8.5 the driest year had an average flow rate at Farad of 144.6 cfs. Therefore, the results again show that on average the flows in the Truckee system are projected by the GCMs to increase with climate change, but there is also an increase in variability such that the dry years are projected to be even drier than what is shown in the historical runs.

4.4 Drought Designation Frequency

The third important result from the RiverWare model runs to explore is the frequency of drought in the basin. Drought is generally defined as "a sustained period of significantly lower soil moisture levels and water supply relative to the normal levels around which the local environment and society have stabilized." (Maidment, 1993) Determining what exactly triggers a drought designation in an area is highly subjective and many indicators have been used to make this determination for different purposes. For the purposes of this analysis of water supply in the Truckee basin, the designation of drought is as defined by the TROA.

TROA identifies two conditions, either of which initiate a drought designation for the year beginning on April 15th. The definition reads:

> "Drought Situation" means a situation under which it is determined by April 15…, either that there will not be sufficient Floriston Rate Water to maintain Floriston Rates through October 31, or the projected amount of Lake Tahoe Floriston Rate Water in Lake Tahoe… on or before the following November 15 will be equivalent to an elevation less than 6,223.5 feet Lake Tahoe Datum"

Either of these two conditions will trigger a drought designation for that year beginning on April 15th, and once a year has been designated a drought, it will remain a drought year until April 15th of the next year regardless of the precipitation that occurs during the balance of the year. Under TROA certain operational criteria change when the basin is in a drought year, including the quantity of water that TMWA is allowed to store for drought supply in the Truckee reservoirs (Truckee River Operating Agreement (TROA), 2008).

In the historical ensemble of model runs, 19.8% of years are designated drought years by this definition. This means that on average approximately two years in every decade meet at least one of the two criteria above. This is the historical frequency of drought that water users in the basin have become accustomed to.

For the climate change ensembles, the frequency of drought increases. In the RCP 4.5 ensemble of model runs, 30.9% of years are designated drought years and in the RCP 8.5 ensemble, 30.6% of years are designated drought years.

Table 15: Likelihood of drought with historical, RCP 4.5 and RCP 8.5 ensembles.

	Historical	RCP 4.5	RCP 8.5
Drought	19.8%	30.9%	30.6%
Non-Drought	80.2%	69.1%	69.4%

In both of the RCP 4.5 and 8.5 emissions scenarios, the drought frequency increases to more than 3 years in each decade. In comparison to the historical ensemble, these scenarios show over 50%

increase in the frequency of drought in the Truckee Basin. This result coupled with the increase in frequency of high annual flows at the Farad gage (Table 14) show a complex picture of future conditions indicated by the GCMs for the Truckee basin. The models indicate an increased frequency of wet years, but also an increased frequency of drought. The conclusion is that the models indicate a significant increase in variability in future water supply conditions. Water supply in the basin will more often be at the extremes than in the middle of the range.

4.5 TMWA'S DROUGHT SUPPLY RELIABILITY

The final result from the model runs is the reliability of TMWA's drought supply. When the Floriston Rate is not able to be met, then TMWA must supplement the available Floriston Rate water with increased ground water pumping and drawing on water stored in Truckee River Reservoirs. In the case of a prolonged drought, water may need to be drawn from storage to supplement Floriston Rate water several years in a row. If a drought were of sufficient duration and severity, eventually TMWA's storage reserves could be depleted. The RiverWare model runs simulated the amount of storage required to meet projected future demands for the three hydrology ensembles. The percentage of scenario years in which supply was unable to meet demand for each decade into the future is summarized in Figure 20. Because each ensemble consists of eight scenarios, there are 80 projections of each decade (8 scenarios x 10 year), with the exception of the 2090's which only has 72 projections as the simulation ends in 2098. For the Historical and RCP 4.5 ensembles there were no years of shortage. For the RCP 8.5 scenario, no scenarios show a shortage until 2088. In total only 1.3% (1 of 80) of scenarios have a shortage in the 2080's and 5.6% (4 of 72) scenarios have a shortage in the 2090's.

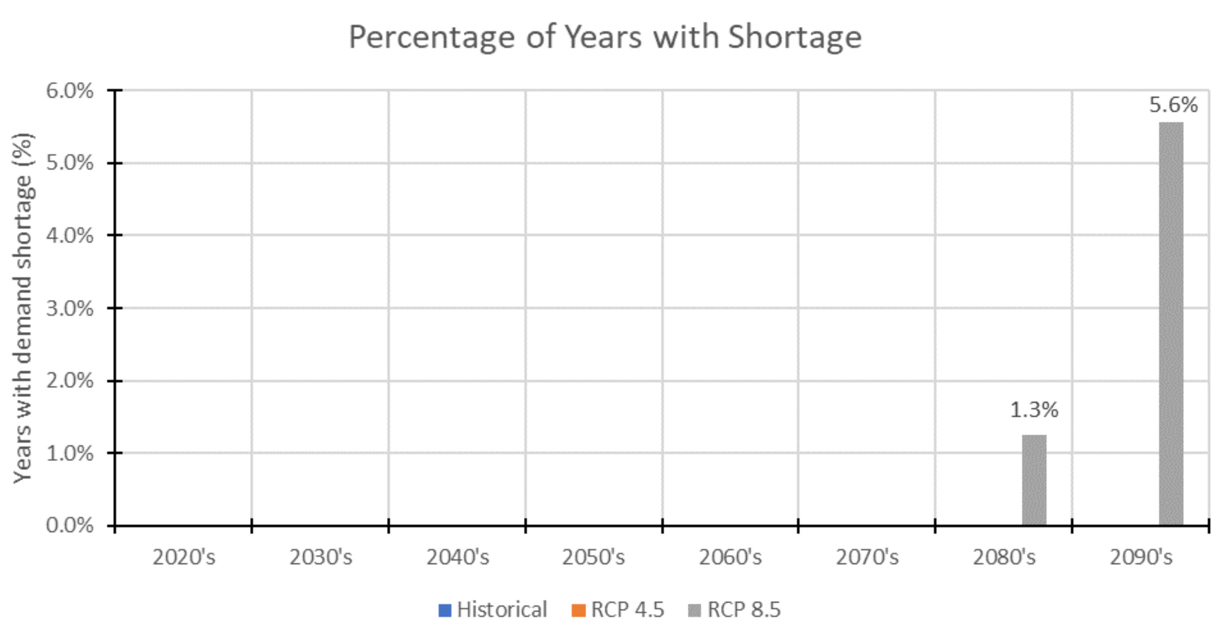


Figure 20: Percentage of Years with Shortage by Decade

Overall, these results show that while stressed beyond what historical hydrology would require, TMWA's drought supply is sufficient to meet growing demands for all Climate Change hydrology scenarios through at least the late 2080's. TMWA's water supply fares very well under the effects of climate change, resiliently meeting demands for all but the most severe droughts in the RCP 8.5 GCM scenarios late in the century. Certainly, the understanding of the impacts of climate change and projections of TMWA's resources and demands will be significantly improved well before any action would need to be taken to address these challenges.

5 SUMMARY

In order to estimate how anticipated changes to future climate will impact water supply in the Truckee River Basin, a multi-model interdisciplinary approach was used (see Figure 3). The first step used the projected concentrations of greenhouse gasses that were developed as Representative Concentration Pathway (RCP) 4.5 and 8.5 by the Intergovernmental Panel on Climate Change. The RCP 4.5 and 8.5 scenarios were used as input to eight general circulation models (GCM's) to simulate how the altered concentrations will impact global climate. The output of the GCM's were then downscaled using LOCA and MACA downscaling methods to give adequate granularity to use as input to the Precipitation-Runoff Modeling System (PRMS) which simulated the resultant hydrology. In parallel, the Complementary Relationship Lake Evaporation (CRLE) model was used to predict the future lake evaporation based on output from the downscaling methods. The PRMS hydrology was validated against historical observations of Farad Natural Flow from 1951-2019. The validation showed that all but one of the models underpredicted the April-July volume. This error generally increased through the validation period such that the average volume for 1989-2019 of the seven under-performing models was 22% below the historical average in the same period. This discrepancy should be considered when evaluating GCM projections.

The PRMS hydrology and CRLE evaporation data were input into the Truckee Carson TROA Planning RiverWare Model to evaluate the reliability of TMWA's drought reserves and other basin characteristics such as Lake Tahoe Elevations and Truckee River flows. The projections of TMWA demand and other water supply parameters used in the RiverWare model for this study are preliminary and were revised in the 2020-2040 Water Resource Plan (Truckee Meadows Water Authority, 2020). Impacts to individual modeled parameters are summarized in Table 16.

Table 16: Summary of the 8-GCM model average values in comparison to reference historical period (water year 1951-2019)

Parameter	RCP 4.5	RCP 8.5
Changes in Hydrology (2070-2098)		
Annual Average Evaporation	+5.1%	+9.2%
Annual Average Precipitation at Boca Reservoir	+4.8%	+16%
Truckee Basin Average Annual Runoff	+11%	+27%
Truckee Basin Average April through July Runoff	-44%	-66%
Truckee Basin Average Non-April through July Runoff	+104%	+178%
Day of water year when 50% of volume occurs	53 days earlier	68 days earlier
Lake Tahoe Average Annual Net Inflow	+17%	+47%
Lake Tahoe Average October-March Net Inflow	+146%	+244%
Lake Tahoe Average April-September Net Inflow	-215%	-308%
Changes in Reservoir Operations (2019-2098)		
Tahoe Average Annual Maximum Elevation	+0.0 feet	+0.1 feet
Tahoe Average Annual Minimum Elevation	-0.7 feet	-0.8 feet
Percentage of Drought Years	+11.1%	+10.8%
Percentage of years in which TMWA's has a shortage[ǂ]	Unchanged	+0.9%

ǂ This represents the absolute percentage of years in outlook. The historical scenario also had zero years where TMWA was unable to meet demands.

Of the most notable impacts to the hydrology, the Truckee Basin April through July volume is projected to decrease 44% in the RCP 4.5 scenario and 66% for the RCP 8.5 scenario. Reductions in April through July runoff is transitioning to increases in streamflow during the remainder of the year (August through March) which is expected to increase and more than offset the losses that are expected in the April through July period. For the last 30 years of the century the non-April through July runoff is expected to more than double with an average increase of 104% in the RCP 4.5 scenario and an average increase of 178% in the RCP 8.5 scenario. These changes result in the runoff shifting 53 days earlier in the RCP 4.5 scenario and 68 days earlier in the RCP 8.5 scenario. For Lake Tahoe the shifts in seasonality are more pronounced, where the RCP 4.5 scenario shows the April through September net inflows are decreasing by 215% (the historical average is 60,000 acre-feet per year gain, while RCP 4.5 shows the average becoming a 68,000 acre-feet per year loss). In the RCP 8.5 Scenario the reduction is over 300%. These reductions in summer net inflows to Lake Tahoe are compensated for by gains in the October through March period of 146% for the RCP 4.5 scenario and 244% in RCP 8.5 scenario. The inflows to Tahoe would shift to be much more heavily concentrated in the fall and winter months, and with less snowmelt to offset evaporation losses, the fall and winter inflows would more consistently outweigh those in the April through September period. The annual average net inflow to Tahoe is expected to increase 17% for the RCP 4.5 scenario and 47% for the RCP 8.5 scenario by the last 30 years of the 21st century.

As a result of the dramatic changes to hydrology timing, the percentage of years for which a drought designation is determined increases from 19.8% based on historical hydrology to just over 30% with both the RCP 4.5 and 8.5 scenarios. Prolonged and more frequent droughts will require that TMWA rely on reservoir storage and additional ground water pumping to meet demands more frequently. Despite the increased frequency of drought, the results show that TMWA can meet demands for all of the RCP 4.5 GCM model scenarios, and only misses demands in two of the eight GCM models under the RCP 8.5 scenario. The shortages in the RCP 8.5 scenario do not occur until the 2080's and 2090's.

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