Water Supply Viability of Lake Tahoe Under Modified Climate Conditions

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Abstract

Lake Tahoe is the largest reservoir in the Tahoe/Truckee system and an important water supply source for the Truckee and Carson River basins. However, the presence of a natural rim and the disproportionate importance of evaporation on the lake's water balance lead to some unique challenges for the lake's viability as a water supply. The goal of this study was to assess the likelihood of the lake pool elevation dropping below the rim elevation under the RCP 4.5 and RCP 8.5 future climate scenarios. Results from eight different GCMs under each scenario were first used as forcing for local hydrologic models. The GCM and hydrologic model results were then used as input to a river and reservoir network model that incorporates current operational procedures for the basin under the Truckee River Operating Agreement. Results of the modeling indicate increased average net inflow to Lake Tahoe, along with increased average outflow from the lake, greater outflow variability, and an increased proportion of time for which the Lake Tahoe pool elevation is below the rim elevation.

Introduction

With an average annual release of 235,000 acre-feet, Lake Tahoe is the single largest water supply source in the Tahoe/Truckee system. When the Lake Tahoe pool elevation drops below the lake's rim, and no water can be released from the lake, the basin begins drought operations. So, the importance of Lake Tahoe as a water supply for the downstream users can hardly be overstated. While the overall volume of water contained in Lake Tahoe (~122 million acre-feet) would seem to suggest a stable water supply for years to come, the details of Lake Tahoe's reservoir and water balance suggest otherwise.

Lake Tahoe has a reservoir capacity of 744,600 acre-feet, which is approximately 68% of the total reservoir storage in the Tahoe/Truckee system (1,089,210 acre-feet), and an average annual inflow of 642,000 acre-feet, which is approximately 66% of the average annual inflows to all reservoirs (969,900 acre-feet). However, while Tahoe's average annual release of 235,000 acre-feet is the largest of the system reservoirs, that release represents only 43% of the water supply from the reservoirs.

The importance of the evaporation component to the Lake Tahoe water balance explains why it contributes such a relatively small volume to the water supply. The total impounded volume behind the Tahoe Dam is ~745,000 acre-feet at a height of 6.1 feet over an area of ~120,000 acres. The large surface area, in combination with the surrounding climate, lead to a relatively high annual average evaporation of ~427,000 acre-feet, or 3.6 feet over the lake surface, which represents more than half of the total reservoir capacity.

Evaporation's influence on the Lake Tahoe water balance means that the reservoir is potentially more susceptible than other reservoirs to climate change impacts that may involve decreased inflows and increased evaporation. Additionally, the low height of the dam means that dam operators are limited in their control of the release rate from the lake, and no release is possible if the pool elevation drops below the lake rim. For those reasons, and Tahoe's importance as a water supply, anticipating the effects of climate changes on the Lake Tahoe pool elevation are critical for understanding its future role in water supply projections for the basin.

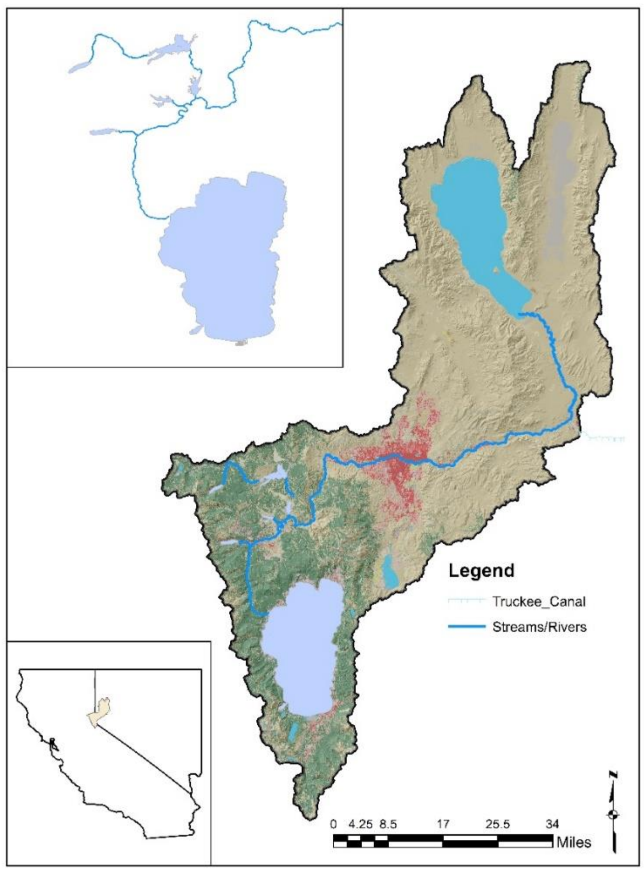

Figure 1. Truckee Basin Map

The major objective of this work is to analyze the effects of plausible future climate scenarios on the likelihood of the Lake Tahoe stage to fall below the lake's natural rim. This objective was pursued through the use of more robust and advanced hydrologic and operations models and climate projections than were previously available or applied to the basin.

Methods

Models and Data

The study was performed by utilizing eight different Global Climate Models (GCMs) (CCSM4, CNRM-CM5, CanESM2, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, MIROC5, bcc-csm1-1) under two Representative Concentration Pathway (RCP) scenarios (4.5 and 8.5) (*van Vuuren, 2011*) to generate forcing for PRMS hydrologic models of Lake Tahoe and the Truckee River basin *(Rajagopal et al., 2015)*. In addition, the GCM output was used to calculate open water evaporation for Lake Tahoe with the CRLE model *(Huntington and McEvoy, 2011)*. The GCM precipitation, PRMS streamflows, and CRLE evaporation time series were then used as input to the Truckee River Operating Agreement Planning Model (Planning Model) (*US BOR, 2015)*. The Planning Model was developed on the RiverWare® platform for performing long-range planning scenarios of the Truckee River Basin operating under the Truckee River Operating Agreement (TROA).

Figure 2 indicates how data flows between the models used. The GCMs produce temperature and precipitation series as output. PRMS uses the precipitation and temperature data as input and produces streamflow data as output. The CRLE uses temperature, humidity and insolation as input and produces open water evaporation on Lake Tahoe as output. The Planning Model operates on a daily timestep uses the precipitation, evaporation, and streamflow time series as inputs and produces reservoir outflows and pool elevations as outputs.

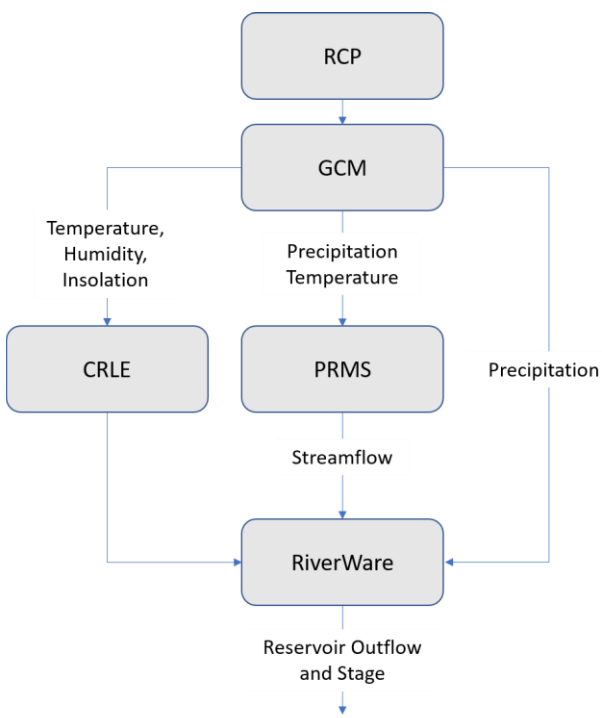

Figure 2. Flow chart showing data flow between the models

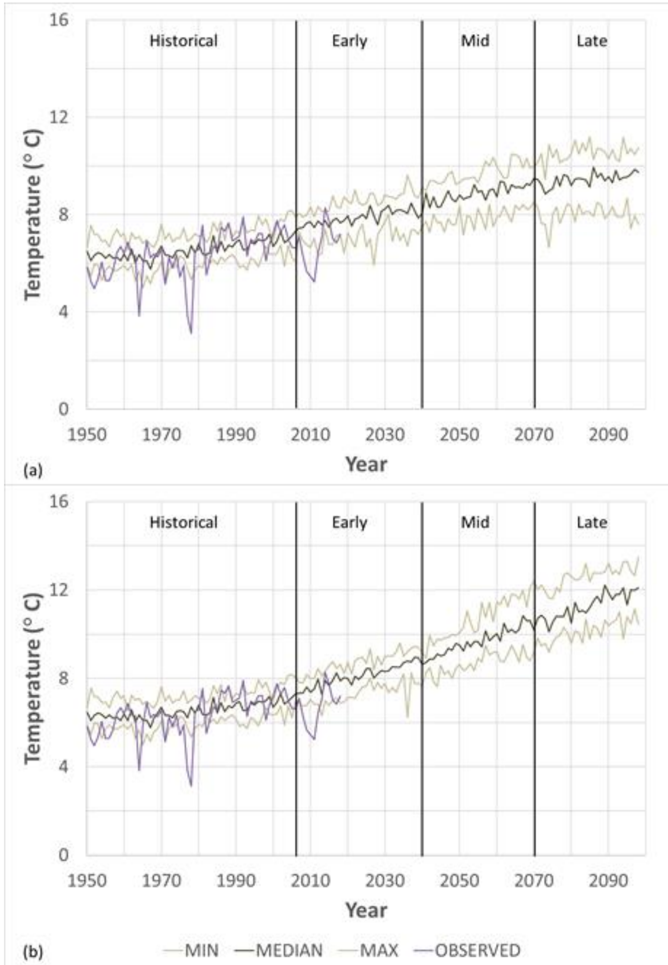

Figure 3. Minimum, Median, and Maximum temperature time series for GCMs under (a) RCP 4.5 and (b) RCP 8.5 scenarios with Historical modeled and observed

Model Calibration/Validation

Two different time series of forcing data were developed from each GCM, for the periods 1951-2005 and 2006-2098. The 1951-2005 series ("Historical") were used for calibration/validation by comparing output from the RiverWare® model forced by the synthetic data with output generated from historical data inputs. Based on those comparisons, the streamflow and precipitation time series for the RCP scenarios were bias-corrected prior to their use as RiverWare® input.

Validation of the GCM-forced hydrologic data was performed by using the PRMS outputs as input to the RiverWare® model and comparing statistically the RiverWare® outputs and historical data. For this purpose, the entire Truckee River basin was divided into three sub-basins corresponding with the individual PRMS models' extents, and referred to as follows: Tahoe, Little Truckee, and Truckee Above Farad. For each GCM, the average of each sub-basin's annual volume and contribution to the overall annual volume was compared to the historical volume and contributions to the overall volume. While the annual volumes for the Little Truckee and Truckee Above Farad sub-basins were in line with the historical modeled values, the annual volumes for Tahoe were deemed unacceptable. In order to remedy that problem, a multiplicative bias-correction factor was applied to each GCM's Tahoe precipitation and streamflow time series and the factor optimized so that the total Tahoe net inflow volumes over the RiverWare® run period (Oct 31, 1950 to Dec 31, 2005) matched the historical volumes for that period. The optimized factor for each GCM was also applied to the RCP (future) scenarios under the assumption that the bias was the same for those scenarios.

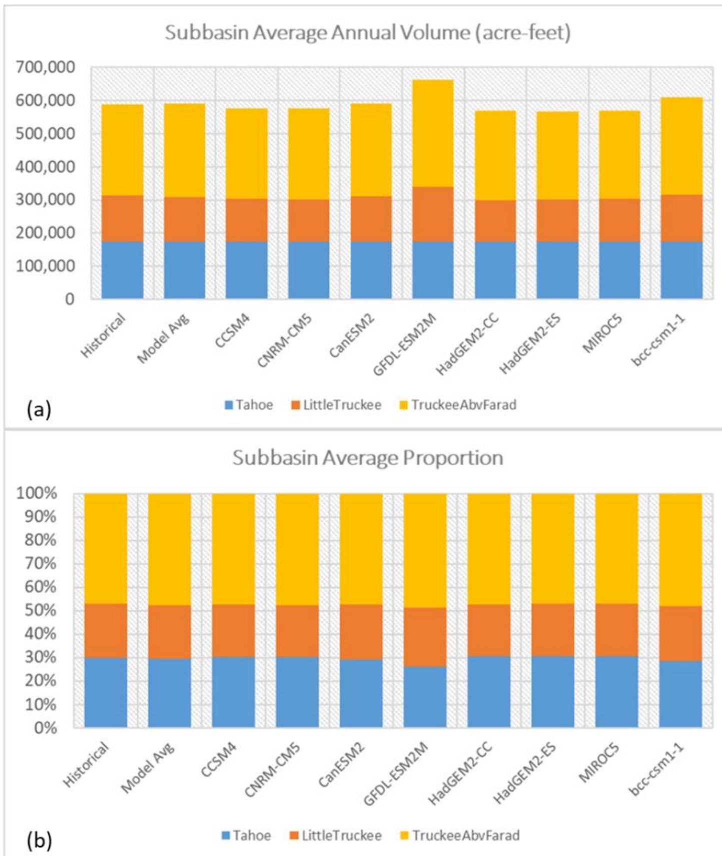

Figure 4. Sub-basin (a) average annual volumes and (b) average annual proportion of total volume after bias correction

Note that the average annual volume for each GCM is not exactly equal to the historical annual average. That discrepancy is due to two factors. First, the optimization was performed based on the total volume and not the annual volumes, and there is a slight amount of shifting of daily volumes based on leap years not being exactly synchronous between the input time series dates and the dates used for the runs in RiverWare® (i.e., a leap year in the input data series is not necessarily counted as a leap year in the RiverWare® run); and second, the annual volumes were calculated based on calendar years, not water years, so the volume for Oct-Dec 1950 is counted as a calendar year when aggregating annually. Nevertheless, the factors bring the annual volumes into what was considered an acceptable margin of discrepancy (<1%) from the historical volumes.

Results

The time series of the minimum, median, and maximum model annual evaporation volumes are shown in Figure 5. The historical period is shown in each figure for comparison, as well as the future period. Observed evaporation is not available for the historical period. From the figure, the modeled median value increases throughout the coming century under both scenarios, more so in the RCP 8.5 scenario than the RCP 4.5 scenario. In the absence of other hydrologic effects of the future scenarios, the increase in evaporation would lead to lower pool elevations and decreased releases for Lake Tahoe; however, the increased evaporation does not occur in isolation, but in conjunction with changes to the lake inflow and precipitation.

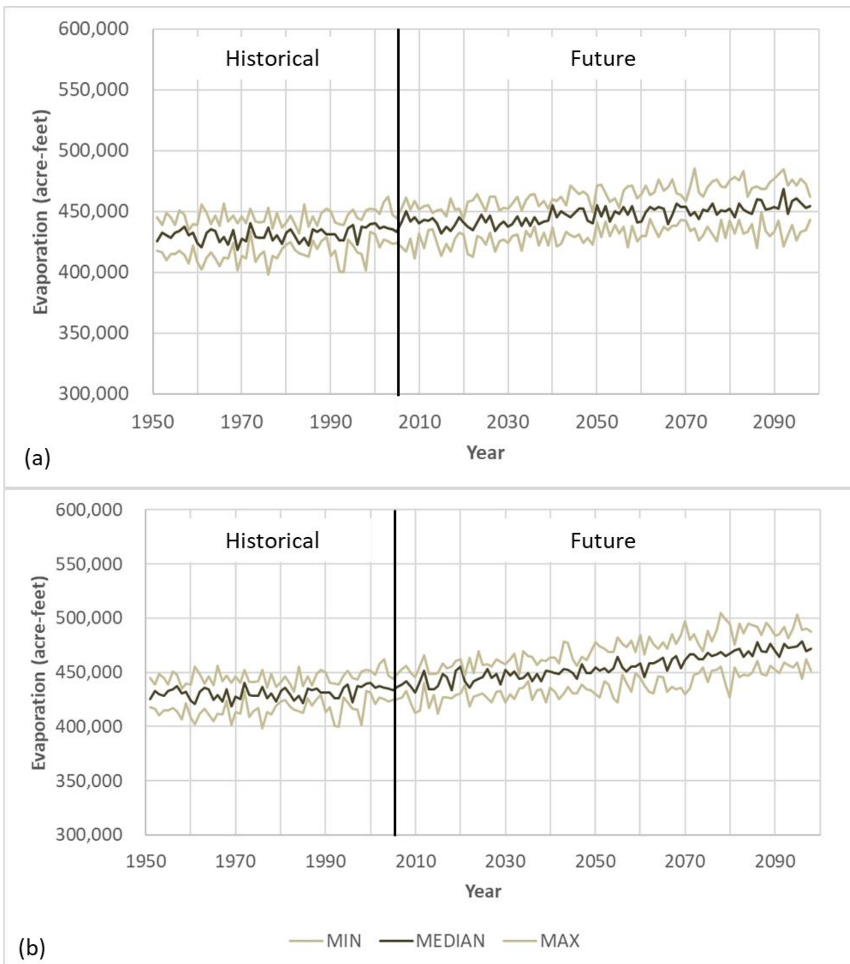

Figure 5. Evaporation time series

The net inflow to the lake contains the combined effects of the climate change scenarios on the hydrologic cycle in the lake watershed. The average annual net inflow to the lake under all three scenarios is presented in Table 1. The model average values for the net inflow under the historical scenario are within approximately 2.5% of the historical values. The individual models' results under the historical scenario are also relatively consistent, varying between -0.8% and 2.4% difference for the net inflow. However, the average annual values increase substantially under both of the future scenarios, along with greater variability between the models. So, it is clear that the increase in evaporation under the future scenarios is, on average and for the majority of the GCMs, outweighed by increases in inflow and precipitation, albeit with wide variation for the different models.

Table 1. Average annual net inflow (acre-feet) and relative difference from historical observed values

	Historical	**RCP 4.5**	**RCP 8.5**
Observed	175,116		
Model Average	177,502 (1.4%)	214,340 (22.4%)	213,689 (22.0%)
CCSM4	176,772 (0.9%)	201,813 (15.2%)	203,259 (16.1%)
CNRM-CM5	173,791 (-0.8%)	397,013 (126.7%)	379,637 (116.8%)
CanESM2	178,736 (2.1%)	255,411 (45.9%)	277,285 (58.3%)
GFDL-ESM2M	177,288 (1.2%)	194,197 (10.9%)	175,691 (0.3%)
HadGEM2-CC	179,100 (2.3%)	155,702 (-11.1%)	196,670 (12.3%)
HadGEM2-ES	179,378 (2.4%)	164,347 (-6.1%)	199,998 (14.2%)
MIROC5	177,452 (1.3%)	191,329 (9.3%)	141,605 (-19.1%)
bcc-csm1-1	177,497 (1.4%)	154,911 (-11.5%)	135,364 (-22.7%)

Figure 6 contains box and whisker plots depicting the Tahoe pool elevation distributions for the historical, RCP 4.5, and RCP 8.5 scenarios. Distributions for the observed historical and modeled values for each individual GCM are presented in each plot, as well as the distribution for all combined modeled values. The box extents reflect the 20^{th} and 80^{th} percentiles of the values, while the whisker extents reflect the minimum and maximum values. The horizontal line in the plots represents the rim elevation of 6,223 ft MSL. The results for the historical scenario indicate that the models reproduce the middle 60% of the distributions very well, while the minimum and maximum values for some models extend substantially above or below those of the observations. The plots for both the RCP 4.5 and RCP 8.5 scenarios reflect increased variability between the individual GCM results, even with the bias correction that was calculated based on historical period modeling. Those results reflect the varying constructions and interactions within the GCMs, and the varying potential outcomes. The All Models distributions under both future scenarios show greater differences between the minimum and maximum relative to the historical observations, but the 20%-80% ranges are very similar to that of the observations.

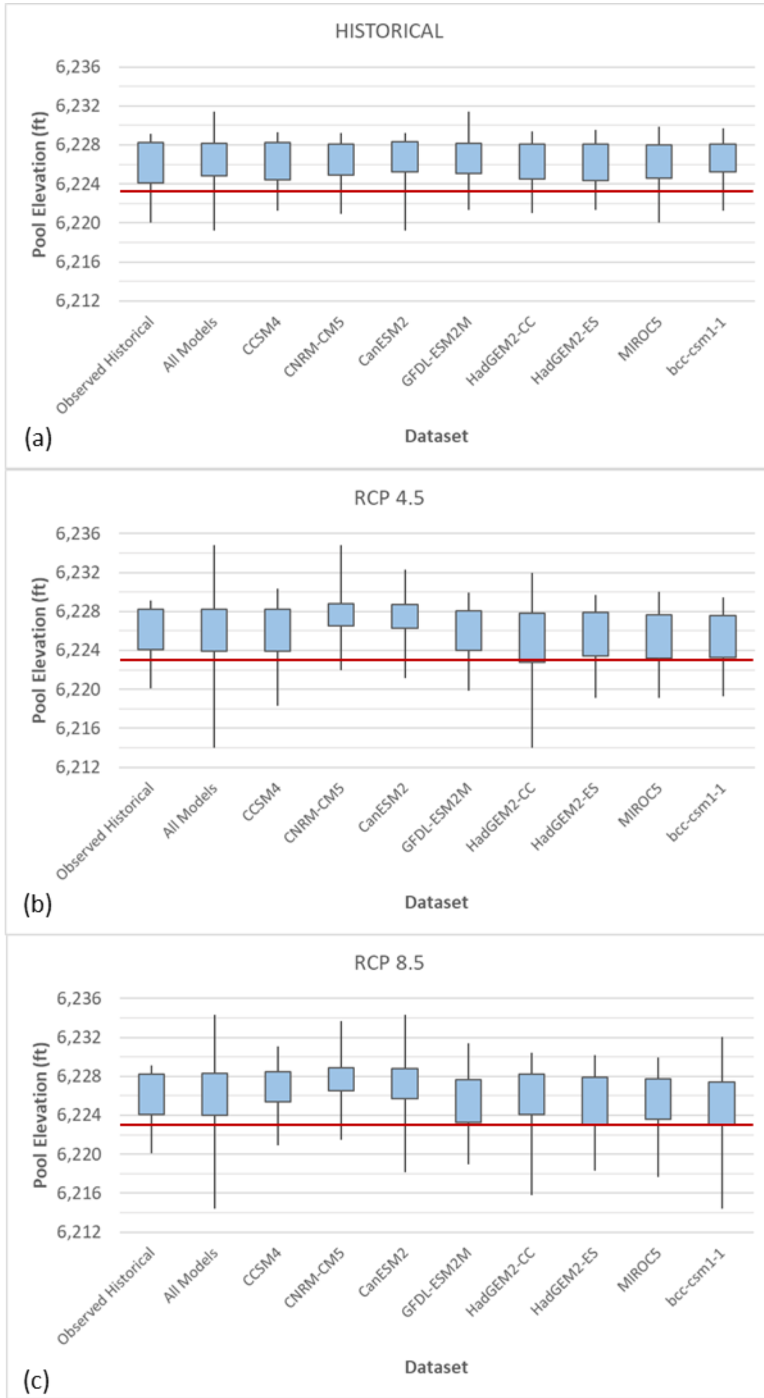

Figure 6. Lake Tahoe pool elevation values with (a) historical input series, (b) RCP 4.5 input series, and (c) RCP 8.5 input series. The red line indicates the natural rim elevation of 6223 ft MSL.

Figure 7 presents box and whisker plots depicting the Tahoe annual outflow volume distributions for the historical, RCP 4.5, and RCP 8.5 scenarios. Distributions for the observed historical and modeled values for each individual GCM are presented in each plot, as well as the distribution for all combined modeled values. The box and whisker extents represent the same quantities as in Figure 6. The historical scenario results indicate that the models reproduce the middle 60% of the distributions closely, although the individual models exhibit slightly more variation in the 20% and 80% outflow values than they did in the pool elevation distributions. Most, but not all, modeled distributions have a minimum annual outflow volume of 0 acre-feet, indicating that at some point in the run period the pool elevation was below the rim elevation. The All Models distribution shows slightly higher 20% and 80% values than the historical observed values. The results for both the RCP 4.5 and RCP 8.5 scenarios again reflect increased variability between the individual GCM results, with the RCP 8.5 scenario exhibiting a greater increase than the RCP 4.5 scenario. The All Models distributions for both future scenarios show greater minimum-maximum and 20%-80% ranges than the historical observations.

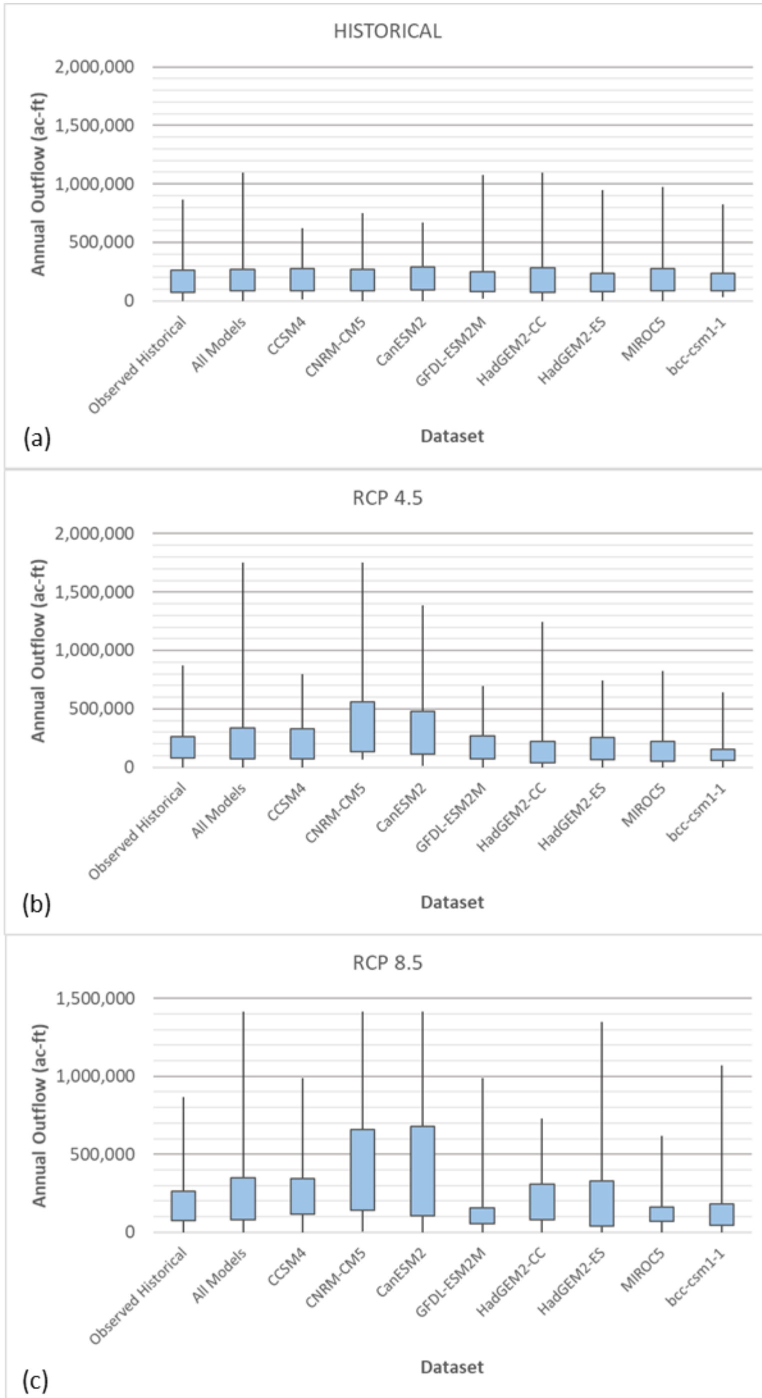

Figure 7. Modeled Lake Tahoe outflow volume distributions with the (a) RCP 4.5 and (b) RCP 8.5 scenarios

Lake Tahoe can only act as a downstream water supply if its pool elevation is greater than the natural rim elevation, 6,223 ft MSL. Therefore, the relative length of time that the pool elevation is below the rim is an important indicator of the lake's water supply viability. The percent of days for which the pool elevation is lower than the rim under each scenario is shown in Table 2. Daily pool elevation readings are only available beginning on October 1, 1957, so the historical observed and modeled values are based on the time period October 1, 1957 through December 31, 2005. The observed data shows that the daily pool elevation was below the rim for 9.2% of that time period. Under the historical modeled scenarios, the model average was 6.3% of daily values during the time period, with a range of 2.6% (bcc-csm1-1) to 11.6% (HadGEM2-CC). So, the modeled historical periods underestimated the duration of time that the lake was unable to release water downstream. The model average percent days lower than the rim for both the RCP 4.5 (11.8%) and RCP 8.5 (11.7%) scenarios was greater than both the observed historical and modeled historical scenarios. In the RCP 4.5 scenario, all modeled hydrology sets except two (CNRM-CM5 and CanESM2), produced percentages below the rim greater than both the observed and respective modeled historical percentages. Those two hydrology sets produced substantially lower percentages of days below the rim elevation. Under the RCP 8.5 scenario, the percentages of days below the rim for those two models' hydrology increased from the RCP 4.5 scenario but remained lower than the observed and respective modeled historical scenarios. Not all models' RCP 8.5 hydrology produced longer durations below the rim elevation relative to the respective models' RCP 4.5 hydrology sets. Hydrology produced by the CCSM4, HadGEM2-CC, and MIROC5 models led to less time below the rim elevation with the RCP 8.5 scenario than with the RCP 4.5 scenario. This is despite the generally higher temperatures in the RCP 8.5 scenario.

Table 2. Percent of days with pool elevation < 6,223 ft MSL

	Historical*	**RCP 4.5**	**RCP 8.5**
Observed	9.2		
Model Average	6.3	11.8	11.7
CCSM4	6.3	11.9	4.2
CNRM-CM5	5.2	0.5	1.2
CanESM2	8.6	0.6	5.5
GFDL-ESM2M	3.5	9.6	16.6
HadGEM2-CC	11.6	21.7	13.6
HadGEM2-ES	6.6	15.2	19.9
MIROC5	5.7	18.2	13.0
bcc-csm1-1	2.6	16.6	19.3

*Based on USGS daily gage heights from Oct 1, 1957 to Dec 31, 2005, the range of daily observations available on the TROA Information System website

The lake's storage and pool elevation are also dependent on the lake's outflow. The average annual outflow is shown in Table 3, along with the relative difference from the historical observed value. The model average value for the outflow under the historical scenario is within 3% of the historical values. The individual models' results under the historical scenario are also relatively consistent, varying between -2.8% and 1.5% difference for the outflow. However, the average annual values increase substantially under both of the future scenarios, along with greater variability in the individual models' difference from the historical value. While the annual average values for the outflow provides information regarding the general trends over the modeling periods, the variability is also important to the lake's function as a water supply.

Table 3. Average annual outflow (acre-feet) and relative difference from historical observed value

	Historical	**RCP 4.5**	**RCP 8.5**
Observed	184,572		
Model Average	184,451 (-0.1%)	219,293 (18.8%)	217,822 (18.0%)
CCSM4	187,331 (1.5%)	204,801 (11.0%)	203,544 (10.3%)
CNRM-CM5	185,886 (0.7%)	399,007 (116.2%)	381,423 (106.7%)
CanESM2	185,963 (0.8%)	256,036 (38.7%)	276,830 (50.0%)
GFDL-ESM2M	182,809 (-1.0%)	199,359 (8.0%)	182,569 (-1.1%)
HadGEM2-CC	179,431 (-2.8%)	160,196 (-13.2%)	201,917 (9.4%)
HadGEM2-ES	186,691 (1.1%)	178,200 (-3.5%)	210,971 (14.3%)
MIROC5	182,451 (-1.1%)	196,497 (6.5%)	145,557 (-21.1%)
bcc-csm1-1	185,046 (0.3%)	160,246 (-13.2%)	139,765 (-24.3%)

Table 4 provides some illumination into the distribution of annual volumes relative to the observed historical annual average. For each scenario presented, the table indicates the percentage of years with annual volume greater than and less than the historical average, as well as the average volume for those two categories of years. The RCP 4.5 and RCP 8.5 values presented are the averaged values over all individual GCM results. The percentage of years in each scenario greater than and less than the historical average is consistent across all three data sets at ~65% greater than the average and ~35% less than the average, as is the average volume for years that fall below that volume. However, the average volume during the years with a volume greater than the historical average volume are substantially larger for the future climate scenarios than for the historical observed period. So, the wet years are greater in magnitude under the climate change scenarios, while the relatively dry years are roughly the same magnitude.

Table 4. Average annual volumes (acre-feet) and occurrences relative to observed historical annual average volume

	Historical Observed	**RCP 4.5**	**RCP 8.5**
Years < Historical Average	66%	66%	65%
Avg Volume for Years < Historical Average	96,273	95,237	98,572
Years > Historical Average	34%	34%	35%
Avg Volume for Years > Historical Average	352,912	419,079	447,218

Conclusions

1. A large degree of variability and uncertainty exists in both the hydrologic variables used as input to the Planning Model, as well as the Lake Tahoe conditions that result from those inputs. As a result, it is not possible to make a definitive statement regarding the direction or magnitude of changes in those conditions from the historical observations.
2. Modeling results from the RCP scenarios indicate that the Lake Tahoe pool elevation will remain below the rim elevation for a greater proportion of time in the future than it has historically, requiring users in the Truckee Basin to employ other water supply sources more frequently.
3. The average net inflow to the lake may increase, even under a generally warmer climate. If the pool elevation is greater than the rim elevation when high net inflows occur, increased outflows may also occur in order to maintain the pool elevation below its maximum.
4. Outflow from Lake Tahoe under the RCP scenarios is likely to exhibit greater variability than historical flows, leading to the need to prepare for high flows as well as more frequent periods requiring the use of alternate water supply sources.
5. The combination of Lake Tahoe remaining below its rim more frequently and greater outflow variability means that water management in the Truckee River watershed is likely to become more challenging in the future.

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