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RECLAMATION

Technical Memorandum No. ENV-2024-023

Evaluation of Operating Criteria and Procedures (OCAP) Performance Under Paleo and Future Climate Scenarios

**Truckee and Carson River Basins, California and Nevada
California-Great Basin Region**



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**Truckee and Carson River Basins, California and Nevada
California-Great Basin Region**

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Errata Sheet

Lake Tahoe Total Inflow Bias Correction

Analysis following the initial publication of this report revealed an over-prediction bias in the modeled, historical Lake Tahoe total inflow. The discovered overbias led the authors to apply an annual bias correction technique to Lake Tahoe inflow before re-running the hydrologic operations model. The bias correction technique involves developing cumulative distribution functions for both modeled and observed historical annual total inflow, then applying correction factors at various quantiles of historical total inflow, correcting the modeled historical and future annual time series. Bias-corrected daily timeseries were then derived by maintaining the daily fraction of annual streamflow on each day computed by the original (uncorrected) daily timeseries. The revised document includes a discussion of the streamflow bias correction method and updated results. Key additions and revisions include:

- Added explanation of the bias correction approach used for total inflow to Lake Tahoe and associated hydrologic modeling assumptions (section 3.5 and appendix D).
- Updated interpretation of future water supply metrics resulting from the bias-correction and revised Lake Tahoe net inflow (section 4.5), including:
 - Reduction in annual average Lake Tahoe and Pyramid Lake elevations.
 - Improved representation of changes in streamflow volume and timing and seasonal variability.
 - More mixed future operational outcomes, exhibiting both improvements and declines in performance.

New Appendix E Data Source Comparisons

The revised document includes supplemental discussion and analysis in appendix E regarding comparisons between hydrologic data sources used in the Pilot Study and those used in previous studies. Key additions include:

- Comparison of gridded and climate station precipitation datasets.
- Comparison of datasets associated with Lake Tahoe evaporation used in this Pilot Study and previous studies.
- Comparison of alternative inflow datasets and modeling approaches used to estimate total inflow to Lake Tahoe.
- Discussion of differences between historical observed datasets, modeled inflow datasets, and bias-corrected hydrologic projections.
- Documentation of the rationale for selecting the revised Lake Tahoe total inflow bias-correction approach incorporated into the updated modeling framework.
- Improved transparency regarding uncertainty associated with hydrologic inputs and bias-correction methodologies used throughout the Pilot Study.

Updated Results and Discussion

Several results in section 4.0, including numerical values and technical descriptions, were revised based on updated input datasets to the RiverWare model. Section 5.0 Discussion was also updated based on new results. Key updates include:

- Revision of climate and hydrologic trend descriptions to better reflect modeled results.
- Revision of Pyramid Lake elevation and inflow discussion to align with updated model outputs and supporting tables.
- Updated discussion of Carson Division Demand reliability and Floriston Rate performance under future climate scenarios.

Executive Summary and Editorial Clarifications

The revised document includes multiple editorial and technical clarifications throughout the Executive Summary to improve readability, consistency, and technical accuracy. Revisions include:

- Standardization of terminology and tense usage throughout the Executive Summary.
- Expanded explanation regarding baseline conditions used in the TROA Planning Model, including clarification that modeled baseline conditions apply TROA and OCAP operational rules across the entire simulation period and therefore do not replicate observed historical operations.
- Improved descriptions of drought metrics, including clarification of:
 - Largest Cumulative Deficit (LCD) droughts.
 - Largest Annual Deficit (LAD) droughts.
 - Rule-based versus zero-crossover drought definitions.

Formatting Corrections

- Minor formatting, punctuation, grammar, and citation consistency edits throughout the document.

Citation and Reference Updates

The revised version retains the previously documented November 1, 2024 errata updates, including:

- Replacement of the citation “Morway et al. 2013” with “Kitlasten et al. 2021.”
- Addition of a new in-text citation to “Kitlasten 2021.”
- Addition of the associated bibliography reference for the USGS data release.

Overall Effect of Revisions

The updated version of the document does not substantially alter the overall conclusions of the Pilot Study; however, it improves technical precision, consistency with model results, interpretation of future climate impacts, and clarity regarding operational assumptions and

hydrologic performance metrics. The revisions primarily strengthen the presentation and interpretation of results while correcting several numerical, editorial, and explanatory issues identified during technical review.

The revisions to the original document have been certified by:

Marketa McGuire, P.E.

Civil Engineer (Hydrologic), Applied Hydrology 2

Technical Memorandum No. ENV-2024-023

Evaluation of Operating Criteria and Procedures (OCAP) Performance Under Paleo and Future Climate Scenarios

**Truckee and Carson River Basins, California and Nevada
California-Great Basin Region**

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Acronyms and Abbreviations

AF	acre-feet
AF/yr	acre-feet per year
AMJ	April, May, June
Basin Study	Truckee Basin Study
CDD	Carson Division Demand
CDFs	cumulative distribution functions
CFR	Code of Federal Regulations
CRLE	Complementary Relationship Lake Evaporation
CMIP	Coupled Model Intercomparison Project
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
EIS	Environmental Impact Statement
ESA	Endangered Species Act
Evap	evaporation
Farad gage	gage in Farad, CA; USGS ID 10346000
Fort Churchill gage	gage in Fort Churchill, NV; USGS ID 10312000
ft	feet
ft ³ /s	cubic feet per second (ft ³ /sec in figures)
GCM	general circulation models
GSFLOW	Groundwater and Surface-water FLOW
Hwy	Highway
JAS	July, August, September
JFM	January, February, March
km	kilometer(s)
LAD	largest annual deficit
LBAO	Lahontan Basin Area Office
LCD	largest cumulative deficit
LCT	Lahontan cutthroat trout
LOCA	Locally Constructed Analogs
LOCA-CMIP5	Locally Constructed Analogs downscaled Coupled Model Intercomparison Project Phase 5
LOESS	localized regression
LSOCM	Lahontan Storage Objective Current Month
mg/L	milligrams per liter
MLR	multiple linear regression

No.	Number
NSE	Nash-Sutcliffe efficiency
paleo	distant past paleohydrology
Pilot Study	OCAP Reservoir Operations Pilot Study
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PRMS	Precipitation Runoff Modeling System
Project	Bureau of Reclamation Newlands Project
PWRE	Precision Water Resources Engineering
RCP	representative concentration pathway
Reclamation	Bureau of Reclamation
RMSE	root mean square error
OCAP	Operating Criteria and Procedures
OND	October, November, December
Secretary	Secretary of the Interior
SECURE Water Act	Science and Engineering to Comprehensively Understand and Responsibly Enhance Water Act of 2009
SNOTEL	snow telemetry
Station ID	Station identifier
SWE	snow-water equivalent
TAF	thousand acre-feet
TCDATFIL	Truckee Carson Data File
TMWA	Truckee Meadows Water Authority
TROA	Truckee River Operating Agreement
TROA Planning Model dataset	TROA Daily Historical Planning Model Dataset
Truckee-Carson Basins	Truckee and Carson River Basins
USGS	U.S. Geological Survey
USWM	U.S. District Court Water Master
West-Wide Assessment	2021 West-Wide Climate and Hydrology Assessment
WftS	Water for the Seasons
WY	water year(s)

Symbols

°C	degrees Celsius
°F	degrees Fahrenheit
/	divided by
=	equals
—	minus
+	plus
%	percent
:	ratio
*	times

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Executive Summary

Background

The Bureau of Reclamation's (Reclamation) Lahontan Basin Area Office (LBAO) manages water supply to the Newlands Project (Project) in western Nevada. The Project receives water from both the Truckee and Carson River Basins (Truckee-Carson Basins), with the Truckee Canal allowing inter-basin transfers from the Truckee River to the Carson River. The Project includes Lake Tahoe Dam, Derby Diversion Dam, Truckee Canal, Lahontan Dam, Carson River Diversion Dam, and canals, laterals, and drains for irrigation of about 1,500 acres in the Truckee Division and 55,000 acres in the Carson Division of the Project.

Water management follows the 1997 Operating Criteria and Procedures (OCAP), which is a Federal regulation promulgated by the Secretary of the Interior (Secretary) that defines the annual water demand of the Project and regulates the diversion of water from the Truckee River to meet that demand, consistent with the Alpine and Orr Ditch Decrees and the Secretary's trust responsibilities to the Pyramid Lake Paiute Tribe and Fallon Paiute-Shoshone Tribe. The objectives of the 1997 OCAP are to maximize use of Carson River waters to meet the requirements of the Project, minimize the use of water from the Truckee River as a supplemental supply, increase efficiency of water use in the Project, establish a regulatory scheme to manage deliveries to Project water users, and conserve Truckee River flows for Pyramid Lake.

Reclamation initiated a scoping effort in late 2020 to update the OCAP (hereafter termed, OCAP Update). During scoping workshops, stakeholders expressed the need to understand the OCAP's ability to satisfy water rights demands into the future under changing climatic and hydrologic regimes. Through Reclamation's WaterSMART (Water Sustain and Manage American Resources for Tomorrow) Basin Study Program, LBAO partnered with the Technical Service Center to conduct a study to support the future OCAP Update by developing a long-term hydrologic dataset to improve understanding of climate variability and change in the Truckee-Carson Basins, and to initially explore the ability of the OCAP to meet its objectives under these conditions. This study, called the OCAP Reservoir Operations Pilot Study (Pilot Study), is a key component of Reclamation's implementation of the Science and Engineering to Comprehensively Understand and Responsibly Enhance Water Act of 2009 (SECURE Water Act). This Pilot Study, along with others, aims to identify innovative approaches to improve water management strategies in the Western United States.

This Pilot Study resulted in four main outcomes, described in more detail in the following sections of this Executive Summary:

1. This Pilot Study produced a 600-year hydrologic dataset, spanning years 1500–2099, which includes paleohydrology information as well as projected future information driven by general circulation models (GCMs), encompassing a broad range of hydrologic variability.

2. This Pilot Study established a modeling framework to support the OCAP Update and other basin applications by linking the 600-year hydrologic dataset to the existing RiverWare model (Truckee River Operating Agreement [TROA] Planning Model), which guides operations and planning in the Truckee-Carson Basins.
3. The Pilot Study demonstrated the utility of the modeling framework by summarizing preliminary water management impacts over the new period of record using key metrics that are meaningful to water managers.
4. Building off this Pilot Study, additional work is recommended. Future reservoir evaporation and water demands need to be quantified and evaluated, which, alongside the dataset described here, will provide a more complete picture of potential water management impacts to inform the OCAP Update.

This Pilot Study is an initial step to inform future assessments of the OCAP's performance under different climatic conditions to determine what, if any, operational and regulatory updates are needed for the OCAP to continue to meet its objectives in the future.

Summary of Hydrologic Variability Over 1500–2099

Developing the requisite TROA Planning Model inputs spanning 1500–2099 involved new methods and modeling that were more comprehensive than any previous single study. To develop the dataset, the Pilot Study team expanded the TROA Planning Model 117-year simulation period (1901–2017) to encompass a 400-year paleohydrology period, and a close to 100-year projected future period (2018–2099) (figure ES-1). To the study teams' knowledge, no other study has combined the paleo, recent historical, and projected future hydrologic data in this manner in the Truckee-Carson Basins. Developing this dataset required incorporating methods unique to each of the three periods. An overview of the methods and preliminary results follows, along with recommendations for future improvements in the data and methods to support the future OCAP Update.

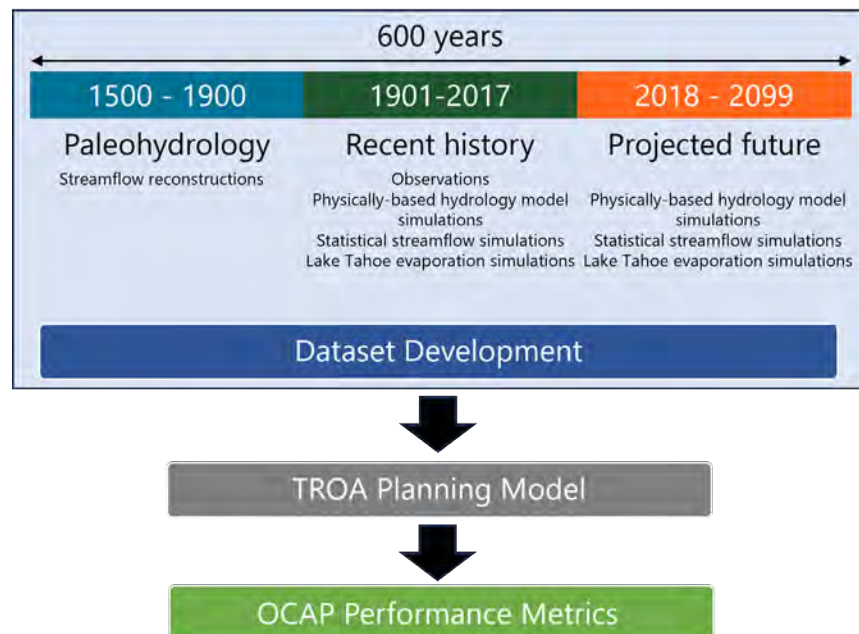


Figure ES-1.—Period components of Operating Criteria and Procedures Reservoir Operations Pilot Study hydrology dataset.

Paleohydrology

Reclamation has increasingly used tree-ring-based reconstructions of streamflow to evaluate how well water systems throughout the Western United States would perform if droughts like those that occurred in the distant past were to occur today. This Pilot Study used unique streamflow reconstructions for the Carson River and Truckee River to develop the paleohydrology portion of the dataset and to evaluate distant past droughts in the context of recent historical droughts. The paleo time series developed in this Pilot Study extends further back in time than previous efforts (e.g., the 2021 West-Wide Climate and Hydrology Assessment; Reclamation 2021a) and encompasses periods of well-documented mega-droughts in the region that were more severe than recent historical droughts.

Using these streamflow reconstructions, the study team identified major drought events between 1500 and 1900. Two definitions of drought were applied to provide a broad understanding of distant past droughts and to illuminate the uncertainty associated with drought definition choice: a rule-based definition, where 2 consecutive years below average conditions indicate the beginning of a drought and 2 consecutive years above average conditions indicate the end of a drought, and a zero cross over definition, where any year below average conditions is considered a drought. While both unique definitions of drought were used, the analysis in the Pilot Study focuses on the rule-based definition of drought.

Additionally, the team used two unique measurements to identify the most substantial drought events: 1) a measure of the combined effects of intensity and duration (termed largest cumulative deficit [LCD] droughts) and 2) a measure focused more on the severity of each drought year

(termed largest annual deficit [LAD] droughts). The recent historical period (1901–2017) experienced lower annual average streamflow (overall drier conditions) compared to the distant past (1500–1900); however, the recent historical period also shows wetter wet years and more wet years than the paleo-period. In both the Carson and Truckee River Basins, the most severe droughts in the paleo-period exceeded the LCD and LAD droughts experienced in the recent historical period (figure ES-2). The paleo evidence suggests that significantly longer droughts occurred in the distant past compared to the recent historical period, including a 32-year drought from 1569 to 1600, which would have resulted in an approximate 37-foot drop in Lake Tahoe elevation over the course of the drought. Interestingly, the late 1980s drought is the only top-ranked drought common to both the Truckee and Carson Basins.

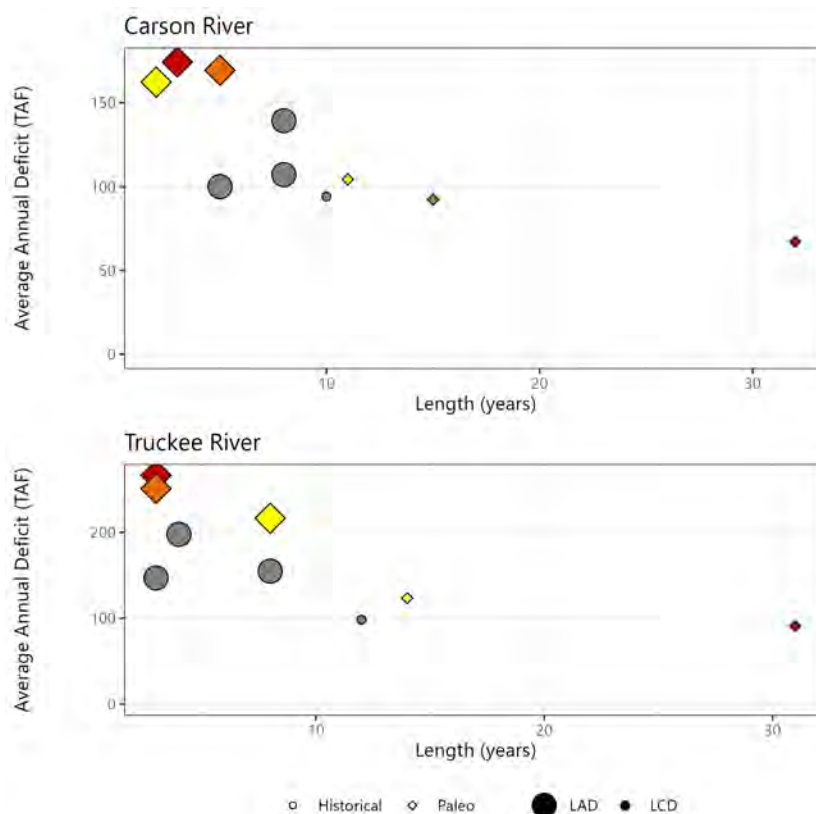


Figure ES-2.—Largest drought events identified using the rule-based definition in the Carson River Basin (top) and Truckee River Basin (bottom) for paleo-period (1500–1900) and recent historical period (1901–2017).¹

¹ Red, orange, and yellow symbols represent the highest, second highest, and third highest (respectively) ranked drought in the paleohydrology period based on drought measurement type. Gray symbols represent the three highest ranked droughts in the recent historical period. It should be noted that in the Truckee River Basin (figure ES-2, bottom panel), the second ranked LCD paleo drought is the same drought (WY 1515–1522 spanning 8 years with an average annual deficit of 216 TAF) as the third ranked LAD paleo drought, though the LCD drought symbol does not appear on the figure.

Recent Historical and Projected Future Hydrology

Recent historical hydrology used in this Pilot Study encompasses existing information from observations as well as simulated information from existing and new modeling tools. An existing dataset of recent daily historical reservoir inflows and other daily historical inputs to the TROA Planning Model was used to represent the recent historical hydrology for water years (WY) 1901 through 2017 (TROA Daily Historical Planning Model Dataset). The TROA Daily Historical Planning Model Dataset was also used to inform the daily disaggregation of the annual paleo-period reconstructed streamflow.

This Pilot Study developed future hydrology projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) archive, which covers the period 1950–2099 (calendar years). The climate projections were statistically downscaled to watershed scale using the Locally Constructed Analogs (LOCA) method (Pierce et al. 2014). The LOCA-CMIP5 ensemble includes 64 climate projections produced from 32 different GCMs, each forced with two emission scenarios (Representative Concentration Pathway [RCP] 4.5 and RCP 8.5, representing a medium and high emissions scenario, respectively). For the future period (2018–2099), the 64 projections encompass a broad range of potential future climate conditions. These projections supported the Fourth National Climate Assessment, published in 2018 (U.S. Global Climate Research Program 2018).

Projected future climate aligns with findings in other studies that indicate warmer, wetter winters and hotter, drier summers with little change in annual average precipitation (figure ES-3). Although there is no clear trend in annual average precipitation, annual mean temperature will continue to rise, with the magnitude of temperature increase dependent on the considered greenhouse gas emissions scenario. Results in figure ES-3 focus on the watershed contributing to Lake Tahoe (called the Lake Tahoe Basin), but similar projected patterns exist in all other basins within the study area.

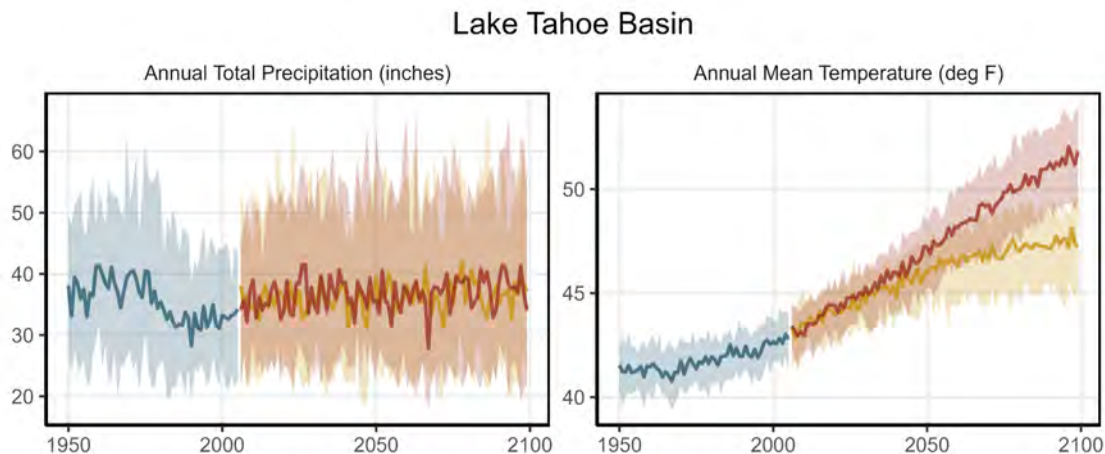


Figure ES-3.—Time series of basin-averaged, bias-corrected, LOCA-CMIP5 historical (blue) and LOCA-CMIP5 projected (yellow = RCP 4.5 and red = RCP 8.5) precipitation and temperature for the Lake Tahoe Basin.²

Future changes in seasonal unregulated streamflow projections developed in this Pilot Study largely align with precipitation projections and show higher winter-spring streamflow and lower summer-fall streamflow, as well as an earlier peak runoff compared to the historical period. Unregulated hydrology was simulated over the recent historical and projected future periods using a combination of modeling tools, including existing Precipitation Runoff Modeling System (PRMS) physically-based hydrology models in the Truckee-Carson Basins developed as part of the Truckee Basin Study (Reclamation 2015) and a statistical model of streamflow in the Carson River near Fort Churchill, NV (described later). Historical and projected future evaporation from Lake Tahoe, which was needed to calculate inflows to Lake Tahoe, was simulated using the Complementary Relationship Lake Evaporation model (Morton 1985, 1983, 1979). Corresponding with continued warming, annual evaporation rates from Lake Tahoe will continue to increase by 2.4 to 6.0 inches by 2100.

Climate Change Impacts on Water Management

The TROA Planning Model was used to produce regulated hydrology to assess the impacts of variable conditions on OCAP operations. The Pilot Study relied on the current TROA Planning Model³ (TROA_PlanningModel_Official008_01.mdl) for simulation of river operations across the 600-year dataset. Evaluation of water management impacts over a long span of time

²Dark colored lines indicate the respective ensemble median value, while shading indicates the 10th and 90th percentile ensemble values. It should be noted that the visual gap in the data in the transition from recent historical period to projected future is only an artifact of the visualization and does not indicate a gap in the data itself.

³ Baseline conditions for the TROA Planning Model include all existing reservoirs and infrastructure and apply operational rules under TROA and OCAP over the entire period of record and thus do not match observed conditions over the historical period.

facilitates understanding of whether distant past and/or projected future conditions are outside the range of the more recent historical record, which relies on observations. It also allows for the testing of water management strategies under conditions not experienced in recent times.

The produced dataset contains notable limitations for assessing climate change impacts on OCAP performance. Importantly, except for simulated evaporation at Lake Tahoe, the newly developed dataset does not include simulated changes in evaporation at the other reservoirs, which is expected to increase under warmer future conditions. This dataset also does not include projected changes in future water demand. Planned future work will address these limitations, as discussed subsequently.

The Pilot Study evaluated metrics in the categories of water supply, environmental flows, and flood risk management, with key highlights below:

- Within the water supply metrics, annual average water supply storage at Lake Tahoe and Lahontan Reservoir showed an increasing trend from the paleo to the historical period. Trends in water supply metrics from the historical period to the near-future period are mixed. These variable trends resulted in a greater ability to meet some water demands, including Carson Division Demands (CDDs; figure ES-4, upper left panel) in the near future, but a decreased ability to meet others, including Floriston Rate demands in the Truckee Basin (figure ES-4, lower left panel). These variable results may be due to increases in winter water supply coupled with changes in streamflow timing, and a greater ability to manage Lahontan Reservoir inflows to meet CDD. The mega-droughts observed in the distant past have the largest impacts on Lake Tahoe's water supply. Alternatively, supplemental inter-basin diversions to Lahontan Reservoir provide resilience to mega-droughts, but Lahontan Reservoir is more susceptible to severe, shorter-duration droughts than Lake Tahoe.
- Considering the OCAP objective to conserve Truckee River flows for endangered fish species, the Pilot Study examined how Truckee River streamflow into Pyramid Lake and Pyramid Lake elevation could change in the future. Climate scenarios indicate an increasing trend in both average annual Pyramid Lake inflow and lake elevation from 3830 feet (ft) on average over the historical period to an average of 3843 ft in the near future, medium emissions scenario (figure ES-4, lower right panel).
- A key flood risk management metric is the maximum annual number of days that streamflow is above the Reno flood flow target, measured as a daily average rate above 5,500 cubic feet per second at the Truckee River at Reno gage in Nevada (USGS ID 10348000). Future scenarios indicate little change in the median number of days over the flood flow target compared to the historical period; however, the future scenarios exhibit a large range of potential variability with many of the scenarios indicating a significantly larger number of days over the flood target, including over 27% of future scenarios that have an increase to over 42 days, which is more than double the maximum in the historical period (figure ES-4, upper right panel).

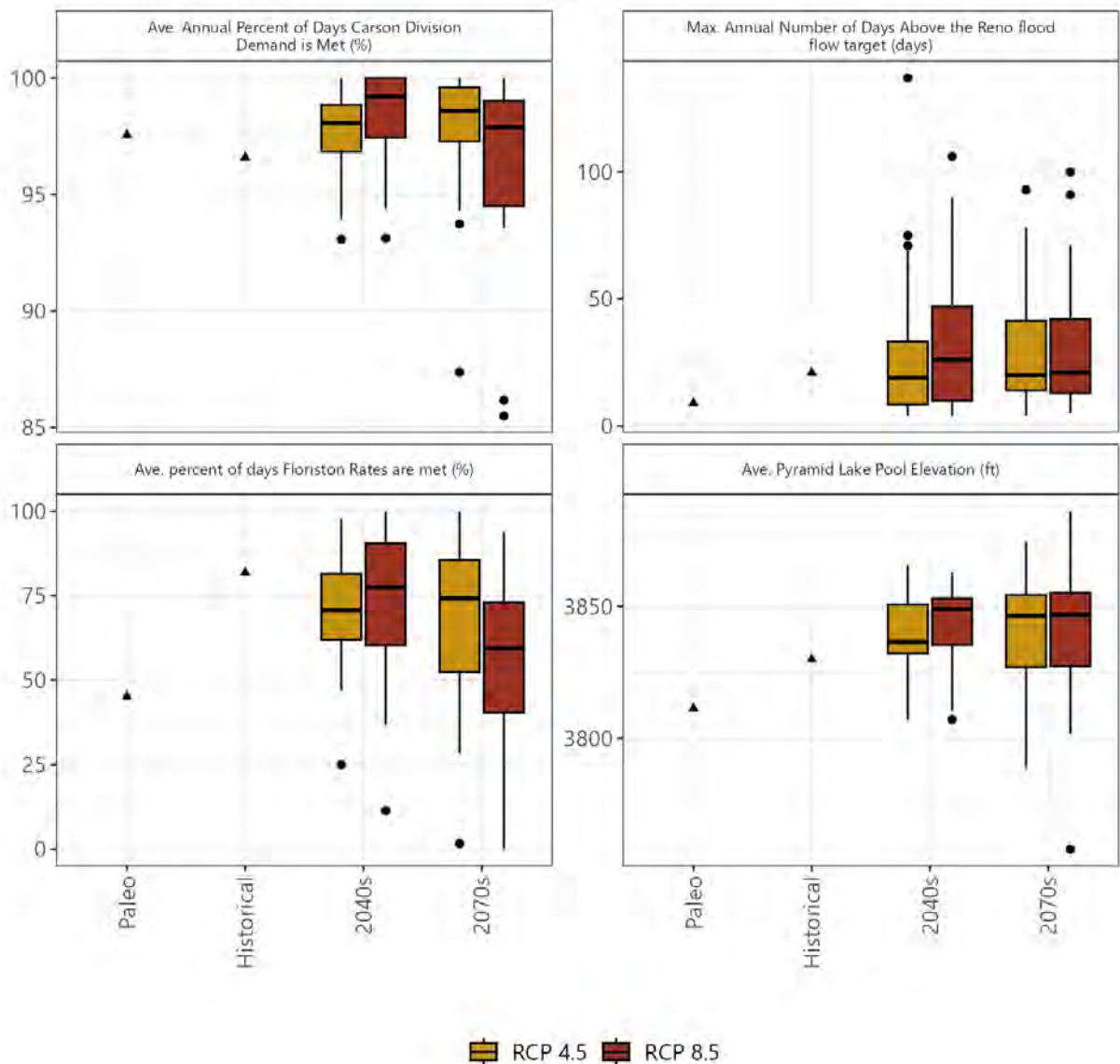


Figure ES-4.—Summary of key water management metrics over the distant past, recent historical period, and two projected future periods (2040s and 2070s).⁴

⁴ Mean values over the distant past and recent historical period are presented by a single, triangular point. The range of projected future period results are presented as box plots for each of the RCP emissions scenarios. The boxes delineate the 25th to 75th percentile values outside that range shown as points, and the median is shown as a horizontal black line.

Recommendations for Future Work

The Pilot Study revealed opportunities to improve upon the developed hydrology dataset and use of the dataset to evaluate the OCAP's performance under climate change. For example, inclusion of future changes in evaporation at all major water bodies within the Truckee-Carson Basins, as well as changes in future demands, is necessary to provide a more complete picture of future water availability. Also, further analysis of the paleo reconstructions in the Truckee-Carson Basins is recommended to improve our understanding of how sensitive streamflow reconstructions are to the methods used for their development.

To ensure that the 1997 OCAP performance results reflect the values and concerns of basin stakeholders and effectively inform the OCAP Update, the study team recommends working with stakeholders to refine and update the metrics list and assessment process. Also, a deeper evaluation of OCAP performance under specific climatic conditions and specific LOCA-CMIP5 runs is recommended to better characterize system vulnerabilities. For example, demands for supplemental supplies from the Truckee River can increase if Carson River streamflow is insufficient to meet the Lahontan storage objective. Combined with projected increases in Truckee River flows, this can result in an increase in diversions from the Truckee River to the Project, in opposition to the OCAP objective to decrease diversions. However, preliminary results show that while the volume of Truckee Canal diversions increases in the future scenarios, the overall percent of Truckee flows above Derby Dam diverted into the canal decreases. Along these lines, the study team recommends applying a bottom-up vulnerability assessment to complement the top-down approach taken in the Pilot Study to identify conditions that stress the system most. This bottom-up assessment would use stakeholder input to identify management concerns around which sensitivity and vulnerability of the OCAP to climate change are then characterized over a large plausible range of future conditions.

1.0 Introduction and Background

The Truckee and Carson River Basins (Truckee-Carson Basins) are heavily managed river systems along the California-Nevada border (figure 1). The Bureau of Reclamation's (Reclamation) Newlands Project (Project) in Nevada provides water from the Truckee-Carson Basins for about 57,000 acres of cropland and wetlands in the Lahontan Valley and the town of Fernley, in western Nevada. To meet Project demand, Derby Dam on the Truckee River diverts water through the Truckee Canal to Lahontan Reservoir to supplement supplies from the Carson River when needed. Diversions through the Truckee Canal are regulated by the 1997 Operating Criteria and Procedures (OCAP) of the Project, a Federal rule published in the Code of Federal Regulations (CFR 418) (OCAP 1997).

The 1997 OCAP established procedures to estimate the annual water demand of the Project and regulate the diversion of water from the Truckee River to help meet that demand, consistent with existing decrees and the Secretary of the Interior's trust responsibilities to the tribes. The decrease in Truckee River flows below Derby Dam, mostly from diversions to the Project, has lowered Pyramid Lake levels, leading to the deterioration of fisheries in Pyramid Lake. The impacts of Project diversions on Pyramid Lake fisheries triggered protracted and repeated litigation by the Pyramid Lake Paiute Tribe and the Federal government against the Truckee-Carson Irrigation District and other users of Truckee River Project water in both Nevada and California. As such, the purpose of the OCAP is to minimize diversions of Truckee River water through the Truckee Canal and maximize the use of Carson River water, while serving valid Project water rights consistent with the Alpine and Orr Ditch Decrees.

In addition to the OCAP, the Truckee River Operating Agreement (TROA) guides operations in the Truckee-Carson Basins. A large consortium of water users, including Federal, State, Tribal, and local agencies, developed the TROA, which was signed in 2008 and implemented in December 2015 (Reclamation 2015). The agreement is required by Public Law 101-618. The TROA intends to provide more effective coordination of reservoir operations on the Truckee River to create flexibility in storage and water use, while maintaining water rights, flood control, and dam safety requirements. Ultimately, the agreement provides a more stable water supply for Truckee River water users, improves water quality, and enhances Truckee River streamflow below Derby Dam for threatened and endangered fish species. While this OCAP Reservoir Operations Pilot Study (Pilot Study) focuses on the performance of the OCAP under distant past paleohydrology (paleo) and future climate scenarios, due to the importance of TROA in guiding basin operations, it also includes some TROA-based metrics.

Reclamation initiated a scoping effort to update the 1997 OCAP, referred to as the OCAP Update. Stakeholders at the scoping workshops identified several possible areas of study to investigate for the OCAP Update, including the need to understand how OCAP performs under different climatic conditions to determine if operational and regulatory updates are needed to meet the purpose of the OCAP into the future (U.S. Department of the Interior [DOI] 2021). Reclamation conducted this Pilot Study to help address that need by developing a hydrology dataset for the Truckee-Carson Basins spanning water years (WY) 1500 through 2099. The Pilot Study includes a workflow to use paleo and future hydrology as input to the existing RiverWare

planning model (TROA Planning Model) used in the Truckee-Carson Basins to evaluate system performance under a changing hydrologic regime; and, preliminary metrics and evaluation of OCAP performance in the paleo and future periods were compared to the recent historical periods. The Pilot Study was funded by Reclamation's WaterSMART (Water Sustain and Manage American Resources for Tomorrow) Basin Study Program and is a key component of Reclamation's implementation of the Science and Engineering to Comprehensively Understand and Responsibly Enhance Water Act of 2009 (SECURE Water Act). This Pilot Study, along with others, aims to identify innovative approaches to improve water management strategies in the Western United States.

The hydrologic dataset developed in this Pilot Study incorporates paleo, recent historical hydrology, and future hydrology projections under a changing climate, comprised of:

- Paleo-reconstructed daily streamflow datasets (1500–1900) for the Carson River at the Fort Churchill gage in Nevada, the Truckee River at the Farad gage in California, and all other inflow locations to the TROA Planning Model.
- Thirty-two simulated historical (1950–2005) and 64 projected (2006–2099) global climate model daily streamflow at 13 defined locations: 10 locations in the Truckee Basin upstream of the Farad gage in California, 2 locations at the outflow of the East and West Carson River Basins, and one location at the Fort Churchill gage in Nevada upstream of Lahontan Reservoir. Locations correspond with inflows into the TROA Planning Model (further described later).
- Reconstructed historical (1901–2017) daily natural streamflow at these same 13 locations developed from a combination of observed gage streamflow and surface hydrology models.

To the extent possible and appropriate, this Pilot Study took advantage of the extensive amount of previous work vested in developing data sets and models for the Truckee-Carson Basins, as described in the following section.

This report first summarizes the previous work performed in the Truckee-Carson Basins that informs this Pilot Study. This report then discusses methods for developing the 600-year hydrologic dataset and methods for using the TROA Planning Model to assess OCAP's performance. Following is a discussion of results, which includes validation of applied models used to develop the dataset, comparison of the dataset across periods (distant past, recent historical, and projected future), and discussion of preliminary results from the TROA Planning Model using the new dataset as input. Finally, the report concludes with an overall discussion including key takeaways and next steps for future analysis and work to inform the OCAP Update.

2.0 Previous Work

The following three subsections (“Previous Distant Past Paleohydrology (Paleo) and Future Streamflow Studies”, “Existing Models and Historical Data”, and “Future Climate Projections”) contain a summary of an extensive literature review (appendix B) that Reclamation conducted before beginning the Pilot Study.

2.1 Previous Distant Past Paleohydrology (Paleo) and Future Streamflow Studies

One of the objectives of the Pilot Study was to investigate historical and projected streamflow trends within the Truckee-Carson Basins. This section summarizes previous efforts to investigate the impact of climate change on streamflow in the Truckee-Carson Basins and how they differ from the current study.

The 2015 Truckee Basin Study (Basin Study) investigated climate change impacts on water supply and demand, using downscaled GCM projections from the CMIP Phase 3 (CMIP3) and corresponding future streamflow scenarios (Reclamation 2015). The Basin Study aggregated all combinations of potential future climates in the Truckee-Carson Basins into five “ensembles” that represent a central tendency and outer bound variations in temperature (“warmer” or “hotter”) and precipitation (“wetter” or “drier”) (Reclamation 2015). Future scenarios were developed by integrating the climate change signal associated with a group of climate projections with historical climate data using a quantile mapping approach. The quantile mapping approach developed cumulative distribution functions (CDFs) of climate variables (precipitation and temperature) using historical data (historical CDF) and future data over a future time horizon (future CDF). Change factors were developed at various percentiles of the CDFs and then applied to historical data, resulting in a perturbed historical time series that incorporates projected future climate change. Future scenarios were developed at the locations of existing climate stations whose historical data were used as input in the three Truckee River Basin Precipitation Runoff Modeling System (PRMS) models used in the Pilot Study.

An interdisciplinary research team and local stakeholders assessed the climate resiliency of the Truckee-Carson Basins through the 5-year Water for the Seasons (WftS) project (Singletary and Sterle 2020). The team of researchers and stakeholders worked collaboratively to develop four scenarios that explored a range of potential changes in climate (Singletary and Sterle 2020; Albano 2019). The scenarios were developed using Locally Constructed Analogs downscaled Coupled Model Intercomparison Project Phase 5 (LOCA-CMIP5) projections. The approach used in this WftS study for developing future climate scenarios is like the approach taken in the Basin Study, in that the scenarios are perturbations of historical climate that reflect future climate change at a future time. The LOCA-CMIP5 projections were used in different ways to develop each of the four scenarios. The four scenarios were defined by: (1) increased temperature, (2) extended drought conditions, (3) increased precipitation variability, and (4) an ensemble of

water level projections for Lake Tahoe. Details of the scenarios and results are provided in appendix B. These four scenarios were then run through the developed Groundwater and Surface-water FLOW (GSFLOW) models to investigate the impact of a changing climate on water resources in the Truckee-Carson Basins.

The Truckee Meadows Water Authority (TMWA) drafts a water resource plan every five years, with the latest one published in 2020⁵ (Truckee Meadows Water Authority 2020). These plans analyze future water resource conditions and outline strategies to meet the region's projected drinking water needs. The future water resource modeling for the 2020 water resource plan built upon the WftS modeling, described above. The TMWA chose 16 LOCA-CMIP5 projections, representing two emissions scenarios, each consisting of an 8 GCM projection ensemble. The eight GCMs were selected based on existing climate change research completed for the northern Sierra Nevada (Lynn et al. 2015). The projections were then run through the Truckee Basin PRMS models, followed by the TROA Planning Model in RiverWare to determine if TMWA could meet the changing supply and demand needs of its customers. In addition, TMWA developed a historical ensemble of nine different hydrologic patterns to test current river and reservoir operations under future demand projections. The nine hydrologic patterns were developed to test the most extreme recent historical droughts (1925–1937, 1987–1994, and 2012–2016) under the highest TMWA demand levels projected toward the end of the 21st century. As discussed in section 3.1.2 where the three highest-ranked droughts in the recent historical period are identified, the same drought events were identified as the most extreme, although the start and end dates do not completely align.

The Pilot Study applies a similar methodology of using future climate projections as input to the PRMS models to simulate streamflow, which are then input into the TROA Planning Model; however, the Pilot Study incorporates 64 LOCA-CMIP5 transient climate projections versus the 16 used in WftS. Similar to this Pilot Study, the WftS study acknowledged biases in precipitation projections, and adjustments were made to precipitation to account for them using a relationship between the historical and projected precipitation. It is unclear whether a quantile mapping approach was used in the WftS study, as was used in this Pilot Study.

The 2021 West-Wide Climate and Hydrology Assessment (West-Wide Assessment; Reclamation 2021b), the technical companion document to the 2021 SECURE Water Act Report to Congress (Reclamation 2021a), summarizes projected changes in climate and hydrology across the Western United States. The West-Wide Assessment also used LOCA-CMIP5 climate and streamflow projections to assess projected changes in hydroclimate across the Western United States, and these were run through the Variable Infiltration Capacity v4.2c (Liang et al. 1996) hydrologic model. The analysis reports on six hydroclimate variables: annual mean temperature, annual total precipitation, April 1 snow-water equivalent, annual runoff, December–March runoff, and April–July runoff, similar to figures shown in the results section of this report. Routed streamflow was also developed for five locations in the Truckee-Carson Basins⁶. The

⁵ TMWA published an updated water resources plan in 2025 after this report was drafted.

⁶ Little Truckee River below Boca Dam; West Fork Carson River at Woodfords; Truckee River at Farad gage; Truckee River at Nixon gage; Carson River near Fort Churchill gage.

same 64 LOCA-CMIP5 were used in the Pilot Study; however, they were first bias-corrected and then input through the five calibrated PRMS models that have previously been developed for the Truckee-Carson Basins versus the Variable Infiltration Capacity model.

In addition to future streamflow projections, the West-Wide Climate and Hydrology Assessment summarizes paleo information based on tree rings. Paleo is an area of study that explores climate and hydrology (termed hydroclimate) processes in the distant past, before recorded data, such as from stream gages. Studying the hydroclimate of the distant past allows for a broad understanding of possible future conditions based on historical drought or pluvial (i.e., wet) events that are evident in records impacted by climate, such as tree rings or other proxies. Reclamation has increasingly used tree-ring-based reconstructions of streamflow to evaluate how well water systems throughout the Western United States would manage if droughts like those that have occurred in the distant past were to occur today. The reconstructed streamflow used in the West-Wide Climate and Hydrology Assessment goes back over 1,000 years and helps characterize long-term patterns of variability that influence drought and flood risk. The reconstructions were developed using a statistical correlation of tree growth patterns to the observed streamflow record from 1685–1977, the common period of record across all available streamflow reconstructions. The streamflow reconstructions used to develop the paleo portion of the dataset for the Pilot Study, described below, have a longer common period of record from 1500 to 1900.

Two paleo streamflow reconstructions in the Truckee-Carson Basins exist at the time of the dataset development for this Pilot Study: the Carson River near Fort Churchill, NV (“Fort Churchill gage”, U.S. Geological Survey [USGS] ID 10312000; Biondi and Meko 2019) and the Truckee River at Farad, CA (“Farad gage”, USGS ID 10346000; Harris and Csank 2023). The Carson River streamflow reconstruction was originally developed as a reconstruction of annual streamflow anomalies, or deviations from a long-term average streamflow. The anomaly streamflow was then translated into a streamflow reconstruction for use in the West-Wide Assessment (Reclamation 2021b). The Truckee River streamflow reconstruction was originally developed as a streamflow reconstruction. Annual streamflow reconstructions in the Truckee-Carson Basins were disaggregated from water-year annual to a daily time series using the pattern of observed streamflow from the TROA Daily Historical Planning Model Dataset, hereafter called the TROA Planning Model dataset. Daily streamflow reconstructions were then used as input to the TROA Planning Model. Section 3.2 describes how droughts based on this paleo-reconstructed streamflow compare with recent historic droughts of interest.

2.2 Existing Models and Historical Data

The TROA Planning Model was built in RiverWare to allow for long-term water management studies under TROA operating criteria. The Planning Model simulates Truckee and Carson River operations over 122 years (1901 to 2022, currently) with periodic extensions of the period of record. Daily streamflow at various key locations throughout the Truckee-Carson Basins serves as input to the TROA Planning Model (figure 1). Daily streamflow data was initially developed by Reclamation in the 1970s and was used as far back as the 1980s in a variety of different

studies. The dataset (called Truckee Carson Data File [TCDATFIL]) has been widely used and accepted; however, documentation of this dataset is incomplete. In 2010, a variety of parties, including Reclamation, the Pyramid Lake Paiute Tribe, the TMWA, and the States of California and Nevada, developed a daily 100-year historical hydrology dataset from 1900 to 2000 based on the monthly TCDATFIL dataset. This daily dataset was derived by disaggregating the TCDATFIL monthly streamflow into daily streamflow (Stetson 2010), primarily by scaling daily hydrographs from nearby locations to conserve monthly volumes (PWRE 2022). Unique methodologies were used over different periods of time in the development of the disaggregated TCDATFIL daily dataset, leading to inconsistencies within the disaggregated daily dataset. More recently, Precision Water Resources Engineering (PWRE) developed an updated methodology for estimating daily flows and extended the dataset from 2000 to 2017. As part of the 2022 Truckee Basin Water Management Options Pilot study, PWRE extended this updated methodology back to 1986 (Reclamation et al. 2024). The PWRE has also extended the record through 2022 (PWRE 2022). The updated TROA Planning Model dataset from 1986 onward uses daily gage data instead of disaggregated monthly data, preserving daily peaks and volumes.

This Pilot Study used the updated TROA Planning Model dataset through 2017, representing the best available data when the Pilot Study began, referred to throughout this report as the TROA Planning Model dataset or TROA historical streamflow. The Pilot Study relied on the TROA Planning Model version titled “TROA_PlanningModel_Official008_01.mdl” for simulation of river operations using the newly developed dataset.

This Pilot Study employed PRMS (Markstrom et al. 2008) models that simulate near-surface hydrologic processes in 5 sub-basins of the Truckee-Carson Basins to develop a hydrology dataset for evaluation of the OCAP (figure 1). For this Pilot Study, these five models were used to develop historical and future projected streamflow from 1950 to 2099 at key locations in the Truckee-Carson Basins. The three models representing the sub-basins within the Truckee River Basin: the Martis Creek Basin, the Lake Tahoe Basin, and the Little Truckee River Basin, together simulate hydrology above Farad, CA, which represents 90 percent of the contributing surface runoff in the entire Truckee Basin (Reclamation 2015). The other two PRMS models encompass the East and West Fork of the Carson River and were originally developed as part of a Groundwater and Surface-water FLOW (GSFLOW) model for the Carson River Valley (Kitlaster et al. 2021).

The TROA Planning Model does not represent water management of the Carson River upstream of Lahontan Reservoir and requires depleted flows at the Carson River near Fort Churchill, NV gage (Fort Churchill gage). Therefore, simulations of streamflow alterations and depletions were needed between the PRMS simulated streamflow points and the Fort Churchill gage location for future climate scenarios. Two approaches exist for developing a model of Fort Churchill historical streamflow for the purpose of using that model to generate projected future streamflow at the same location. As part of the Basin Study (Reclamation 2015), Reclamation’s Technical Service Center developed monthly regressions between the Truckee

River unimpaired streamflow at several locations (including inflows to Donner Lake, Prosser Creek Reservoir, Martis Creek Lake, Independence Reservoir, Stampede Reservoir, and Sidewater streamflow⁷) and observed streamflow at Fort Churchill (Reclamation 2014).

Secondly, the USGS (Kitlasten et al. 2021) linked a river systems model (MODSIM) to a GSFLOW model of the Carson Valley, representing depletions directly below the East Fork and West Fork Carson Rivers. Depletions within the reach from Carson Valley to Fort Churchill are represented in the groundwater module of the GSFLOW model called the USGS modular hydrologic model (Kitlasten et al. 2021). Linking the three models (East Fork and West Fork Carson Rivers PRMS models; Carson Valley MODSIM/GSFLOW models; and middle Carson River Basin MODSIM) provided a physical framework to represent depletions under future climate scenarios (Kitlasten et al. 2021).

As it was not within the scope of this Pilot Study to model depletions and accretions in the Carson Valley upstream of Lahontan Reservoir by updating and implementing the described MODSIM/GSFLOW models approach, an updated regression approach was developed (described in section 3.8) to simulate regulated streamflow at Fort Churchill for input to the TROA Planning Model.

⁷ The term “Sidewater” refers to inflows from ungaged tributaries to the Truckee River, downstream of the reservoirs and upstream of the gage at Farad, NV.

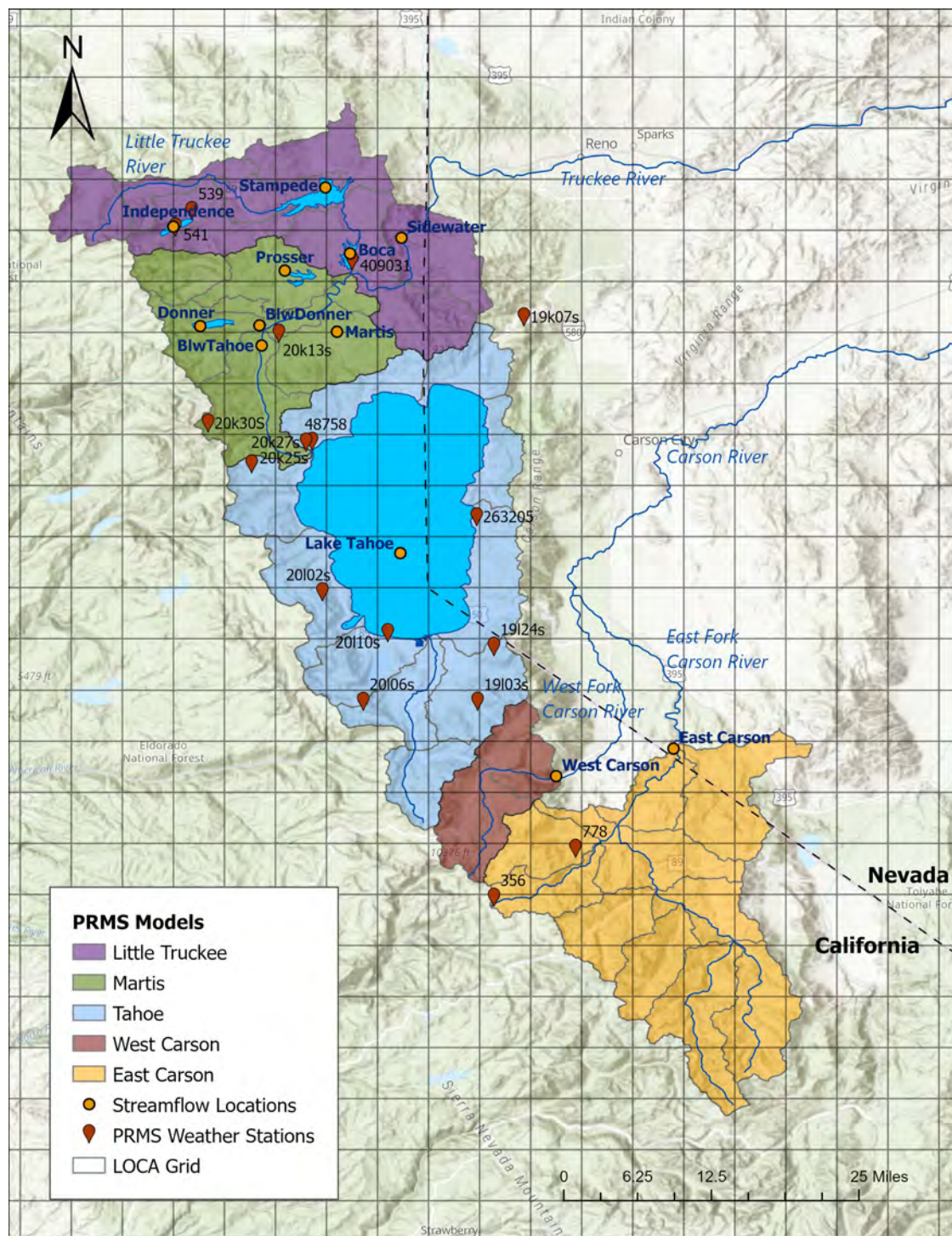


Figure 1.—The modeled area of the Truckee-Carson Basins.⁸

⁸ The PRMS sub-basin models are shaded in different colors, the PRMS weather stations are indicated in red teardrops, output streamflow locations are indicated by orange circles, and the 6 kilometers (km) by 6 km LOCA grid cells are overlain.

2.3 Future Climate Projections

The Pilot Study relies on global climate model projections of future climate as a basis for future projections of streamflow in the developed dataset. This section provides a general description of this information as well as how it has been used in previous studies in the region. The scientific community has developed multiple datasets of global and regional climate projections to support planning and decision-making across a broad range of sectors, including water resource management. Climate projections are developed by using general circulation models (GCMs) to simulate climate conditions under a range of emissions scenarios. Each emissions scenario consists of a set of time-evolving values representing emissions and corresponding atmospheric concentrations of various greenhouse gases and aerosol compounds that affect the Earth's energy balance, as well as corresponding land use and land cover data.

The spatial resolution of most GCM-based climate projections is around one to two degrees latitude by 1 to 2 degrees longitude, or roughly 110–220 kilometers (km) by 110–220 km over mid-latitudes. Local weather and climate conditions, by contrast, exhibit substantial variability across a degree of latitude or longitude due to variations in topography, land cover, and other factors that affect weather and climate conditions (Wood et al. 2004). In addition, GCMs often exhibit biases compared to observed climate, resulting from the relatively coarse spatial resolution of GCMs and the use of simplified parameterizations to represent finer-scale physical processes.

To address these limitations, numerous studies have developed methods to bias-correct and spatially downscale coarse-resolution climate data to the watershed scale. One method of downscaling is the Locally Constructed Analogs (LOCA) method (Pierce et al. 2014) to statistically downscale and bias-correct GCMs projections to a 1/16th degree grid (approximately 6 km). The LOCA ensemble includes 64 downscaled climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) archive, covering the period 1950–2099 (calendar years). Each LOCA-CMIP5 projection corresponds to a single GCM and emissions scenario. The LOCA-CMIP5 ensemble includes projections from 32 different GCMs and two emission scenarios (Representative Concentration Pathway [RCP] 4.5 and RCP 8.5). The RCP 8.5 emission scenario represents a 'business as usual', high emissions scenario, where there are no significant efforts to reduce future global greenhouse gas levels and the radiative level reaches 8.5 watts per square meter by 2100. The RCP 4.5 represents a stabilization, medium emissions scenario, which means radiative forcing levels stabilize at 4.5 watts per square meter by 2100. This stabilization is only possible using a range of technologies and strategies for reducing greenhouse gas emissions.

3.0 Methods

The Pilot Study developed a hydrology dataset that encompasses a distant past period (WY 1500 through 1900), the recent historical period (WY 1901 through calendar year 2017), and a projected future period (herein defined as calendar years 2018 through 2099⁹). The development of this 600-year dataset for use in the TROA Planning Model combined the use of streamflow reconstructions, five PRMS surface hydrology models, an open water evaporation model, historical streamflow datasets, regression analysis, and 64 LOCA-CMIP5 climate projections (figure 2).

⁹ The dividing point between the historical period and projected future period was based on the availability of historical data and the fact that CMIP5 projected hydrology begins in 2006.

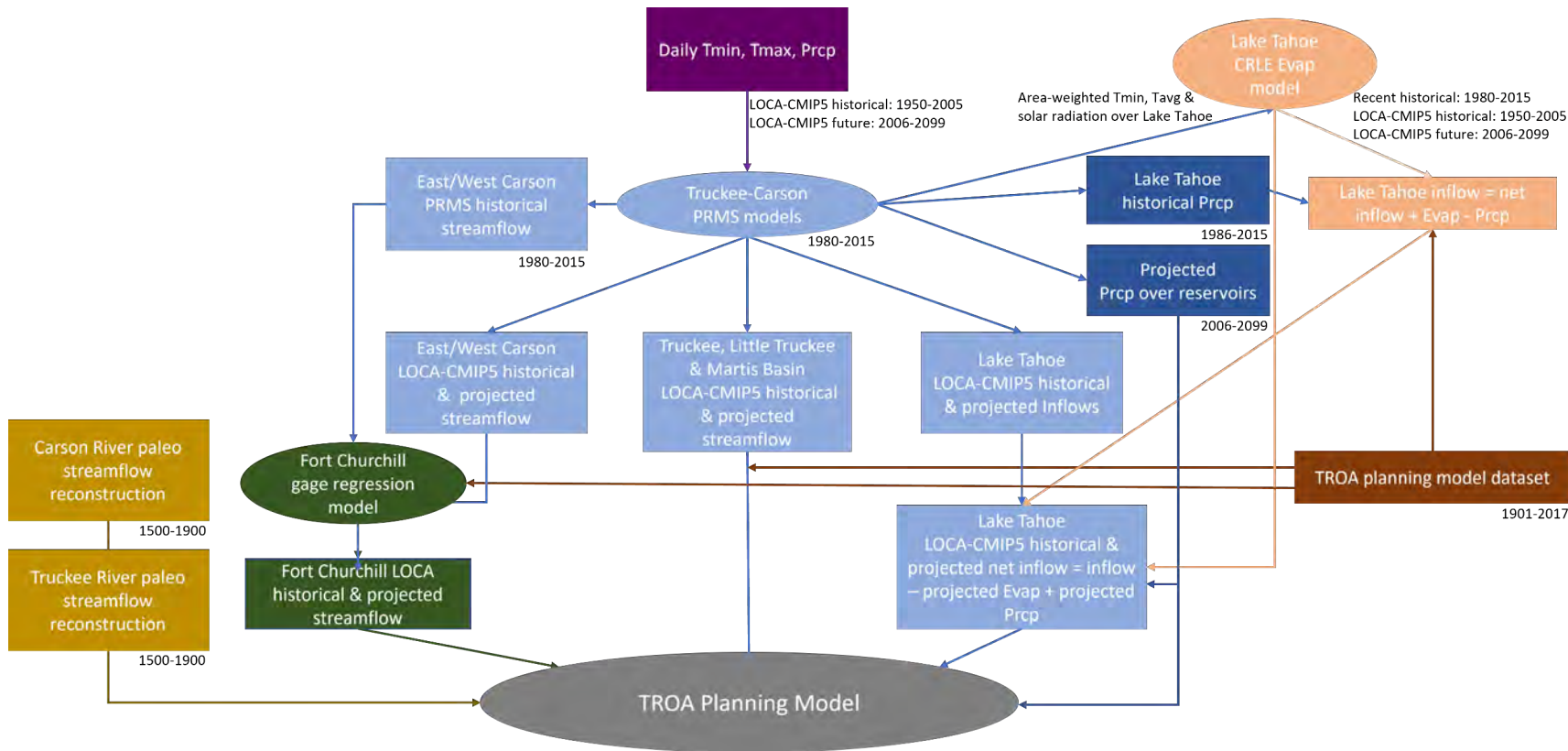


Figure 2.—A schematic of the tools and data resources used to develop the hydrology dataset for use in evaluating future scenarios of the Operating Criteria and Procedures for the Newlands Project.¹⁰

¹⁰ Circles indicate models. Rectangles indicate datasets.

3.1 Paleohydrology

The general approach to reconstructing streamflow involves the statistical correlation of growth patterns in tree rings to variability in an observed streamflow record. This allows for the development of a statistical model to estimate annual streamflow from annual growth rings. Most often, the approach takes the form of a multiple linear regression (MLR) model based directly on composite tree-ring records called chronologies. Chronologies are generally developed from multiple trees for multiple sites (Meko and Graybill 1995; Woodhouse et al. 2006; Woodhouse 2001) but may use larger pools of tree-ring data via the principal components (i.e., a statistical summary of common variance) of numerous chronologies (Hidalgo et al. 2000; Littell et al. 2016). Further, streamflow reconstructions may also be developed based on non-parametric or Bayesian network models (Gangopadhyay et al. 2009; Ravindranath et al. 2019).

3.1.1 Annual Reconstructed Streamflow

For the Truckee-Carson Basins, two streamflow reconstructions were used to develop a paleo dataset for the TROA Planning Model and to evaluate distant past droughts. The first reconstruction dataset for the Carson River near Fort Churchill, NV (Fort Churchill gage) is a 501-year reconstruction of WY annual streamflow (WY 1500 through 2000, with calibration based on 1901–2017 data) previously developed for the Reclamation 2021 SECURE Water Act Report (Reclamation 2021b). Before this work, the annual reconstruction consisted of streamflow anomalies, not actual streamflow, to evaluate long-term hydroclimatic variability in the Truckee-Carson Basins (Bondi and Meko 2019). The second reconstruction dataset for the Truckee River at the Farad gage is a 513-year reconstruction of WY annual streamflow (WY 1491 through 2003, with calibration based on 1907–2003 data), which was developed using a combination of chronologies for the Truckee River (Harris and Csank 2023).

The objectives for developing the paleo dataset for the TROA Planning Model were (a) to place the most recent droughts and wet spells in a longer historical context, (b) to determine if recent episodes were anomalous with respect to the range of natural variability, and (c) to obtain an updated assessment of water resources in the Truckee-Carson Basins toward improving science-based management and risk assessments.

The Truckee and Carson paleo reconstruction datasets rely on observational records for the 20th century to develop the annual streamflow variability reconstruction and the annual streamflow reconstruction. Therefore, the paleo dataset for the Pilot Study uses WY 1500–1900 to represent the actual reconstructed paleo-period.

3.1.2 Daily Reconstructed Streamflow for 1500–1900

The Carson River near Fort Churchill and the Truckee River at Farad annual streamflow reconstructions were disaggregated to a daily time series using a similar approach to that developed by Nowak et al. (2010). To develop daily time series from these annual datasets, this Pilot Study used daily streamflow patterns in the recent historical period (1986–2017) from the TROA Planning Model dataset. These daily streamflow patterns were then scaled to match average annual streamflow from the streamflow reconstructions. Naturalized streamflow from the California Data Exchange Center for the Truckee River at Farad was used to identify the year in the TROA Planning model dataset that would provide the daily pattern (called analog year). Similarly, the TROA Planning Model dataset streamflow at Fort Churchill was used to identify the analog year as well as the daily pattern.

More detailed steps for disaggregating the Truckee and Carson streamflow reconstructions are provided below:

- Daily streamflow datasets for the recent historical period (1986–2017) were aggregated to a WY average annual time series (in cubic feet per second [ft^3/s]) at each location, to match the timestep of the paleo streamflow reconstructions. In the case of the Lahontan Reservoir inflow, the range of the recent historical period represents a portion of the TROA Planning Model dataset developed using the most updated and consistent methods (PWRE 2022).
- Flow ranks are assigned to each year within each of the streamflow reconstructions and recent historical period dataset. For example, in the TROA Planning Model dataset for the Lahontan Reservoir inflows, 2017 has the highest mean annual streamflow, so this year is ranked one. The ranks are then divided by the number of years in the dataset so that ranks within each dataset range from almost zero to one.
- For each year of the streamflow reconstruction dataset, the study identified the closest six recent historical years to each reconstruction year (the selection of the six closest years is based on the square root of the number of recent historical years (Nowak et al. 2010), i.e., the square root of 34 rounds to 6). The six closest years were selected based on the least difference in the historical year rank and paleo year rank. Then one year was randomly selected from the six most similar historical analog years.
- A streamflow weight, the streamflow reconstruction annual average streamflow divided by the analog recent historical period year annual average streamflow, was calculated for each year of the reconstruction.
- Daily streamflow for the streamflow reconstruction year was calculated as the daily streamflow from the analog recent historical period multiplied by the flow weight.

Inflows to the TROA Planning Model (table 1) were developed using the same historical analog years selected for the streamflow reconstructions and the corresponding flow weight. Each of the inflow locations was given a Station identifier (Station ID) and assigned to either the Truckee or

Carson paleo reconstruction based on their basin locations (table 1). Then, the daily TROA Planning Model dataset at that inflow location of the selected analog year was multiplied by the same weight that was used for the paleo daily disaggregation. The spatial correlation between locations was maintained because the same analog year in the historical period was selected at each inflow location. Notably, the TROA Planning Model (streamflow) dataset over the period 1986–2017 contains negative values for several inflow locations. Because the daily reconstructed streamflow dataset over the paleo-period of 1500–1900 is based on this historical dataset, the daily paleo streamflow may also be negative.

Table 1.—Truckee River Operating Agreement Planning Model inflow locations and the paleohydrology reconstruction dataset used to develop its daily paleohydrology time series

TROA Planning Model Slot Name	Station ID	Short Name	Reconstruction
PlanningData.Lahontan	LHNTI	Lahontan	Carson
PlanningData.HunterCreek	HNTCR	Hunter	Truckee
PlanningData.SteamboatCrAtSteamboat	STBCR	Steamboat	Truckee
PlanningData.BlwDonner	BLDON	BlwDonner	Truckee
PlanningData.BlwTahoe	BLTAH	BlwTahoe	Truckee
PlanningData.SidewaterLocalInflow	SDWLI	Sidewater	Truckee
PlanningData.Farad	FRADI	Farad	Truckee
PlanningData.Boca	BOCAI	Boca	Truckee
PlanningData.Donner	DONRI	Donner	Truckee
PlanningData.Independence	INDEI	Independence	Truckee
PlanningData.Martis	MARTI	Martis	Truckee
PlanningData.Prosser	PROSI	Prosser	Truckee
PlanningData.Stampede	STMPI	Stampede	Truckee
PlanningData.Tahoe	TAHOI	Tahoe	Truckee
PlanningData.BocaPrecip	BOCAP	BocaPrecip	Truckee
PlanningData.DonnerPrecip	DONRP	DonnerPrecip	Truckee
PlanningData.IndependencePrecip	INDEP	IndepPrecip	Truckee
PlanningData.MartisPrecip	MARTP	MartisPrecip	Truckee
PlanningData.ProsserPrecip	PROSP	ProsserPrecip	Truckee
PlanningData.StampedePrecip	STMPP	StampPrecip	Truckee
PlanningData.TahoePrecip	TAHOP	TahoePrecip	Truckee
PlanningData.BlwDerbyLocalInflow	BLDLI	BlwDerby	Truckee
PlanningData.WadsworthToNixonLocalInflow	WDNLI	WadsworthToNixon	Truckee
FaradToDerbyDepletions.FaradToMogulLocalInflow	FRMLI	FaradToMogul	Truckee
FaradToDerbyDepletions.MogulToRenoLocalInflow	MRNLI	MogulToReno	Truckee
FaradToDerbyDepletions.RenoToGlendaleLocalInflow	RNGLI	RenoToGlendale	Truckee
FaradToDerbyDepletions.GlendaleToSparksLocalInflow	GSPLI	GlendaleToSparks	Truckee
FaradToDerbyDepletions.SparksToVistaLocalInflow	SPVLI	SparksToVista	Truckee
FaradToDerbyDepletions.VistaToDerbyLocalInflow	VDBLI	VistaToDerby	Truckee
FaradToDerbyDepletions.BlwDerbyLocalInflow	BLDDI	BlwDerby	Truckee

3.1.3 Definition of Drought and Pluvial Events

The developed paleo dataset for the Pilot Study encompasses both drought events and wet events (commonly called pluvial events). The existence of a paleo dataset allows for investigations of how current infrastructure and operations policies might perform in the face of droughts or wet events of the distant past that may be more severe than anything experienced in the more recent historical past. However, dendochronologists cite that tree rings more robustly show signatures of droughts, compared with pluvial events. Tree-ring reconstructions can often underestimate years of extremely high streamflow, since a tree can still only grow so much in a season, even in the presence of an overabundance of water (Harris and Csank 2023). Although using tree rings to evaluate pluvial events can be valuable, predominantly paleo studies have focused on the evaluation of drought events as opposed to pluvial events, both because the trees more accurately track drought, and drought is generally of greater societal concern. The Pilot Study also focuses on drought events in the Truckee-Carson Basins. Identification of pluvial events in the paleo record and recent historical period is recommended in future work, particularly as methods improve for identifying pluvial events in tree rings.

No single universal definition exists for hydrologic droughts and pluvial events. For this Pilot Study, the study team employed two unique definitions to provide a broad understanding of distant past droughts and to illuminate the uncertainty associated with methodological choices in paleo drought analysis (i.e., what definition to use and what metrics could be used to calculate the magnitude and duration of droughts).

The first drought (and pluvial event) definition is based on the same rule that was applied to identify distant past droughts in the 2021 SECURE Water Act Report to Congress (Reclamation 2021b). The annual streamflow reconstruction developed as part of the 2021 SECURE Water Act Report (refer to the discussion in section 3.1.1) was used as the basis of rule-based droughts. The rule may be summarized as follows and is illustrated by figure 3 using the TROA historical dataset for the Carson River at Fort Churchill (note: this figure illustrates the largest historical rule-based drought in table 6):

“A drought (pluvial) event beginning with, and including, two or more consecutive years of streamflow less than (greater than) the median flow level that is ended only by, and excludes, two or more consecutive years of streamflow greater than (less than) the median flow level. An event may include one or more individual wet (dry) years within the drought (pluvial) only when bounded on both sides by dry (wet) years.”

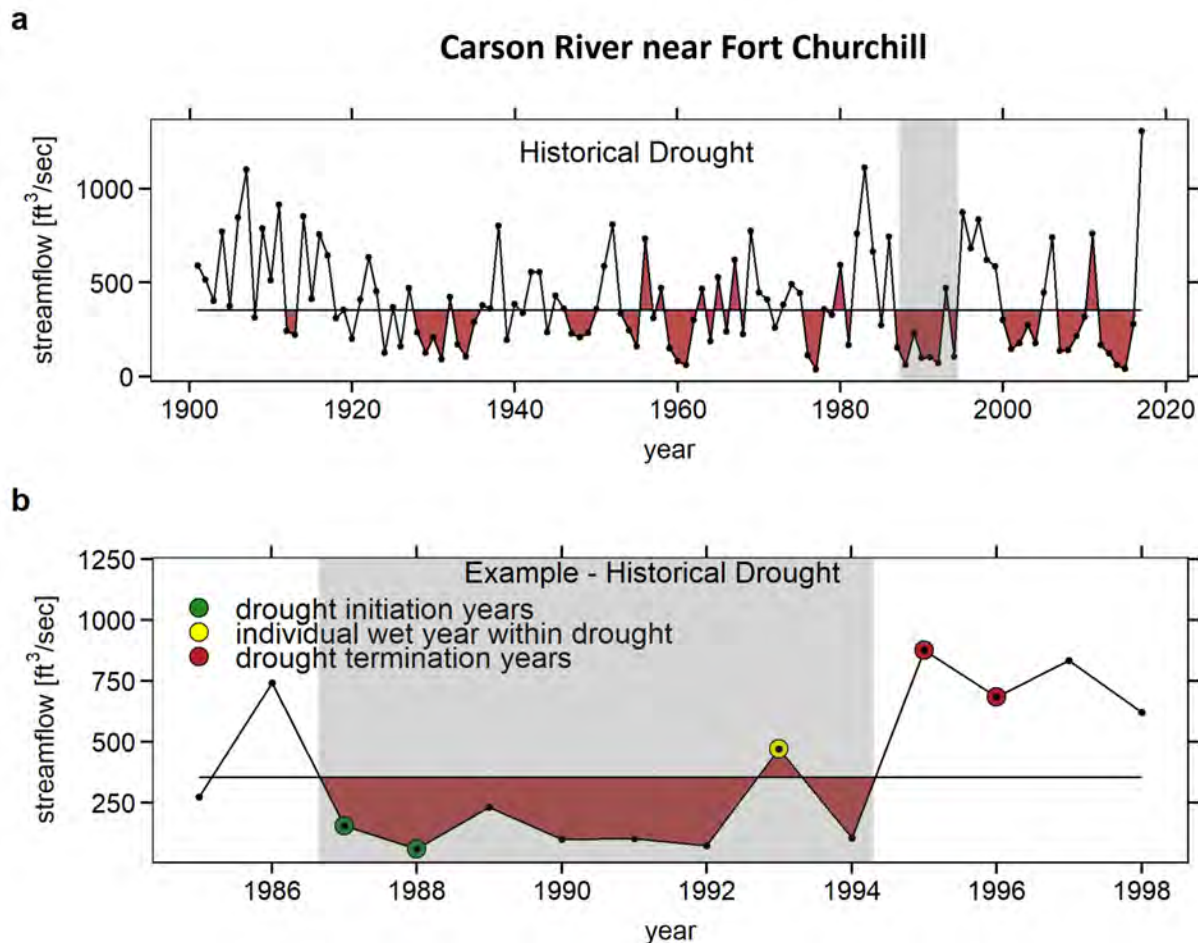


Figure 3.—Illustration of rule-based drought definition from the 2021 SECURE Water Act Report.¹¹

The rule-based definition captures the prolonged nature of potentially challenging wet and dry periods and recognizes that such events generate cumulative water deficits and surpluses, despite the brief cessation of difficult conditions that may occur during a single intervening wet or dry year.

The second drought (and pluvial event) definition is based simply on whether the WY annual streamflow each year is greater than or less than the long-term median streamflow calculated over the 1500–1900 paleo streamflow reconstruction period. Formally, the rule may be summarized as:

“A drought (pluvial) event beginning with streamflow less than (greater than) the median flow level that is ended only by one year of streamflow greater than (less than) the median flow level.”

¹¹ The brown shaded areas represent drought periods.

This definition is commonly termed zero-crossover and is illustrated by figure 4. For this Pilot Study, the study team used a 3-year smooth dataset to evaluate the median flow level crossover and define drought (or pluvial) years; however, the original unsmoothed dataset was evaluated for these identified drought (or pluvial) years. A 3-year smoothed annual reconstruction time series has been used in previous studies in the identification of zero-crossover droughts (Reclamation 2021). The purpose of 3-year smoothing is to reduce the number of low-severity drought and pluvial events. Figure 4 shows the 3-year smoothed annual streamflow time series. As stated previously, the focus of the Pilot Study is on drought events in the distant past, and although pluvial events were identified in the dataset, they are not discussed in this report.

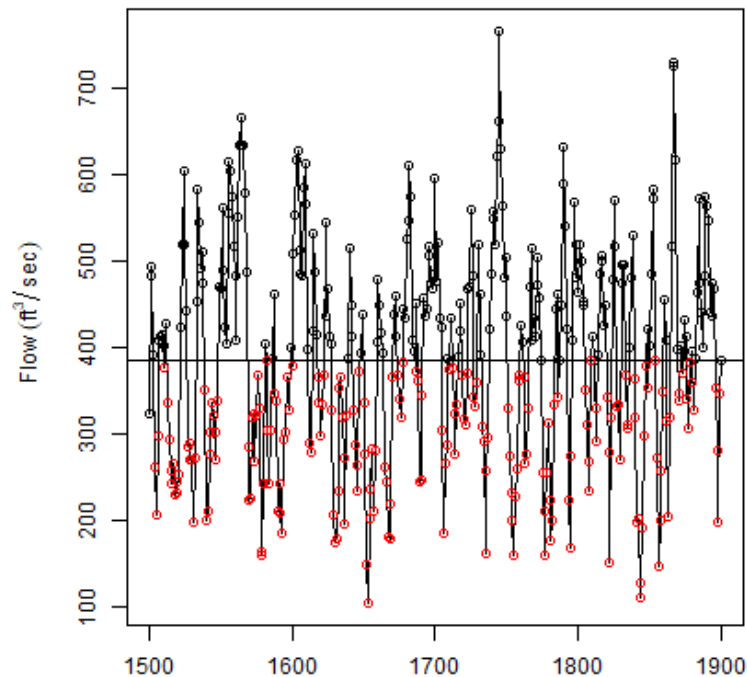


Figure 4.—Illustration of zero-crossover drought definition.¹²

Another step in describing drought dynamics over time is to quantify the magnitude and duration of each identified drought event. Two measures of magnitude and/or duration were determined for each event. These measures were applied over the paleo and recent historical periods to quantify the most impactful droughts in these periods. The measures are summarized as follows:

1. Largest annual deficit (LAD) – represented by the average difference between the annual streamflow and the long-term median over the course of an identified drought event (using either the rule-based or zero-crossover definition).

¹² Droughts are simply any year when annual streamflow was below the long-term median.

2. Largest cumulative deficit (LCD) – represented by the accumulated flow deficit over the course of the drought event (i.e., the total sum of annual deficits greater than the long-term median).

3.2 Precipitation Runoff Modeling System (PRMS) Hydrology Models

The Pilot Study uses the five existing PRMS hydrology models developed and calibrated for the 2015 Basin Study to simulate historical and future unimpaired (i.e., natural, or absent of water management effects) streamflow in the Truckee-Carson Basins (figure 1). This section describes the data used as input to these models and how the models were used in the Pilot Study.

In these models, climate data input into the PRMS models at individual station locations is distributed to each grid cell based on mean monthly precipitation patterns from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly 2000). The stations in all the PRMS models and their associated metadata can be found in table 2. These stations represent locations where the current Pilot Study developed past and future climate projections to simulate hydrology using the Truckee Basin PRMS models.

The other two PRMS models used in the Pilot Study were previously developed and calibrated for the Carson River Valley (Kitlachen et al. 2021) as part of a GSFLOW model that encompasses both the East Fork and West Fork of the Carson River (figure 1). These two models employ the same climate distribution modules as the three Truckee Basin PRMS models but are based on a 168-meter grid. Climate data was input from two weather stations (table 1) and distributed using PRISM to all active grid cells. These stations represent locations where Reclamation has developed bias-corrected, past and future climate projections to simulate future hydrology in the Upper Carson River Basin.

Table 2.—The weather stations used to calibrate the Precipitation Runoff Modeling System models and associated metadata

Station ID	Station Name	Latitude	Longitude	Elevation (meters)	Model	Climate Variable
356	Blue Lakes SNOTEL*	38.61	-119.92	2456	East/West Carson	tmax, tmin, pr
778	Spratt Creek SNOTEL	38.67	-119.82	1864	East/West Carson	tmax, tmin, pr
539	Independence Camp SNOTEL	39.45	-120.29	2128	Little Truckee	tmax, tmin, pr
541	Independence Lake SNOTEL	39.43	-120.31	2541	Little Truckee	pr
409031	GHCND BOCA	39.3886	-120.0936	1699	Little Truckee	tmax, tmin
20k13s	Truckee No.**2 SNOTEL	39.3	120.183334	1984	Martis	tmax, tmin, pr
20k30S	Palisades Tahoe SNOTEL	39.19	-120.27	2101	Martis	pr
19k07s	Mt Rose SNOTEL	39.32	-119.88333	2683	Martis	tmax, tmin
19k07s	Mt Rose SNOTEL	39.32	-119.88333	2683	Tahoe	tmax, tmin, pr
20l10s	Fallen Leaf SNOTEL	38.933334	-120.05	1901	Tahoe	pr
19k04s	Marlette Lake SNOTEL	39.15	-119.88333	2402	Tahoe	pr
48758	USC00048758***	39.167778	-120.14278	1899	Tahoe	tmax, tmin
263205	USC00263205***	39.07528	-119.94111	1935	Tahoe	pr
19l03s	Hagans Meadow SNOTEL	38.85	-119.94	2370	Tahoe	pr
19l24s	Heavenly Valley SNOTEL	38.916668	-119.92	2616	Tahoe	pr
20k25s	Ward Creek #3 SNOTEL	39.14	-120.21667	2028	Tahoe	pr
20k27s	Tahoe City Cross SNOTEL	39.166668	-120.15	2072	Tahoe	pr
20l02s	Rubicon #2 SNOTEL	38.983334	-120.13	2344	Tahoe	pr
20l06s	Echo Peak SNOTEL	38.85	-120.08	2338s	Tahoe	pr

* snow telemetry

** number

*** Global Historical Climatology Network daily stations

3.3 LOCA-CMIP5 Downscaled Historical and Future Climate

This Pilot Study used LOCA-CMIP5 projections from 32 GCMs that encompass a historical period from 1950 to 2005 and a future period from 2006 to 2099. Although the Pilot Study developed LOCA-CMIP5 data over these periods, the final hydrology dataset uses an excerpt (2018-2099) from the full period (1950–2099). The Pilot Study includes two scenarios of future emissions for each GCM, one representing high emissions (RCP 8.5) and one representing medium emissions (RCP 4.5). In summary, there are 32 projections over the historical period (termed GCM historical simulations) and 64 time series over the projected future period. Each projection consists of daily precipitation and daily maximum and minimum temperature, which were then bias-corrected before use as input to the hydrologic models (PRMS) to develop historical and future streamflow time series.

The 32 historical and 64 future LOCA-CMIP5 projections were extracted for each of the grid cells overlying a meteorological station used in the PRMS models (table 1). Given the large spatial scale of the LOCA projections and the large elevation range in the mountainous Truckee-Carson Basins, the climate data averaged over the entire LOCA-CMIP5 grid cell does not always represent a point location or meteorological station well. To address this, each LOCA-CMIP5 climate projection was further bias-corrected at a daily timescale to each weather station used in the PRMS models (table 1).

3.3.1 Bias Correction of Climate Data

This Pilot Study uses a modified quantile mapping approach to bias-correct the statistically-downscaled LOCA-CMIP5 projections. Standard quantile mapping is used extensively for downscaling daily temperature and precipitation projections (Maurer et al. 2010; Abatzoglou and Brown 2012). The advantage of a quantile mapping approach is that it accounts for all GCM biases in all statistical moments; however, like any statistical bias correction approach, it assumes that biases that exist in historical simulations will similarly exist in future projections. In other words, traditional bias correction approaches assume that biases are stationary in time.

When using a quantile mapping bias correction approach, the question of what to do with the tails of the distribution arises, or how to best represent the extremes, especially when bias correcting precipitation. This extrapolation to unobserved quantiles has previously taken the following routes (Maraun 2016): (1) a constant transfer function past the highest observed quantile (Boé et al. 2007), (2) extrapolation based on the distribution used for the quantile mapping (Hay and Clark 2003), or (3) applying a specific extreme value or model (Michelangeli et al. 2009). In addition to direct quantile mapping, previous efforts have applied a quantile delta mapping algorithm that explicitly preserves relative changes in temperature or precipitation (Cannon et al. 2015). All options contain shortcomings. For example, standard quantile mapping has been shown to inflate extremes of precipitation by upwards of 500 percent as compared to raw GCM trends, whereas quantile delta mapping only inflates those trends by approximately

140 percent (Cannon et al. 2015). This Pilot Study applied a new modified quantile mapping approach that begins to address the question of how to best represent extremes, while also allowing for shifts in seasonality that are likely to occur in the future.

In the modified quantile mapping approach developed in this Pilot Study, termed the combined CDF approach, bias correction factors are applied individually for each day of the year and calculated as differences between the CDFs of observed station data and each of the 32 GCM historical simulations at corresponding CDF quantiles. The daily bias correction factors generated from the GCMs over the historical period are applied to each of the 64 future LOCA-CMIP5 projections. Although the CMIP5 climate projections were trained using a gridded historical climate dataset developed by Livneh et al. 2013, these data were not used in the bias correction process. Instead, as noted earlier, bias-correction factors were developed between observed station data and historical GCM data. All CDFs were created using a base period where both daily observations from the PRMS stations and daily GCM-simulated values were available. For all climate bias corrections, the base period is October 1, 1980, to December 31, 2005 (figure 1). The beginning of the base period aligns with the beginning of the simulation period of the PRMS models, and the end of the base period represents the end of the GCM historical simulation period. The future simulation period for LOCA-CMIP5 projections begins January 1, 2006.

The CDFs were created from a 1-, 2-, 3-, 5-, 7-, and 15-day moving window centered on each day of the year (Julian days 1 through 366; figure 5). For example, for a 7-day window, the CDFs developed for March 10 included the 7 previous days of data and the 7 following days (March 3–March 17) to encompass 15 days of data for each year of the base period. Assuming a complete dataset (which is not always the case for the observed station data), each 7-day window CDF is generated from 15 days around each day of the year and up to 26 years of data, yielding up to 390 data points. CDFs generated for days in January through September only contain 25 years of data and up to 275 data points due to the beginning of the simulation period in October 1980. Julian days 360 through 366 have fewer data points, given the incomplete window length for the last year (2005).

The different window length CDFs are used to develop the combined CDF. A K-Nearest Neighbor Algorithm weighting (Lall and Sharma 1996) of the CDF of each window length was used to create the combined CDF. In this approach, individual window CDFs are sampled and given weight based on the proximity of the values to the observed CDF. This combined CDF approach allows for mimicking the historical dynamics of the climate near that particular day, while also allowing for seasonal shifts given the weight of the 15-day CDF, which extends the tails. This method for extending the tails of the distribution is a data-driven approach that allows for increased extreme values that have been observed historically and are not arbitrarily set. For example, the 15-day January 9 precipitation CDFs for the Mount Rose snow telemetry (SNOTEL) station extend the distribution tail to include daily precipitation two inches greater than the maximum precipitation included in shorter CDF windows, from just under 5 inches to almost 7 inches (figure 5, right). In practice, if the projected daily precipitation on January 9, 2070, is 8 inches with a corresponding quantile of 0.995 in the projected CDF, the bias-corrected value corresponds to the 0.995 quantile in the observed CDF (shown on figure 3),

and changes based on what window length is selected for bias correction. Using the 5-day window, the bias-corrected projected precipitation value would be approximately 4.2 inches, while using the combined CDF, the bias-corrected projected precipitation value would be approximately 4.75 inches. While the study team's combined CDF approach helps account for seasonality shifts by using multiple windows in the generation of the CDFs, it does limit the bias-corrected values to those that were observed historically within the 31-day window centered around each day.

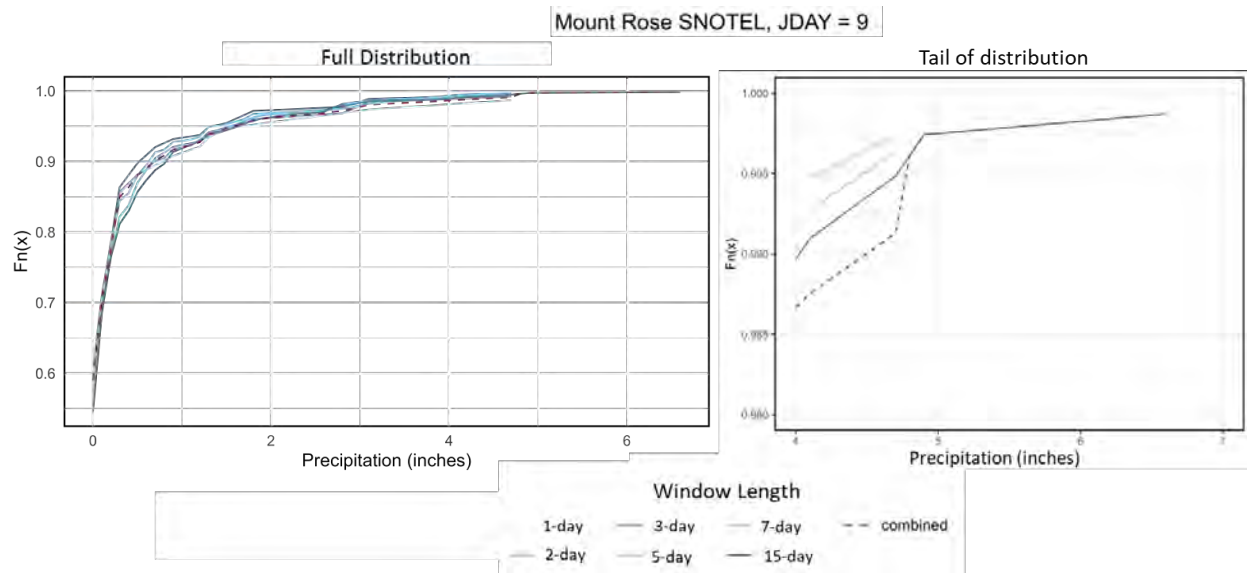


Figure 5.—Precipitation cumulative distribution functions (full on left; tail end on right) for the Mount Rose SNOTEL station on January 9, developed from observed data from 1980 to 2005.¹³

The CDFs and bias-corrected projections were developed for precipitation, maximum temperature, and the diurnal temperature range (maximum temperature minus minimum temperature). Bias-corrected minimum temperatures were calculated by taking the bias-corrected maximum temperature minus the bias-corrected diurnal temperature range (Thrasher et al. 2012). This approach for determining bias-corrected minimum temperature ensures that the bias-corrected daily maximum temperature is always larger than the daily minimum temperature. Daily bias-corrected projections were developed by mapping the quantile from the projection CDF value to the same quantile from the respective station CDF. Then the bias-corrected value for that day is equal to the station value associated with the mapped quantile for that JDAY.

As an example of the need for bias correction, figure 6 shows January 1 minimum temperature CDFs for each of the LOCA-CMIP5 historical period simulations at the Mount Rose SNOTEL

¹³ Blue shaded lines represent CDFs generated from different window lengths while the dark red line represents the 'combined CDF'. The subset shows the tail of the distribution, highlighting that the combined CDF extends out to the 15-day CDF tail.

station, compared to the CDFs of the measured station data. The difference in the minimum temperature CDFs is quite apparent, where LOCA-CMIP5 presents a grid cell average minimum temperature, which is much lower compared to the station's measured minimum temperature. The Mount Rose SNOTEL station is located in a LOCA-CMIP5 grid cell northeast of Lake Tahoe with highly variable elevations (figure 1). However, the station itself is in a lower-elevation valley. The bias correction of the LOCA-CMIP5 data reduces this discrepancy to better match the station's observed data.

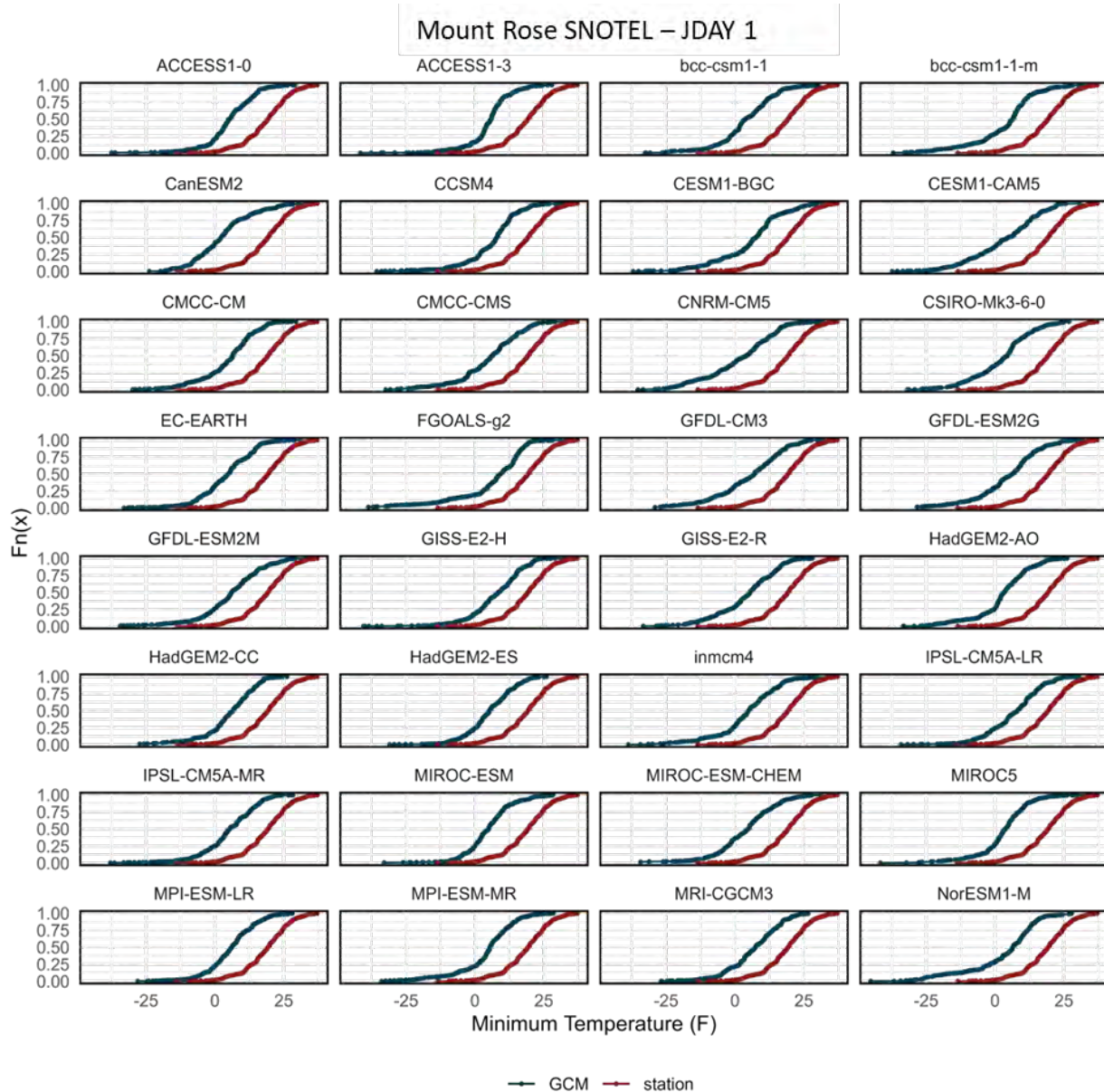


Figure 6.—The January 1 minimum temperature cumulative distribution function for Mount Rose SNOTEL Station 19k07s, in the Truckee River Basin, and each of the 32 general circulation models.

3.4 Observed Historical Streamflow

For this Pilot Study, Reclamation used the daily TROA Planning Model dataset developed by PWRE, from 1901 through 2017, to represent observed historical streamflow. This dataset provides a complete time series for all inflow locations into the TROA Planning Model, specifically all the local inflow locations, many of which are not included in the original TCDATFIL daily dataset.

3.5 Simulated Historical and Future Streamflow

The Pilot Study used the bias-corrected climate data described in section 2.3 as input to the five different PRMS models to simulate streamflow at key locations (figure 1 and table 3). Systematic annual biases between simulated historical total inflow from PRMS and reconstructed historical observed total inflow to Lake Tahoe from the TROA Planning Model dataset were removed using a quantile mapping approach based on annual (calendar year) CDFs. However, streamflow output from PRMS at all other locations was not bias-corrected (See appendix A for a more detailed explanation about the decision to bias correct Lake Tahoe inflow and not other PRMS streamflow output).

Table 3.—Simulated streamflow within the Precipitation Runoff Modeling System models

PRMS-Simulated Streamflow Location	PRMS Model	Latitude	Longitude
Donner Creek at Highway 89	Martis	-120.207	39.321
Truckee River near Truckee	Martis	-120.204	39.296
Boca Reservoir inflow	Little Truckee	-120.096	39.409
Donner Lake inflow	Martis	-120.280	39.320
Independence Lake inflow	Little Truckee	-120.312	39.442
Martis Creek Lake inflow	Martis	-120.112	39.313
Prosser Creek Reservoir inflow	Martis	-120.176	39.388
Sidewater	Little Truckee and Martis	-120.033	39.428
Stampede Reservoir inflow	Little Truckee	-120.126	39.490
Lake Tahoe inflow	Lake Tahoe	-120.035	39.042
East Carson Watershed Outlet	East Carson	-119.700	38.804
West Carson Watershed Outlet	West Carson	-119.844	38.770

The following equation was used to calculate net inflows into Lake Tahoe (which is required in Riverware) from unimpaired inflows that were output from PRMS.

$$\text{TROA Planning Model dataset net inflow} = \text{Naturalized Lake Tahoe inflow} + \text{precipitation} - \text{evaporation}$$

Precipitation and evaporation over Lake Tahoe were estimated as described in section 3.6 and 3.7, respectively.

3.6 Projected Precipitation Over Reservoirs

The TROA Planning Model includes inputs of daily precipitation over each reservoir to account for changes in storage due to large precipitation events. Precipitation over each reservoir was developed by (Huntington and Mcevoy 2011) and consists of historical monthly average values. Monthly averages were estimated from nearby precipitation gaging stations. When gage data were unavailable, the precipitation over the surface of a reservoir was estimated using the average of the ratio between available point precipitation measurements and the PRISM values.

Daily precipitation for 32 GCM historical and 64 LOCA-CMIP5 future PRMS simulations was developed for each of the six smaller reservoirs (Donner Lake, Martis Creek Lake, Prosser Creek, Independence, Stampede, and Boca) in the Truckee-Carson Basins. As stated above, precipitation at individual climate station locations is distributed within PRMS to each model grid cell based on mean monthly PRISM precipitation patterns (from October 1980 through December 2015). One central grid cell overlying each reservoir was chosen to output daily bias-corrected precipitation at each reservoir (figure A-1). For Lake Tahoe, PRMS was able to output an area-weighted precipitation for the entire lake. This is possible as the grid cells overlying Lake Tahoe were designated as a unique sub-basin. This is not the case with the other smaller reservoirs, as they were part of larger sub-basins.

3.7 Lake Tahoe Evaporation

The Pilot Study estimated historical (October 1980 through December 2015, corresponding with the PRMS model period) and LOCA-CMIP5-based evaporation over Lake Tahoe (1950–2005 for the historical period, and 2006–2099 for the future period) using the Complementary Relationship Lake Evaporation (CRLE) model (Morton 1985, 1983, 1979). Lake Tahoe evaporation over the historical period (1980–2015) was needed to support development of Lake Tahoe inflows, while evaporation over the future period was needed to support development of projected inflows to Lake Tahoe. The full 1901–2017 historical period was not simulated because the TROA Planning Model dataset implicitly accounts for Lake Tahoe evaporation in its “Lake Tahoe net inflows” variable. CRLE model accounts for air temperature, albedo, emissivity, and heat storage effects to estimate surface water evaporation on a monthly timescale. Because the CRLE model is insensitive to differences in air temperature, humidity, and wind speed from land to water, it overcomes the shortcomings of other estimation methods requiring accurate over-water humidity and wind speed. The CRLE model instead relies on the strength of the available energy approach, in which wind speed is not used directly. Application of the CRLE model requires local weather data, specifically solar radiation, air temperature, and dewpoint (or relative humidity) from weather stations or gridded climate data near the reservoirs and lakes of interest. Data on reservoir location, depth, and salinity of the water (e.g., total dissolved solids) are also required. The CRLE model has been used in multiple studies to provide accurate estimates of monthly reservoir evaporation across the United States (Huntington and Mcevoy 2011).

For the Pilot Study, climate inputs into the CRLE model included bias-corrected climate data, which was processed within PRMS to generate area-weighted averages over Lake Tahoe on a daily timescale. The area-weighted climate data include maximum and minimum temperatures, which are used to estimate an average daily temperature, and solar radiation. These variables were aggregated to a monthly timestep for input to the CRLE model. The CRLE model also requires a monthly average dewpoint temperature, which is not directly calculated within PRMS. Monthly average dewpoint temperatures were estimated using PRISM mean monthly dew point depression coefficients and the processed PRMS minimum temperature extracted from PRMS. Dewpoint temperature was then estimated as the average monthly minimum temperature minus the mean monthly dewpoint depression coefficient. The final inputs CRLE requires are an average lake depth and total dissolved solids concentration, both of which are held constant throughout the model simulation. For Lake Tahoe, an average depth of 60 meters and a total dissolved solids concentration of 60 milligrams per liter (mg/L) was used, which is consistent with previous applications of the CRLE over Lake Tahoe (Reclamation 2021b). The monthly evaporation rates output from these CRLE runs were then used as part of the naturalization equation (refer to section 3.5) to compute net inflows into Lake Tahoe.

3.8 Fort Churchill Regression

As mentioned previously, the TROA Planning Model input requires depleted flows at the Carson River near Fort Churchill gage in Nevada, requiring simulations between the PRMS streamflow points on the East and West Forks of the Carson River and the Fort Churchill gage. The intervening reaches between these points are hydrologically complex, and flows are impacted by significant depletions and groundwater interactions, as well as intermittent tributary inflows.

Similar to the Basin Study, this Pilot Study developed a regression model to estimate streamflow at the Fort Churchill gage. Whereas the Basin Study developed monthly regressions between the Truckee River and Fort Churchill gage, simulation of streamflow in the East Fork and West Fork Carson Rivers over WY 1980–2015 used in the Pilot Study provides more direct approximations of unimpaired streamflow, yielding improvements over the Basin Study estimates. Simulated streamflow based on regression terms within the Carson River Basin represents potential changes in future streamflow that may differ in timing and volume from streamflow within the Truckee River Basin, which was used. Developing a linked river systems model, such as USGS (Kitlsten et al. 2021), would require significant effort outside of the scope of the Pilot Study.

Various autoregressive modeling approaches (e.g., SARIMAX) were considered and eliminated from consideration due to a lack of skill. The Pilot Study uses a localized regression (LOESS; Cleveland and Devlin 1988) between the sum of simulated PRMS streamflow in East Fork and West Fork Carson Rivers and streamflow at Fort Churchill from the TROA Planning Model dataset. The LOESS is a method of smoothing least squares polynomial LOESSs. Smoothing is controlled by a parameter that increases or reduces the response of the LOESS regression function to fluctuations in data.

As described in Kitlasten et al. (2021), depletions in the Carson Valley vary throughout the year. Likewise, local inflows from intermittent tributaries occur primarily during periods when precipitation occurs. This Pilot Study examined differing responses throughout the year by clustering the data using Gaussian Mixture Model clustering. Clustering is a technique that identifies meaningful groups within datasets (Tan 2018), as shown on figure 7. The two clusters (denoted by different colors) show distinct differences in the relationship between unimpaired inflow to the system (East Fork plus West Fork) and Fort Churchill streamflow. In particular, low flows react differently in late summer and early fall as compared to winter flows. This is most likely due to depletions in the intervening reaches.

For these reasons, the study team built models using two-dimensional LOESS, using the week of the year to represent temporal variability. The Pilot Study examined monthly, weekly, and daily LOESS models, with weekly models providing a balance between maintaining streamflow timing and model skill. Models were initially built using observed gage data, reserving 70 percent of the dataset for training and 30 percent of the dataset for testing. The final model uses PRMS historical streamflow as a predictor for gaged Fort Churchill flows. Modeled weekly flows are then upsampled to daily using Akima spline resampling (Akima 1970).

Clusters Identified by Guassian Mixture Model

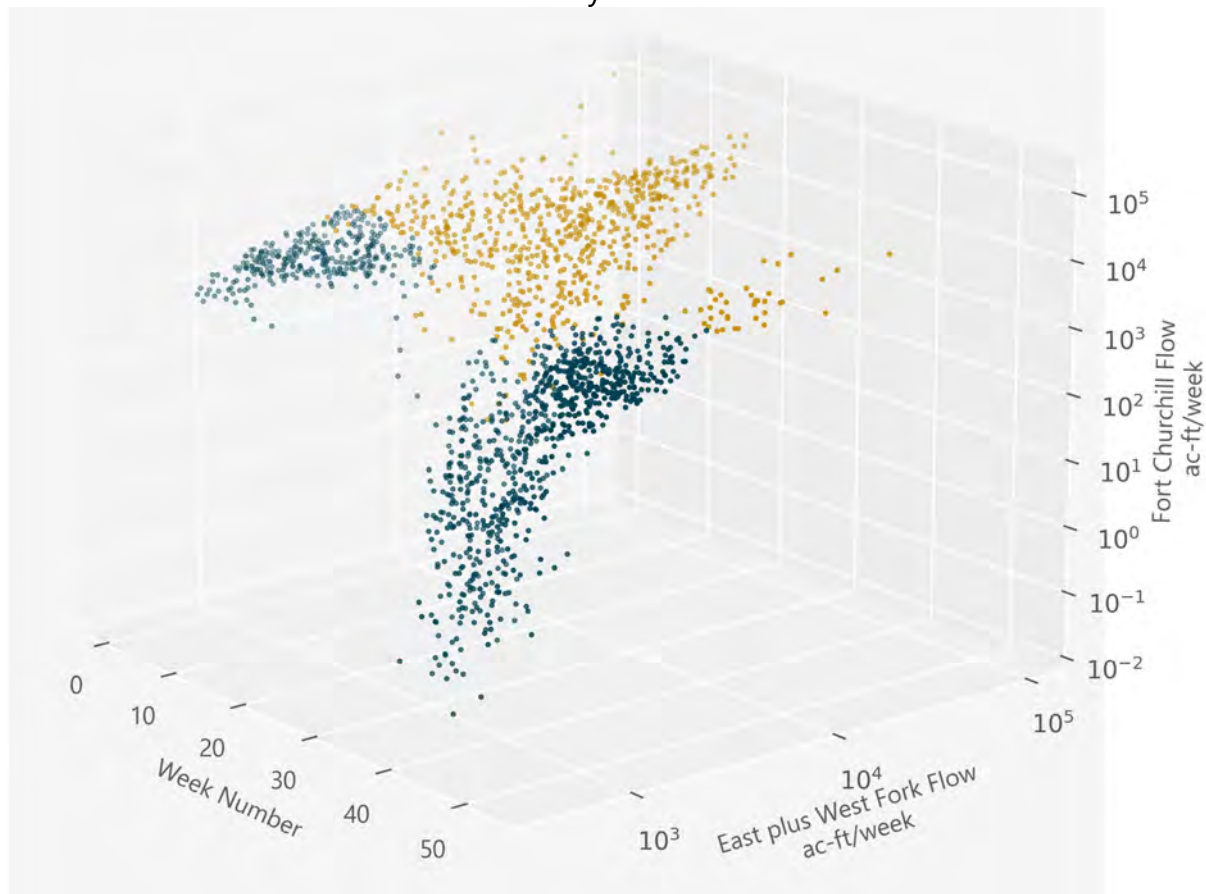


Figure 7.—Cluster analysis of Fort Churchill streamflow, with two clusters denoted by different colors.

Weekly models built with observed data and PRMS data showed Nash-Sutcliffe efficiencies (NSE) of 0.87 and 0.79, respectively, for the testing dataset. Upsampled daily data resulted in an NSE of 0.70 (figure 8). Note that the gray line in the top panel of figure 8 represents the 1:1 line.

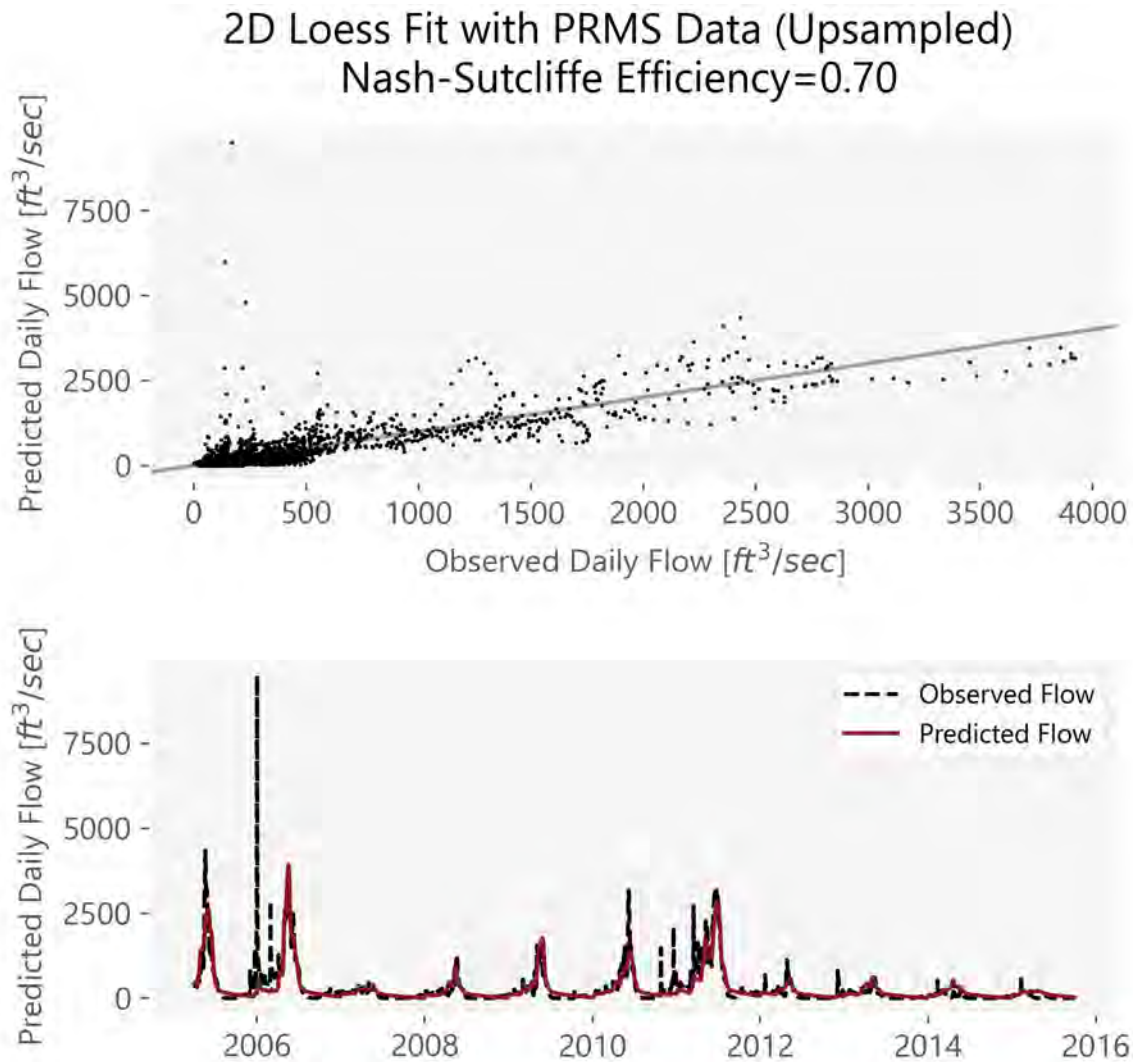


Figure 8.—Testing dataset for two-dimensional LOESS model of Fort Churchill flows upsampled to daily data.

The Pilot Study compared the LOESS model to the Basin Study MLR model using PRMS streamflow at multiple locations as predictors over the LOESS model testing period. For comparability to the monthly timestep of the Basin Study’s MLR model, the LOESS model outputs were down-sampled from daily to monthly values. Figure 9 shows estimates of historical Fort Churchill streamflow over the testing period using both approaches. The LOESS model results in higher NSE, supporting the use of this approach for developing future climate Fort Churchill streamflow.

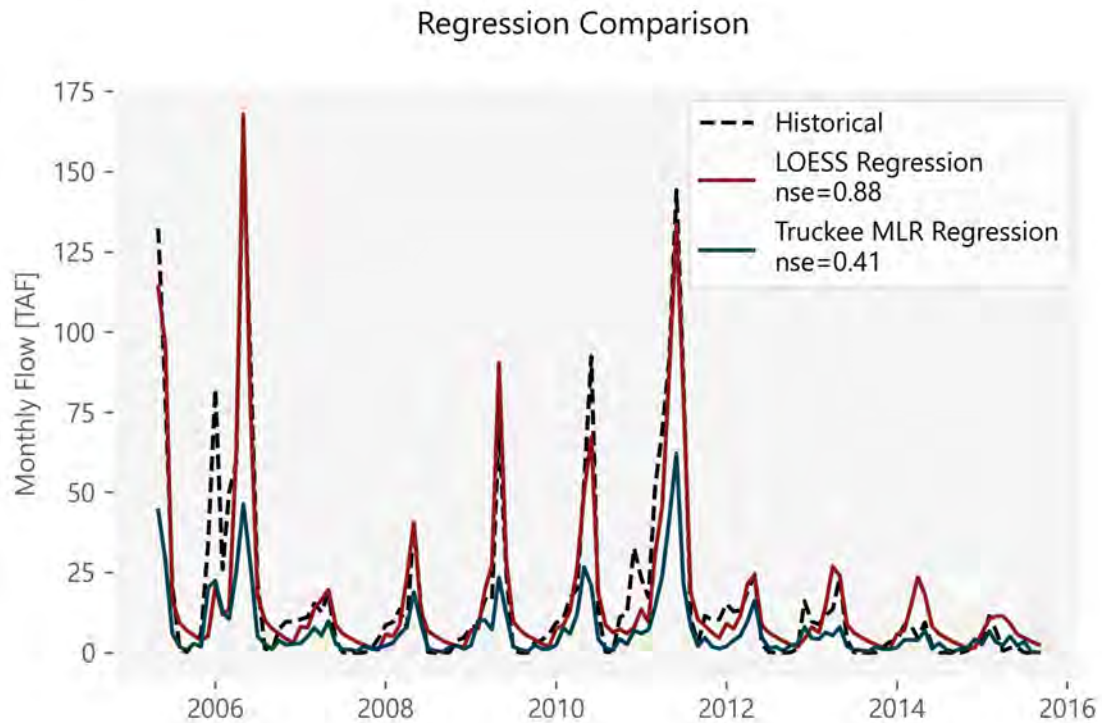


Figure 9.—Comparison of the Basin Study multiple linear regression approach and the two-dimensional LOESS approach to representing depleted inflows at Fort Churchill.

3.9 River Systems Model

The TROA Operations Model was developed in RiverWare to model daily operations under TROA. The TROA Planning Model was developed for scenario planning studies from the TROA Operations Model and evaluates operations over a recent historical simulation period.

At the beginning of the Pilot Study, the dataset encompassed 117 years from 1901 to 2017, although it has since been extended to 2022. Baseline conditions for the TROA Planning Model apply operational rules under TROA and OCAP over the entire period of record and thus do not match observed conditions over the historical period before 1997, which is when OCAP was implemented. The impacts on water supply reliability of the paleo and future climate scenarios developed for the Pilot Study, as well as the previously developed historical hydrology dataset, were evaluated using the TROA Planning Model. The TROA Planning Model has also been used in other studies for scenario planning using different hydrologic periods, including different historical periods as well as projected future periods. Additional studies using the model are described in Appendix B: Literature Review.

Hydrologic inputs developed as part of the Pilot Study were formatted for input into the TROA Planning Model. Model initial conditions at WY 2018 levels were used to start the 400-year paleo simulation. The model state from the end of the paleo model run was used to initialize the historical period run from WY 1900 through 2017. Future hydrology simulations used the same

initial conditions from the model state at the end of the historical period run. All simulation periods used the same set of demands, which were set to 2018 levels with the same repeating demand sequence for each year throughout the runs.

Several adjustments to the TROA Planning Model ruleset were required to complete the paleo and future hydrology model runs. These model adjustments were evaluated over the historical period and compared to previous historical runs of the TROA Planning Model to ensure that they did not significantly impact modeling results. These model adjustments are detailed in appendix C.

3.10 Performance Metrics

The study team selected metrics to evaluate managed conditions in the distant past (1500–1900) and projected future (2018–2099), in the context of the recent historical period (WY 1901 to 2017). The selected metrics were derived from metrics evaluated as part of the West-Wide Assessment (Reclamation 2021b) and a Technical Memorandum on the “Status of the Operating Criteria and Procedures, Conservation Measures, and the Evaluation of the Effect of Improved Efficiency in the Carson Division” (Reclamation 2018). These metrics quantify climate impacts in terms of water supply, environmental flows, and flood risk.

Metric selection also considered performance in terms of ability to meet major objectives of the 1997 OCAP, including:

- Maximize the use of Carson River waters to meet the requirements of the Project
- Minimize the use of water from the Truckee River as a supplemental supply
- Conserve Truckee River flows for Pyramid Lake (OCAP 1997)

The dataset set developed in the Pilot Study could also be used to inform the other two major OCAP objectives to increase the efficiency of water use in the Project and establish a regulatory scheme to manage deliveries to Project water users (OCAP 1997).

Given the complexity of the system and focus of the Pilot Study on dataset development and modeling workflow development using the TROA Planning Model, it was not possible to develop and evaluate an exhaustive list of metrics. Similarly, due to the wide variety of stakeholder interests, there likely exist differing opinions on the “best” metrics to assess the performance of the OCAP under climate change. The selected metrics demonstrate the capabilities and impacts of this modeling framework and hydrologic dataset. Section 4.2 recommends refining and updating this set of metrics collaboratively with stakeholders and diving deeper into an analysis of metric results.

3.10.1 Water Supply Metrics

The water supply metrics focus on conditions of supplies in Lake Tahoe and Lahontan Reservoir, and the ability of these supplies to meet Project demand, particularly CDD, representing the largest portion of Project water use. In addition, the study team examined the amount of water diverted from the Truckee River under different hydrologic scenarios to assess changes in the ability to meet the OCAP objectives to minimize diversions of Truckee River water through the Truckee Canal and maximize the use of Carson River water.

The water supply metrics also quantify the ability of water operations and management in the Truckee-Carson Basins more generally to meet demands within and outside the Project. The Floriston Rate is a required average daily flow rate intended to ensure secure water to meet hydroelectric, municipal and industrial, environmental streamflow, and agricultural water demands; meeting the Floriston Rate is one of the basin's top operational priorities. The target Floriston Rate varies seasonally from 400 ft³/s from November through March to 500 ft³/s from April through October. The metrics examine the ability to meet the Floriston Rate as well as the percent of years in a TROA designated "Drought Situation" (table 4).

3.10.2 Environmental Metrics

As mentioned previously, Project diversions through the Truckee Canal have contributed to the decrease in Truckee River flows below Derby Dam and the lowering of Pyramid Lake levels, leading to the deterioration of Pyramid Lake fisheries. These impacts triggered litigation by the Pyramid Lake Paiute Tribe and the Federal government, resulting in the 1997 OCAP. To assess the ability of OCAP to meet its objectives under different climatic conditions, the environmental metrics examine changes in Pyramid Lake elevation and inflows (Truckee River near Nixon, NV, gage [USGS ID 10351700]; https://waterdata.usgs.gov/nwis/uv?site_no=10351700&legacy=1) (table 4). Further, the study team examined the portion of Truckee River streamflow diverted to meet Project demand and the portion of Truckee River water used to meet CDD to assess changes in the ability to meet the OCAP objectives.

3.10.3 Flood Risk Metrics

While flood risk management is not an OCAP objective, nor a purpose of the Project reservoirs, high flows impact the performance of the OCAP. High flow events can force precautionary releases or spills from the Lahontan Reservoir, which poses challenges to implementing OCAP and calculating Project debits or credits. Further, increases in flood risk pose an overall challenge for water management in the Truckee-Carson Basins. The Pilot Study looked at changes in the frequency of occurrence of the unregulated 10-year (10 percent chance of occurrence) and 100-year (1 percent chance of occurrence) floods predicted in a previous study (Reclamation 2022) in the paleo and future period to identify differences in flood size and frequency. Flood frequency estimates from the 2022 study were estimated using unregulated flow data. In addition, the study examined the number of days flows exceed the Reno flood flow target (6,000 ft³/s instantaneous streamflow, estimated as 5,500 ft³/s daily average streamflow), which governs flood operations.

Table 4.—Metrics for quantifying changes in water supply, environmental, and flood considerations in the Truckee and Carson River Basins*

ID	Metric Name (units)	Metric Description	Drought Reconstruction Location
Water Supply			
W01	Average percent (%) of years Lake Tahoe reaches legal filling limit (%)	Average of all model runs' percent of years that Lake Tahoe elevations reach or exceed the legal filling limit, 6,229.2 feet, on any day in the year	Truckee
W02	Average percent of days Lake Tahoe falls below the natural rim (%)	Average of all model runs' percent of days that Lake Tahoe elevations fall below the natural rim, 6,223, at which point no water flows into the Truckee River	Truckee
W03	Average percent of days Floriston Rates are met (%)	Average of all model runs' percent of days Floriston Rates are met. The Floriston Rate is the required average daily flow rate at the Farad gage on the Truckee River near the California-Nevada border, intended to ensure secure water to meet hydroelectric, municipal and industrial, environmental streamflow, and agricultural water demands (300 ft ³ /s November–March; 500 ft ³ /s April–October)	Truckee
W04	Average percent of years in TROA designated "Drought Situation" (%)	Average of all model runs' percent of years in a TROA designated "Drought Situation", meaning a situation when on April 15 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, and including Lake Tahoe Floriston Rate Water in other Truckee River Reservoirs as if it were in Lake Tahoe, on or before the following November 15 will be equivalent to an elevation less than 6,223.5 feet.	Truckee
W05	Average percent of years Lahontan reaches the end-of-June storage objective (LSOCM)** (%)	Average of all model runs' percent of years Lahontan reservoir reaches or exceeds 95% end-of-June storage objective on June 30 (LSOCM)	Carson
W06	Average peak Lahontan elevation (ft)	Average of all model runs' peak Lahontan elevation	Carson
W07	Average date of peak Lahontan Elevation (Julian day)	Average of all model runs' date of peak Lahontan elevation	Carson
W08	Average annual Truckee Canal diversions (AF/yr)	Average of all model runs' annual diversions to the Truckee Canal, calculated as the annual volume of streamflow at the Truckee Canal near Wadsworth gage	Carson

ID	Metric Name (units)	Metric Description	Drought Reconstruction Location
W09	Average annual percent of days CDD is met (%)	Average of all model runs' percent of days Lahontan releases meet or exceed 95% of CDD	Carson
W10	Average annual volume of CDD shortage (acre-feet per year)	Average of all model runs' difference between the annual CDD and Lahontan releases	Carson
Environmental Flows and Conditions			
E01	Average Pyramid Lake pool elevation (ft)	Average of all model runs' daily Pyramid Lake pool elevation (ft) over all runs	Truckee
E02	Average Nixon streamflow: annual (ft ³ /s)	Average of all model runs' daily streamflow at the Nixon gage (ft ³ /s) over all runs	Truckee
E03	Average Nixon streamflow: August through February (ft ³ /s)	Average of all model runs' daily streamflow at the Nixon gage (ft ³ /s) from August 1 through February 28 (29) over all runs	Truckee
E04	Average Nixon streamflow: March through July (ft ³ /s)	Average of all model runs' daily streamflow at the Nixon gage (ft ³ /s) from March 1 through July 31 (29) over all runs.	Truckee
E05	Average annual percent of CDD met by the Truckee River water	Average of all model runs' annual percentage of Carson Division Diversion met by Truckee River water, measured at the Hazen Gage at the end of the Truckee Canal.	Carson
E06	Average annual percent of Truckee River streamflow diverted to Truckee Canal	Average of all model runs' annual diversions to the Truckee Canal (W07) divided by the annual streamflow above Derby Dam, as measured from TROA Planning Model output.	Carson
Flood Risk (regulated)			
F01	Maximum annual number of days above the Reno flood flow target (days)	Maximum of all model runs' annual number of days above the Reno flood flow target (6,000 ft ³ /s instantaneous streamflow, estimated as 5,500 ft ³ /s daily average streamflow), which governs flood operations.	Truckee
F02	Average percent of years exceeding 10-year rain flood streamflow (%)	Average of all model runs, number of years that flows exceed the 10-year rain flood event at Reno, calculated based on observed historical events (Reclamation 2022). Flows are expected to exceed the 10-year event 10% of the time; high values indicate an increase in the frequency of historical high flow events	Truckee

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ID	Metric Name (units)	Metric Description	Drought Reconstruction Location
F03	Average percent of years exceeding 100-year rain flood streamflow (%)	Average of all model runs, number of years that flows exceed the 100-year rain flood event at Reno, calculated with observed historical events (Reclamation 2022). Flows are expected to exceed the 100-year event 1% of the time; high values indicate an increase in the frequency of historical large flood events	Truckee
F04	Average percent of years exceeding 10-year Snowmelt Flood Streamflow (%)	Average of all model runs, number of years that flows exceed the 10-year snowmelt flood event at Reno, calculated with observed historical events (Reclamation 2022). Flows are expected to exceed the 10-year event 10% of the time; high values indicate an increase in the frequency of historical high flow events	Truckee
F05	Average percent of years exceeding 100-year snowmelt flood streamflow (%)	Average of all model runs, number of years that flows exceed the 100-year snowmelt flood event at Reno, calculated with observed historical events (Reclamation 2022). Flows are expected to exceed the 100-year event 1% of the time; high values indicate an increase in the frequency of historical large flood events	Truckee

* Metrics are calculated for each drought event, the paleo-period, the historical period, and for each of the future traces individually. Metrics for historical and paleo-period drought events are presented for rule-based droughts identified at the specified drought reconstruction location.

** Lahontan Storage Objective Current Month

4.0 Results

This section summarizes the results of the various methods applied and discussed in section 2.0 for development of the hydrologic dataset (including distant past, recent historical, and projected future conditions) and the use of that dataset in the TROA Planning Model to calculate and evaluate the OCAP performance metrics. The workflow and computed metrics allow water managers in the Truckee-Carson Basins to identify existing operational challenges and challenges that could arise if paleo conditions were to occur again and/or projected climate scenarios were to occur.

Of note, the historical results do not exactly match observed conditions due to two primary reasons. First, the initial conditions for the modeled historical period match the ending conditions of the paleo simulations, not the observed initial conditions. Secondly, the baseline conditions for the TROA Planning Model apply operational rules under the TROA (enacted in 2015) and the OCAP (last updated in 1997) over the entire period of record and thus do not match observed conditions.

4.1 Paleohydrology

4.1.1 Daily Reconstructed Streamflow for 1500–1900

As discussed in section 2.1, two streamflow reconstructions—the Carson River near Fort Churchill, NV, and the Truckee River at Farad, CA—were used to inform the paleo dataset developed in the Pilot Study.

Compared to the streamflow reconstructions over the paleo-period, water-year annual streamflow over the recent historical period from the TROA Planning Model dataset shows a(n):

- Skew to lower annual average streamflow (overall drier conditions) as evidenced by greater density of historical streamflow at lower average annual flow rates and lower median values,
- Higher variability and larger range in annual streamflow values (greater interannual variability) as evidenced by a larger range on the x-axes,
- Higher annual flows (wetter, wet years) as evidenced by historical flows reaching higher levels on the x-axes, and
- Larger portion of high annual flows (more wet years) (table 5, figure 10, and figure 11) as evidenced by higher density at high average annual flow rates.

The TROA Planning Model dataset over the recent historical period for both the Carson and Truckee Rivers shows significantly higher maximum annual streamflow than in the paleo-period. For the Truckee River Basin, the maximum annual streamflow in the recent historical period of 1,600 ft³/s is greater than one standard deviation removed from the highest annual average flow rate in the paleo-period of 1,049 ft³/s (table 5).

Table 5.—Statistical comparison of the Carson River and Truckee River annual average flows in the paleohydrology reconstruction and recent historical period datasets

Dataset	Carson River near Fort Churchill, NV (ft ³ /s)				Truckee River at Farad, CA (ft ³ /s)			
	Mean	Median	Maximum	SD*	Mean	Median	Maximum	SD*
Paleo Reconstruction (1500–1900)	385	392	902	172	572	580	1,049	205
Recent Historical Period (1986–2017)	357	222	1,311	313	527	387	1,600	396

*Standard deviation

This lack of higher water-year annual streamflow in the paleo reconstructions (right tail of figure 10 and figure 11) is likely due to the current limitations of the paleo reconstruction methods, which may not be able to capture shorter-term higher flow events and ultimately higher annual flows (see section 3.1).

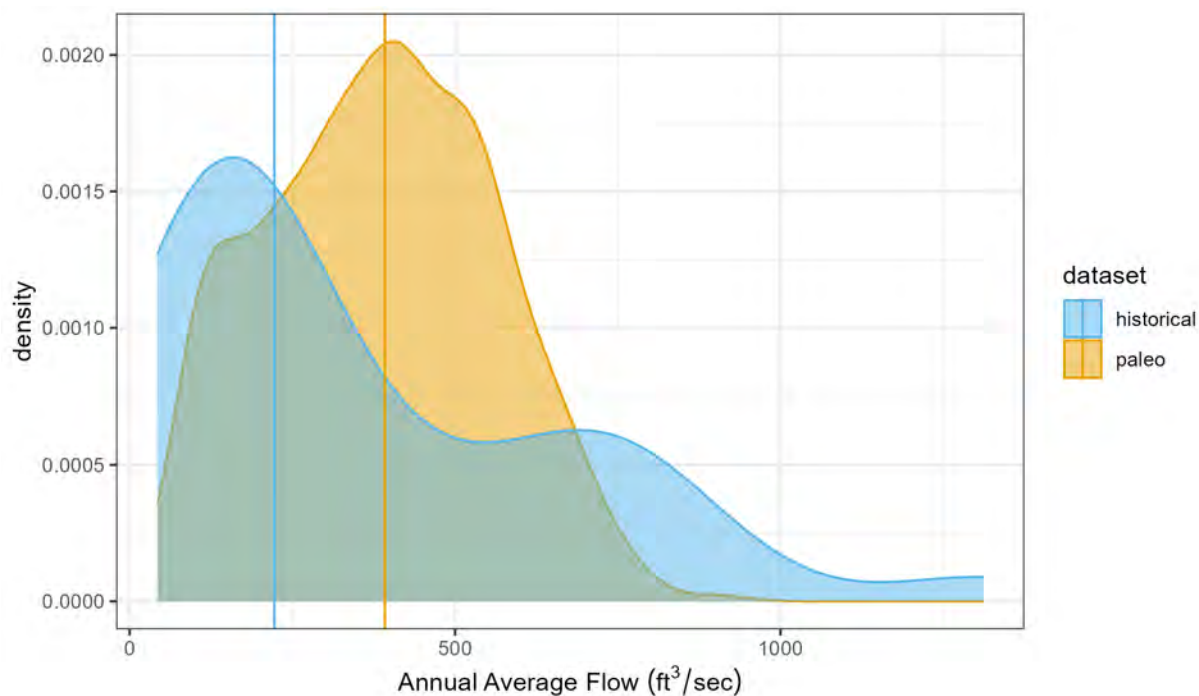


Figure 10.—Distribution of water-year annual average flow rates for the Carson River daily disaggregated distant past paleohydrology reconstruction dataset and the recent observed historical period dataset used for the daily disaggregation (historical).¹⁴

¹⁴ The horizontal lines indicate the median of the respectively colored dataset.

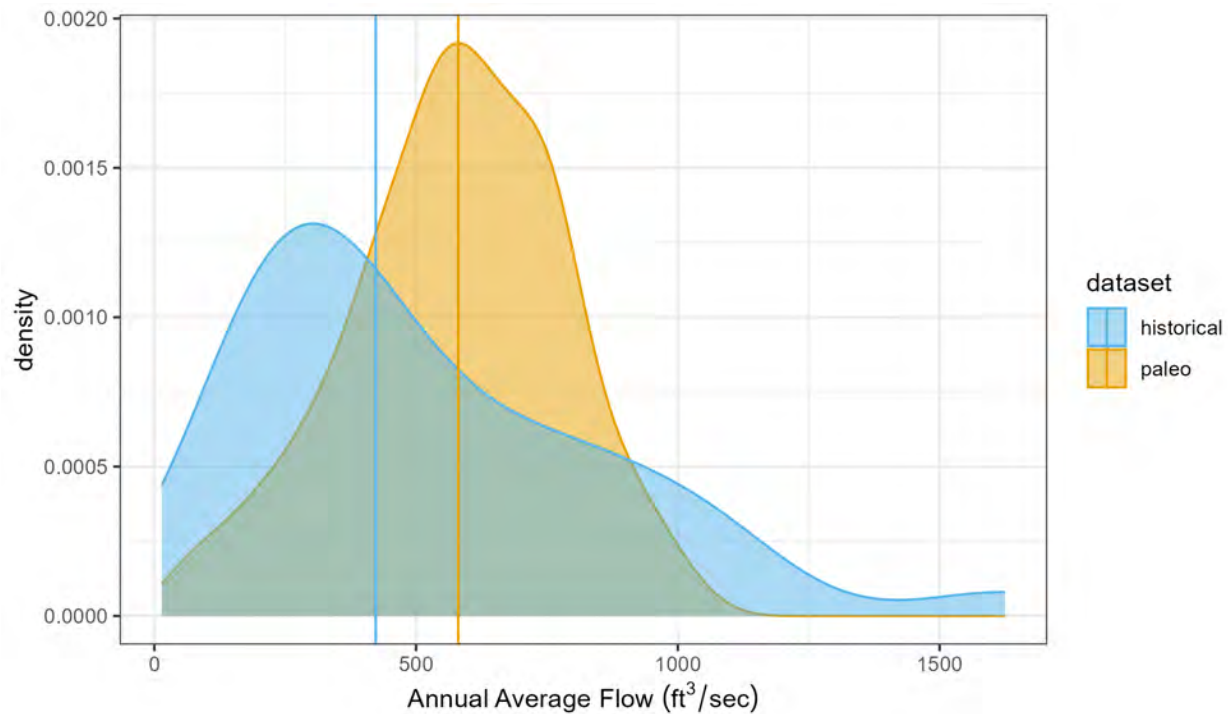


Figure 11.—Distribution of water-year annual average flow rates for the Truckee River daily disaggregated distant past paleohydrology reconstruction dataset and the recent observed historical period dataset used for the daily disaggregation (historical).¹⁵

The paleo streamflow distributions for the sites within the TROA Planning Model exhibit similar trends to those on the basin scale. Figure 12 and figure 13 group together higher flow sites (annual average streamflow is greater than 100 ft³/s) and lower flow sites (annual average streamflow is generally less than 100 ft³/s), respectively, for illustration purposes only, to allow for focus on the difference in distributions for each site. For most locations, the paleo dataset contains a smaller range of annual streamflow relative to the historical dataset and often exhibits lower maximum annual flows. However, the median annual flows are lower in the paleo datasets compared to the historical dataset.

¹⁵ The horizontal lines indicate the median of the respectively colored dataset.

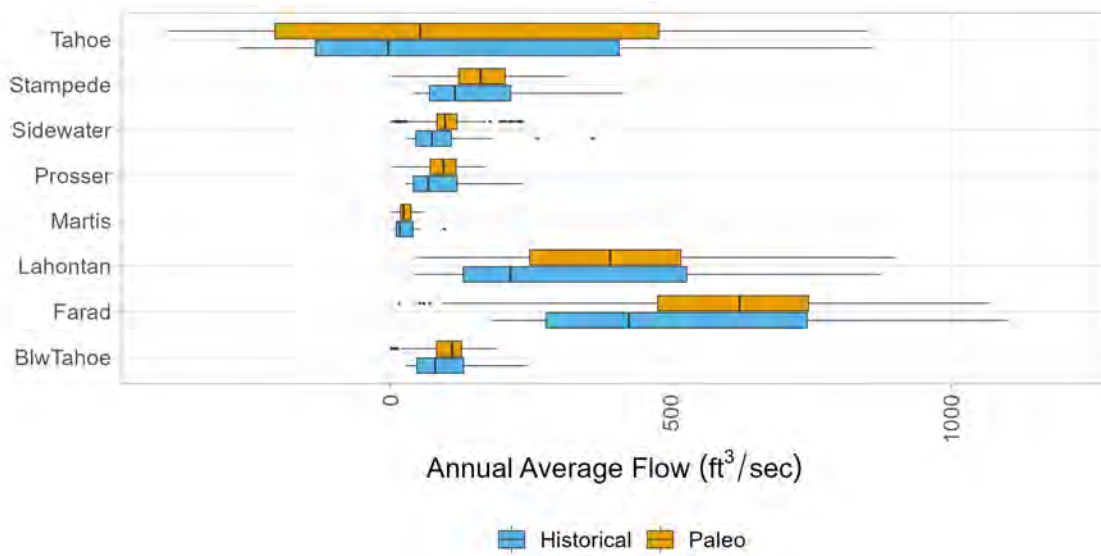


Figure 12.—Ranges of annual streamflow (ft^3/s) for each Truckee River Operating Agreement Planning Model inflow location (higher flow locations), comparing the recent historical (WY 1986–2017) dataset with the daily reconstructed streamflow (WY 1500–1900) dataset.

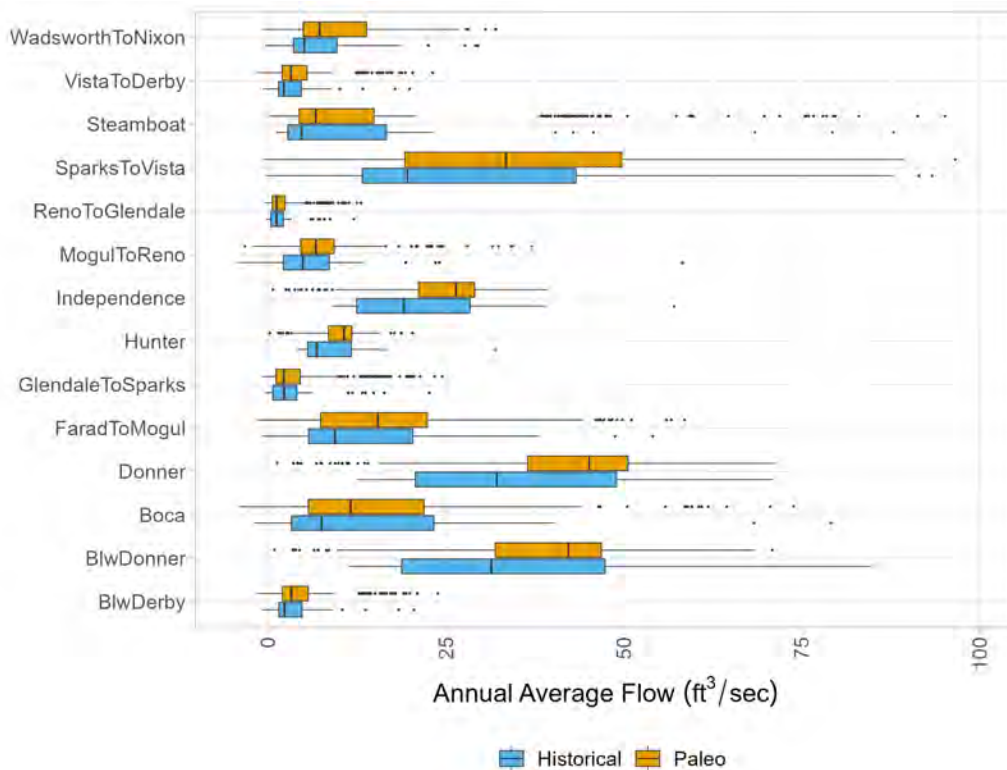


Figure 13.—Ranges of annual streamflow (ft^3/s) for each Truckee River Operating Agreement Planning Model inflow location (lower flow locations), comparing the recent historical (WY 1986–2017) dataset with the daily reconstructed streamflow (WY 1500–1900) dataset.

4.1.2 Historical and Distant Past Paleohydrology (Paleo) Period Droughts

Droughts for each of the rivers were identified using the rule-based and zero-crossover methods identified in section 2.1. Identified droughts are summarized below by duration and severity, where severity is defined using two metrics: cumulative deficit over the full drought period and average annual deficit.

In the Carson River Basin, the LCD (table 6) and LAD (table 7) droughts from the paleo-period exceed historical deficits for any given rank and drought identification method. The same is true for droughts in the Truckee River Basin (table 8 and table 9). All three of the LCD droughts identified using the rule-based method occur before the paleo-period (1685 to 1977) evaluated as part of the 2021 SECURE Water Act Report (table 6, Reclamation 2021b). The LCD drought identified for that study, 1841 to 1851, is not included in the top three LCD droughts listed in table 6. The rule-based and zero-crossover drought definitions identify similar drought periods in the late 1500s and in the mid-1600s in the Carson River Basin. However, the defined droughts vary in their start and end years, resulting in longer droughts using the rule-based drought definition and ultimately larger total cumulative deficits (table 6; figure 14).

Table 6.—Largest cumulative deficit drought events identified in the Carson River at Fort Churchill over the distant past paleohydrology period and recent historical period using the rule-based and zero-crossover drought definitions*

Period	Drought Definition	Rank	Start Year	End Year	Drought Length (years)	Cumulative Deficit (AF**)	Average Annual Deficit (AF)
Paleo	Rule based	1	1569	1600	32	2,150,000	67,180
		2	1645	1659	15	1,386,000	92,430
		3	1629	1639	11	1,148,000	104,300
	Zero-crossover	1	1775	1783	9	1,057,000	117,500
		2	1569	1580	12	1,032,000	86,040
		3	1650	1658	9	977,800	108,600
Historical	Rule based	1	1987	1994	8	1,114,000	139,300
		2	2007	2016	10	941,000	94,070
		3	1928	1935	8	856,900	107,100
	Zero-crossover	1	1923	1935	13	994,500	76,500
		2	1986	1992	7	736,600	105,200
		3	1957	1962	6	541,000	90,170

* Highlighted droughts correspond with the shaded droughts presented on figure 14.

** acre-feet

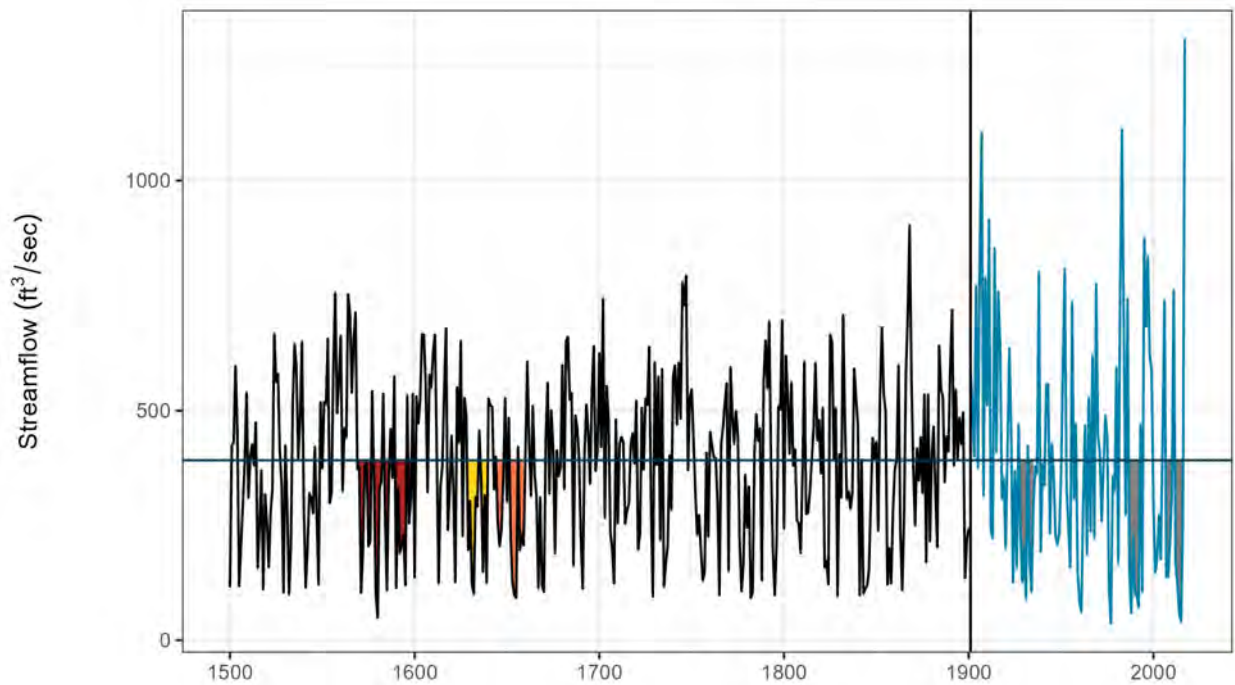


Figure 14.—Largest cumulative deficit droughts in the Carson River near Fort Churchill in the historical (gray) and distant past paleohydrology periods (red, yellow, and orange) based on a rule-based drought definition.¹⁶

Table 7.—Largest average annual deficit drought events identified in the Carson River streamflow reconstruction and naturalized streamflow dataset using the rule-based and zero-crossover drought definitions

Period	Drought Definition	Rank	Start Year	End Year	Drought Length (years)	Cumulative Deficit (AF)	Average Annual Deficit (AF)
Paleo	Rule based	1	1822	1824	3	522,666	174,222
		2	1843	1847	5	846,742	169,348
		3	1690	1691	2	324,571	162,286
	Zero-crossover	1	1600	1600	1	184,484	184,484
		2	1686	1686	1	165,784	165,784
		3	1665	1670	6	746,235	124,372
Historical	Rule based	1	1987	1994	8	1,114,265	139,283
		2	1928	1935	8	856,912	107,114
		3	2000	2004	5	499,996	99,999
	Zero-crossover	1	1964	1964	1	119,702	119,702
		2	1939	1939	1	116,402	116,402
		3	1986	1992	7	736,629	105,233

¹⁶ Results include reconstructed paleo annual flows (black line) and historical period annual flows (blue line).

Like the most severe droughts identified on the Carson River, the Truckee River droughts identified within the paleo-period by measure of LCD (table 7) or LAD (table 8) are more severe than the recent historical period. The mid-1600s drought appears in both reconstructions; however, they vary significantly in the starting and ending years. Droughts within the recent historical period are more consistent between the two basins, with the largest occurring at the end of the 1980s. Additionally, the rule-based drought definition method resulted in more severe droughts, especially when evaluated for cumulative deficits (table 7).

Table 8.—Largest cumulative deficit drought events identified in the Truckee River at Farad over the distant past paleohydrology period and recent historical period using the rule-based and zero-crossover drought definitions*

Period	Drought Definition	Rank	Start Year	End Year	Drought Length	Cumulative Deficit (AF)	Average Annual Deficit (AF)
Paleo	Rule based	1	1651	1681	31	2,821,066	91,002
		2	1515	1522	8	1,730,677	216,335
		3	1754	1767	14	1,726,780	123,341
	Zero-crossover	1	1650	1679	30	2,737,594	91,253
		2	1753	1770	18	1,742,243	96,791
		3	1513	1521	9	1,639,612	182,179
Historical	Rule based	1	1987	1994	8	1,238,114	154,764
		2	1923	1934	12	1,180,230	98,353
		3	2012	2015	4	790,461	197,615
	Zero-crossover	1	1922	1934	13	1,012,948	77,919
		2	1985	1992	8	924,722	115,590
		3	1957	1961	5	333,170	66,634

* Highlighted droughts correspond with the shaded droughts presented on figure 15.

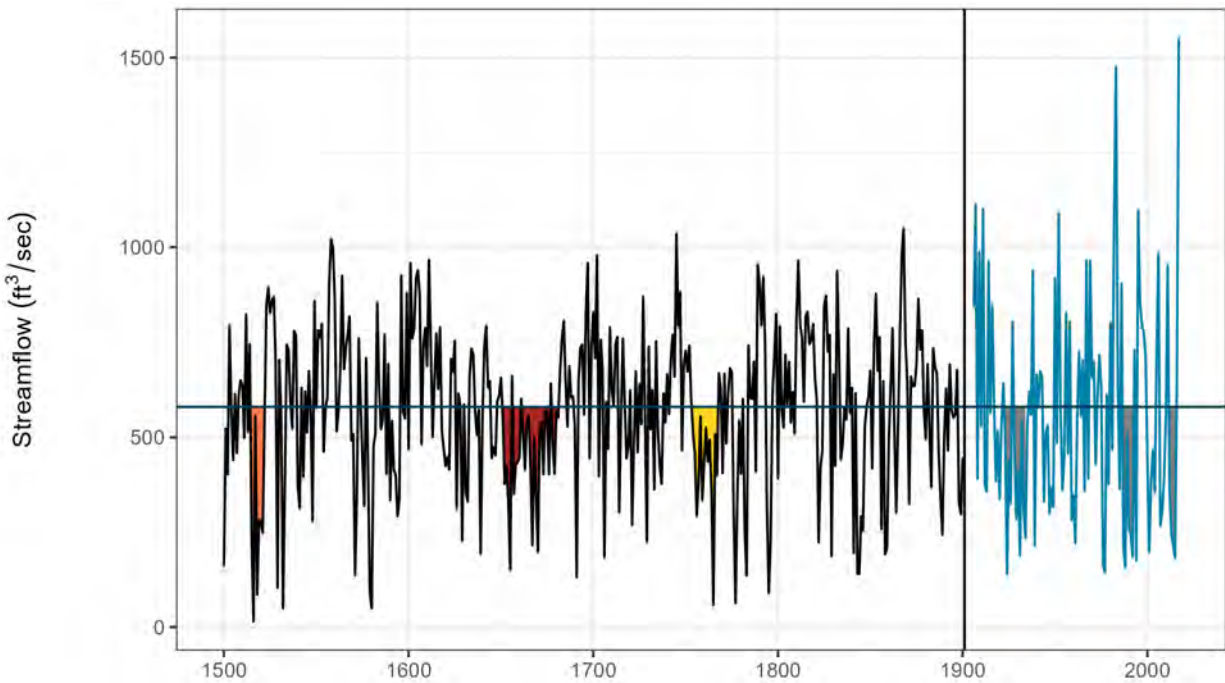


Figure 15.—Largest cumulative deficit droughts on the Truckee River at Farad in the historical (gray) and distant past paleohydrology periods (red, yellow, and orange) based on a rule-based drought definition.¹⁷

Table 9.—Largest annual deficit drought events identified on the Truckee River at Farad over the distant past paleohydrology and recent historical period using the rule-based and zero-crossover drought definitions

Period	Drought Definition	Rank	Start Year	End Year	Drought Length	Cumulative Deficit (AF)	Average annual Deficit (AF)
Paleo	Rule based	1	1794	1796	3	798,409	266,136
		2	1531	1533	3	752,146	250,715
		3	1515	1522	8	1,730,677	216,335
	Zero-crossover	1	1513	1521	9	1,639,612	182,179
		2	1500	1501	2	345,667	172,834
		3	1793	1796	4	676,390	169,098
Historical	Rule based	1	2012	2015	4	790,461	197,615
		2	1987	1994	8	1,238,114	154,764
		3	2007	2009	3	440,718	146,906
	Zero-crossover	1	1939	1939	1	217,126	217,126
		2	1985	1992	8	924,722	115,590
		3	1922	1934	13	1,012,948	77,919

¹⁷ Results include reconstructed paleo annual flows (black line) and historical period naturalized annual flows (blue line).

4.2 Bias-Corrected Climate

4.2.1 Comparisons Between Cumulative Distribution Functions (CDF) Window Length

The combined CDF approach (described in section 2.3) was developed with the intent to extend the tails of the distribution of values used in bias correction. As mentioned in section 2.3, the method incorporates more data by using multiple time windows around the day being corrected. This method, when applied to future projections, makes it less likely that a future value will be beyond the range of the historical distribution. For example, on figure 16 for precipitation, the combined CDF approach uses the maximum quantile on average less than 0.1 percent of the days that were bias-corrected, as compared to the 1-day CDF, which hit that maximum quantile approximately 1.75 percent of the time (as shown on figure 5).

Using different CDF window lengths impacts the distribution of future precipitation more significantly than it does for temperature. Differences in temperature distributions between window lengths are most apparent in RCP 8.5 scenarios. For example, at the Independence Lake SNOTEL station (refer to table 2 for Station ID 541 and figure 1 for location), the median maximum daily temperature during the 30 years is 71.2 degrees Fahrenheit (°F) when using the combined CDF approach and 70.6 °F when using the 1-day CDF approach (figure 17). While the differences in projected temperatures are not large between different methods of bias correction, using the combined CDF approach allows for higher projected temperatures. In contrast, the differences in median precipitation projections between the different CDF methods are more apparent. Looking at the Independence Lake SNOTEL station again (figure 17), and RCP 8.5, the median annual precipitation using the combined approach is 49.7 inches, compared to 44.6 inches using the 15-day CDFs, and 52.0 inches using the 1-day CDF approach. The combined approach more closely mimics the distribution of annual precipitation generated from the 1-day CDF, while allowing for higher daily bias-corrected precipitation values that are not limited to those observed on the specific day of the year, but those that were observed within a 31-day window centered on the particular day of interest. In short, the method allows for an increase in the magnitude of an extreme value on a given day, but it is limited to the historically observed extreme values on days in proximity to the given day.

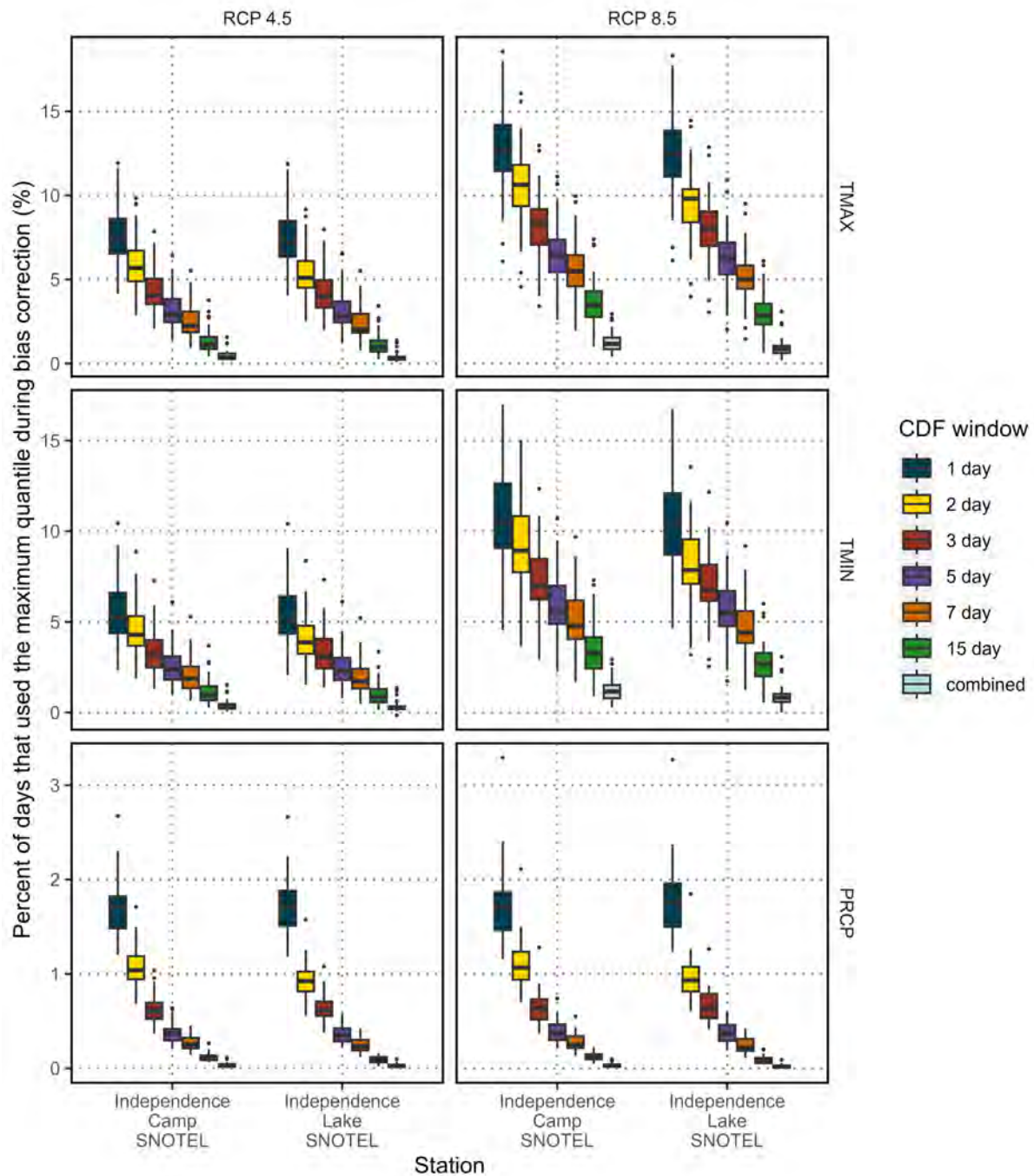


Figure 16.—The distribution of the percent of total days the bias correction used the maximum quantile value when correcting maximum temperatures (top), minimum temperatures (middle), and precipitation (bottom) at the two weather stations used in the Lower Truckee Precipitation Runoff Modeling System model.¹⁸

¹⁸ Color indicates the CDF window length used during bias correction. TMAX = maximum temperatures; TMIN = minimum temperatures; and Prcp = precipitation.

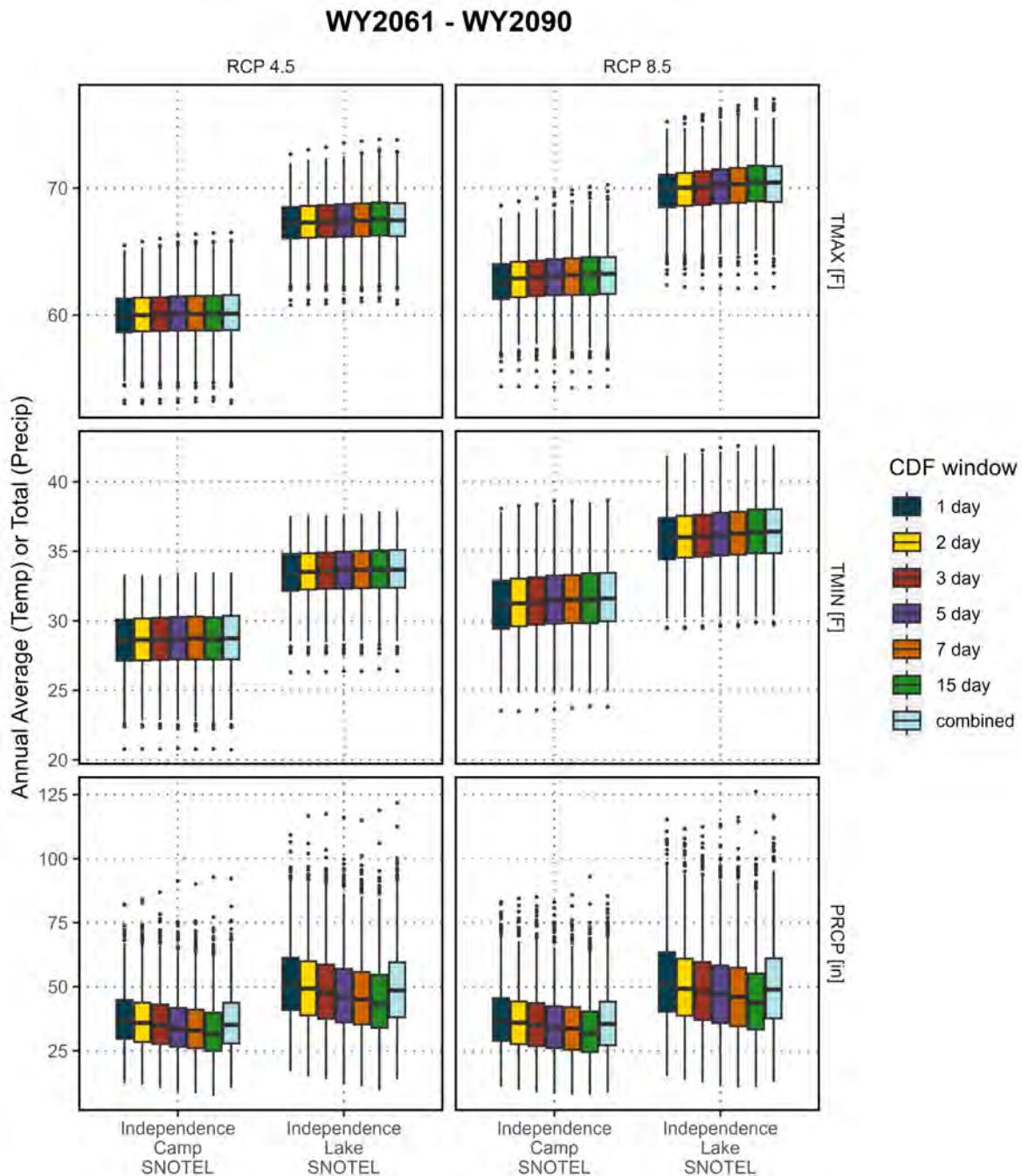


Figure 17.—The distribution of the water year average maximum (top) and minimum (middle) temperature and annual total precipitation (bottom) from water year 2061 through 2090 for both RCP 4.5 (left) and RCP 8.5 (right) at the two weather stations used in the Lower Truckee Precipitation Runoff Modeling System model.¹⁹

¹⁹ Color indicates the CDF window length used during bias correction. TMAX = maximum temperatures; TMIN = minimum temperatures; and Prcp = precipitation.

4.2.2 LOCA Historical and Projected Climate, Snowpack, and Runoff

To generate the simulated GCM historical and projected future streamflow time series, the LOCA-CMIP5 downscaled climate data were first bias-corrected to individual weather station data and then used as PRMS input to generate streamflow projections. Depending on the location of the weather station within the gridded climate data, a 6 km by 6 km grid cell (figure 1), temperature and precipitation were adjusted to better represent the climate trends at each station. For example, figure 18 shows the bias-corrected, raw, and observed total annual precipitation, average annual maximum temperature, and average annual minimum temperature for the Mount Rose SNOTEL station (19k07s) and the ACCESS1-0 GCM historical trace from WY 1981 through WY 2005. The station temperatures are lower than the projected temperatures for the overlying grid cell, and thus, bias correction lowers the projected temperatures. This is because the 19k07s weather station is above 2,600 meters at the summit of Mount Rose, and the surrounding topography is much lower in elevation and warmer in temperature. Observed precipitation for this station is also slightly higher than the projected precipitation during this period, and thus, the bias correction increases the projected precipitation to be more in line with observed precipitation while still maintaining the projected temporal trends.

While interannual precipitation amounts are highly variable, there are minimal changes in average annual precipitation projected throughout the next century. Figure 19 shows the bias-corrected GCM historical and projected future annual hydroclimate indicators for the Martis Creek Basin, with similar trends found in the other basins (appendix A contains similar figures for all other sub-basins). Table 10 and table 11 show the projected change between a 30-year historical period (WY 1976 through WY 2005, which is the most recent 30-year period available in the GCM historical simulations for the LOCA-CMIP5 ensemble of models) and a 30-year far future period (WY 2061 through WY 2090) for annual and seasonal values, respectively. Table 10 does show annual increases in precipitation between the historical period (WY 1976 through WY 2005) and the far future 30-year period (WY 2061 through WY 2090); however, this is primarily due to the 30-year historical period encompassing a long dry period in the area. Implications of method choices, such as the historical period for evaluating projected changes due to climate change, are important to make transparent. In this case, the most recent 30-year historical period was chosen for analysis despite the state of natural variability that existed during that time. Seasonal precipitation is projected to increase the most during the winter months, with small decreases projected during the spring and summer months (table 11).

Annual mean temperature is projected to substantially increase by the end of the century, regardless of future emission scenarios (figure 19). At the Independence Camp SNOTEL station, for instance (refer to table 2 for Station ID 539 and figure 1 for location), the median change in average annual maximum temperature is 5.6 °F for RCP 4.5 scenarios and 8.7 °F for RCP 8.5 scenarios (table 10) compared with the GCM historical period. Other stations show similar changes in annual average temperatures by the 2070s, with projected changes in 30-year average annual maximum temperatures increasing anywhere from 4.3 °F to 9.4 °F by the 2070s (appendix A). Seasonal changes in temperature are fairly consistent across all seasons (table 11), although increases in temperatures are projected to be largest in summer and fall.

In response to increasing temperatures, snow-water equivalent on April 1, which is based on PRMS simulations driven by LOCA-CMIP5 projections, is projected to decrease consistently throughout the remainder of the century (figure 19). In addition, while annual runoff (also generated by PRMS simulations) appears to slightly increase throughout the remainder of the 21st century, seasonal trends in runoff shift with more runoff occurring in the winter months (January–March) and less occurring in the spring and early summer months (April–July) (figure 19). Currently, the OCAP calculates storage targets for Lahontan Reservoir and allowable diversions through Truckee Canal partial based on the April through July Carson River forecast, and a decrease in these flows has implications for Project operations and OCAP performance, as discussed in Section 4.5 Water Planning Modeling.

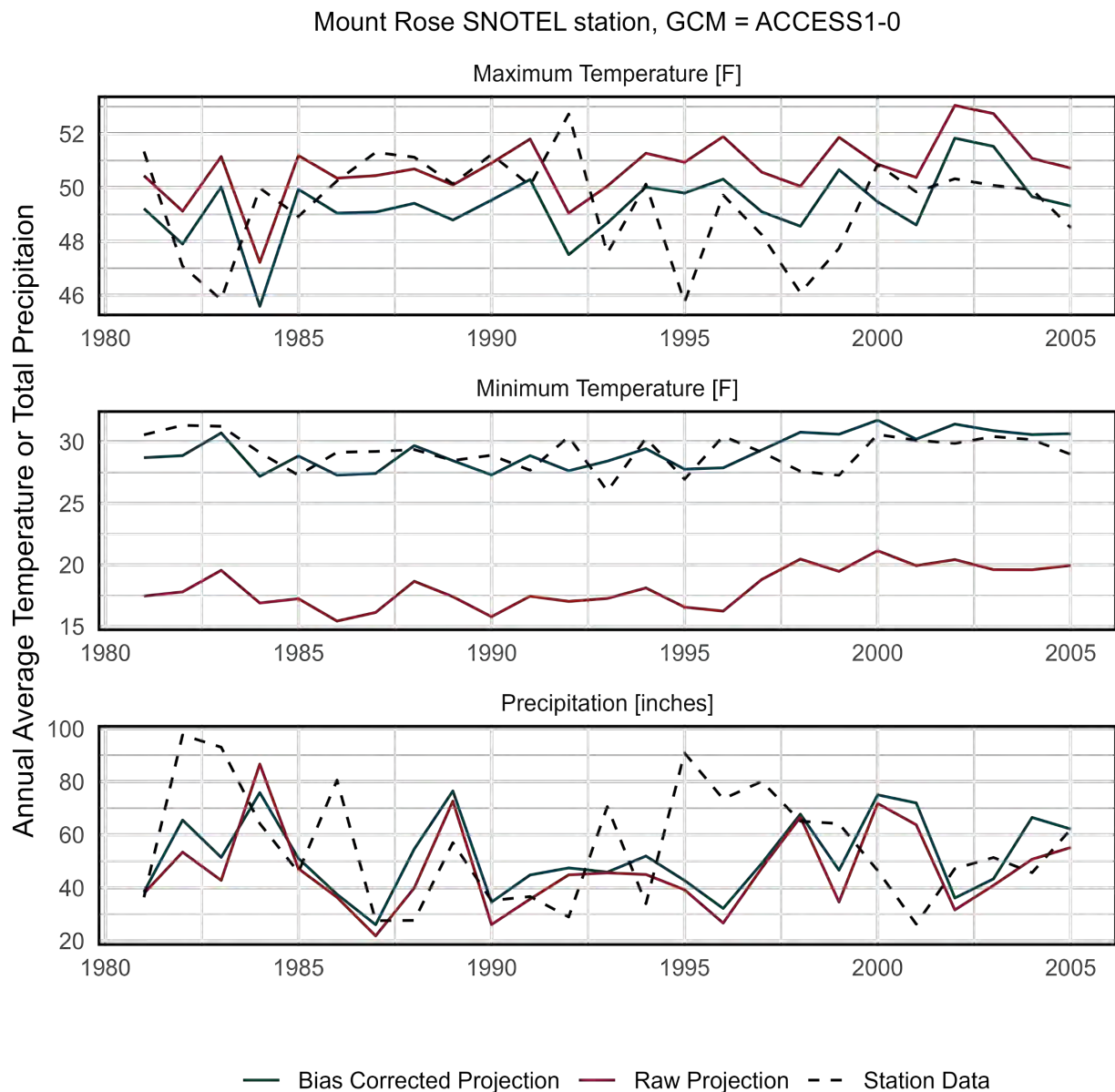


Figure 18.—Water year time series of bias-corrected (blue solid line) and uncorrected (red solid line) maximum temperature (°F; top row), minimum temperature (°F; middle row), and precipitation (inches; bottom row) projection data from the general circulation model ACCESS1-0.²⁰

²⁰ Observed data from the Mount Rose SNOTEL station (used in both the Lake Tahoe and Martis Creek PRMS models) is shown by the dashed black line.

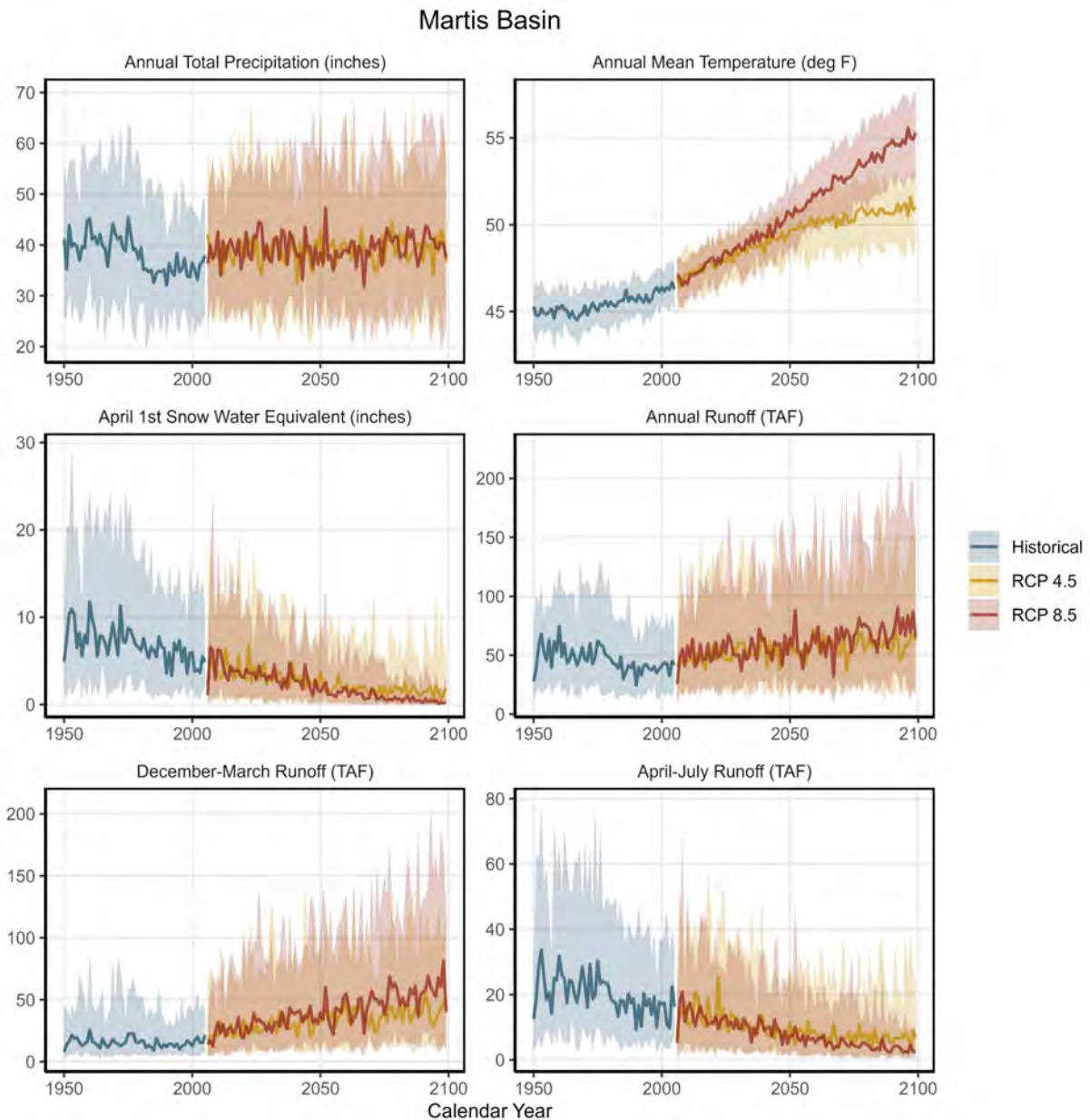


Figure 19.—Time series of basin-averaged, bias-corrected, historical general circulation model (blue) and projected general circulation model (yellow = RCP 4.5 and red = RCP 8.5) hydroclimate indicators for the Martis Creek Basin.²¹

²¹ Dark colored lines indicate the respective ensemble median value, while shading indicates the 10th and 90th percentile ensemble values. It should be noted that the visual gap in the data in the transition from recent historical period to projected future is only an artifact of the visualization and does not indicate a gap in the data itself.

Table 10.—Projected changes in 30-year medians between the bias-corrected historical and projected future general circulation models output at each weather station location*

Station**	Projected Change in 30-year Median Values (WY 2061 and WY 2090) minus (WY 1976–WY 2005)					
	RCP 4.5			RCP 8.5		
	Precipitation (inches)	Maximum Temperature (°F)	Minimum Temperature (°F)	Precipitation (inches)	Maximum Temperature (°F)	Minimum Temperature (°F)
Blue Lakes	4.8	6.1	5.6	4.5	9.4	8.6
Spratt Creek	4.7	6.1	5.4	4.4	9.4	8.5
Independence Camp	3.0	5.6	5.0	3.4	8.7	7.8
Independence Lake	4.5	5.2	4.7	4.8	8.2	7.4
Truckee No. 2	2.7	4.7	4.3	3.8	7.6	6.9
Palisades Tahoe	0.8	-	-	1.3	-	-
Mount Rose	5.7	5.6	5.3	7.3	8.9	8.2
Fallen Leaf	4.7	-	-	4.4	-	-
Marlette Lake	3.8	-	-	3.8	-	-
USC00048758	-	4.7	4.3	-	7.3	6.7
USC00263205	3.1	-	-	3.0	-	-
Hagans Meadow	3.6	-	-	2.5	-	-
Heavenly Valley	3.8	-	-	3.3	-	-
Ward Creek No. 3	4.8	-	-	5.9	-	-
Tahoe City Cross	3.7	-	-	3.8	-	-
Rubicon No. 2	3.9	-	-	4.4	-	-
Echo Peak	5.6	-	-	3.8	-	-

* Color indicates magnitude of future change, with darker orange indicating larger temperature increases and darker blue indicating larger precipitation increases.

** Changes are only shown for the stations that are used in PRMS for that respective variable.

Table 11.—The projected change in 30-year medians between the bias-corrected historical and projected future general circulation models output at each weather station location, including seasonal precipitation, maximum temperature, and minimum temperature for both RCPs 4.5 and 8.5 at each Precipitation Runoff Modeling System station*

Variable	Station**	Projected Seasonal Changes in the 30-year Median Climate (WY 2061 and WY 2090) minus (WY 1976–WY 2005)							
		RCP 4.5				RCP 8.5			
		Oct.–Dec.	Jan.–Mar.	Apr.–Jun.	Jul.–Sep.	Oct.–Dec.	Jan.–Mar.	Apr.–Jun.	Jul.–Sep.
Maximum temperature (°F)	Blue Lakes	6.5	5.1	6.4	6.7	10.0	7.7	9.4	10.5
	Spratt Creek	6.3	5.5	6.0	6.8	9.8	8.2	8.8	10.5
	Independence Camp	5.6	4.8	5.2	7.1	8.9	7.3	7.8	10.6
	Independence Lake	5.2	4.6	4.8	6.3	8.5	6.9	7.5	9.4
	Truckee No. 2	4.6	4.4	4.5	6.0	7.4	6.5	6.9	9.2
	Mount Rose	5.9	5.6	5.1	6.4	9.3	7.9	7.8	9.8
	USC00048758	4.5	4.1	5.0	5.3	7.4	6.0	7.6	8.2
Minimum temperature (°F)	Blue Lakes	5.8	4.6	4.9	6.9	9.1	7.4	7.4	10.4
	Spratt Creek	5.6	4.8	4.2	6.8	8.9	7.9	6.3	10.6
	Independence Camp	4.7	4.6	3.8	6.8	7.6	7.1	5.7	10.7
	Independence Lake	4.6	4.4	3.7	6.1	7.4	6.8	5.5	9.8
	Truckee No. 2	4.0	4.1	3.4	5.7	6.6	6.4	5.2	9.2
	Mount Rose	5.1	5.2	4.2	6.2	8.5	7.9	6.2	9.8
	USC00048758	4.1	4.0	4.0	5.1	6.7	5.8	6.0	8.3
Precipitation (inches)	Blue Lakes	0.8	2.5	-0.1	0.4	0.1	2.7	-0.5	0.4
	Spratt Creek	0.9	2.1	0.2	0.5	0.4	2.6	-0.2	0.4
	Independence Camp	0.2	1.8	0.0	0.4	-0.1	2.1	-0.1	0.4
	Independence Lake	0.1	2.5	0.0	0.4	-0.1	2.9	-0.3	0.4
	Truckee No. 2	0.3	1.9	0.1	0.3	0.0	2.5	0.1	0.3
	Palisades Tahoe	-1.0	0.6	-1.1	0.4	-2.1	1.6	-1.5	0.4
	Mount Rose	0.5	3.5	0.0	0.3	-0.2	4.5	-0.1	0.3
	Fallen Leaf	1.2	2.2	0.0	0.4	0.5	2.2	-0.3	0.3

Variable	Station**	Projected Seasonal Changes in the 30-year Median Climate (WY 2061 and WY 2090) minus (WY 1976–WY 2005)							
		RCP 4.5				RCP 8.5			
		Oct.–Dec.	Jan.–Mar.	Apr.–Jun.	Jul.–Sep.	Oct.–Dec.	Jan.–Mar.	Apr.–Jun.	Jul.–Sep.
	Marlette Lake	0.5	2.0	0.0	0.4	0.1	2.5	-0.3	0.4
	USC00263205	0.4	1.1	0.1	0.3	0.1	1.6	0.1	0.2
	Hagans Meadow	0.7	1.6	0.0	0.5	0.4	1.8	-0.4	0.3
	Heavenly Valley	0.7	2.0	0.1	0.4	0.3	2.1	-0.4	0.4
	Ward Creek No. 3	0.6	3.3	-0.1	0.4	-0.4	3.7	-0.2	0.4
	Tahoe City Cross	0.3	1.8	0.0	0.5	-0.2	2.1	-0.1	0.5
	Rubicon No. 2	0.6	1.8	-0.1	0.6	-0.1	2.4	-0.5	0.5
	Echo Peak	1.0	3.4	0.0	0.7	-0.3	3.4	-0.6	0.6

* Color indicates magnitude of future change with darker blue indicating larger precipitation increases, darker red indicating larger precipitation decreases, and darker orange indicating larger temperature increases.

** Changes are only shown for the stations that are used in PRMS for that respective variable.

4.3 Historical and Projected Streamflow

Projected daily streamflow at the TROA Planning Model streamflow locations (figure 1) was output from the respective PRMS model for each of the 64 LOCA-CMIP5 projections. The East Fork and West Fork Carson River streamflow were used to generate a regression for streamflow at the Fort Churchill gage upstream of the Lahontan Reservoir, as described in section 3.8.

4.3.1 Precipitation Runoff Modeling System (PRMS) Model Validation

It is important to understand how well PRMS output compares with the TROA Planning Model dataset at each location. Table 12 shows the PRMS model error statistics as compared to the TROA Planning Model, and figure 20 shows annual streamflow at each location from the TROA Planning Model dataset compared to the PRMS simulated historical streamflow. The validation period encompasses January 1986 to December 2015, because this is the common period between the PRMS historical simulations and the TROA Planning Model dataset that incorporates the most updated and consistent methods (PWRE 2022). Annual trends between the TROA Planning Model streamflow and PRMS streamflow are similar across all locations, and the PRMS simulations represent hydrology in these basins well. Some of the larger discrepancies occur in the simulation of inflows into Lake Tahoe. The annual simulated Lake Tahoe inflow is consistently greater than the reconstructed naturalized inflow, thereby justifying application of a quantile-mapping bias correction at an annual timestep.

4.3.2 Historical and Projected Streamflow

Annual streamflow simulations based on historical climate station observations, GCM-historical climate, and LOCA-CMIP5 projected future climate are shown on figure 21. Long-term trends in annual streamflow are not apparent at all locations. **Like the GCM projections of annual precipitation patterns, the annual streamflow projections exhibit high interannual variability**, visualized in the shaded portions of figure 21. Historically, annual streamflow has also varied substantially at each of these locations within the Truckee River Basin (black line on figure 21) in response to annual precipitation patterns.

Seasonal patterns in projected streamflow show increased streamflow in winter and fall by the end of the century, while spring and summer flows are projected to decrease. Figure 22 shows a time series of seasonal streamflow from 1950 through the end of this century at Prosser Reservoir, where inflows are projected to decrease by 39 percent (RCP 4.5) to 44 percent (RCP 8.5) in April, May, and June by the 2070s (table 13). Conversely, inflows into Prosser Reservoir are projected to increase by up to 39 percent in October, November, and December and by up to 36 percent in January, February, and March by the 2070s (table 13).

Projections indicate a shift in seasonal streamflow on a monthly timescale, with earlier peak runoff at several modeled locations (figure 23). These trends are likely due to increased precipitation events during the fall and winter months as opposed to snow events, which leads to

a lower maximum snowpack (figure 19) and a smaller runoff peak in the spring and summer months. Further, for many of the basins, projected mean monthly streamflow patterns show a more gradual hydrograph (e.g., Independence Lake or Stampede Reservoir; figure 23 blue and gold lines) than the historical hydrograph (figure 23 black line).

Table 12.—Quantitative statistics comparing the raw Precipitation Runoff Modeling System streamflow to the Truckee River Operating Agreement planning model streamflow on a daily, monthly, and annual scale from 1986–2015

Location	Daily			Monthly			Annual		
	Percent Bias (%)*	NSE (-)	RMSE** (AF)	Percent Bias (%)	NSE (-)	RMSE (AF)	Percent Bias (%)	NSE (-)	RMSE (AF)
Independence Lake inflow	-1.3	0.51	47	-1.3	0.79	750	-1.3	0.91	2285
Sidewater	-5.5	0.35	194	-5.5	0.57	3598	-5.5	0.73	18598
Stampede Reservoir inflow	-18.7	0.58	318	-18.7	0.76	5683	-18.7	0.82	24548
Boca Reservoir inflow	-11	0.57	74	-11	0.74	1122	-11	0.77	5711
Donner Lake inflow	-7.3	0.34	112	-7.3	0.74	1500	-7.3	0.89	4326
Donner Creek at Highway 89	-4.5	0.22	98	-4.5	0.65	1717	-4.5	0.89	4282
Truckee River near Truckee	-0.7	0.25	242	-0.7	0.73	3681	-0.7	0.95	7338
Prosser Reservoir inflow	-2	0.38	201	-2	0.78	2873	-2	0.93	8468
Martis Creek Lake inflow	2.1	0.49	67	2.1	0.80	821	2.1	0.91	3313
Lake Tahoe inflow – NOT bias corrected	68.1	0.09	2474	68.1	0.62	20258	68.1	0.12	150285
Lake Tahoe inflow – bias corrected	0.0	0.14	2399	0.0	0.73	17054	0.0	0.95	37266

* Percent Bias = $100 * [\text{sum}(\text{PRMS} - \text{TROA}) / \text{sum}(\text{TROA})]$

** RMSE = root mean square error

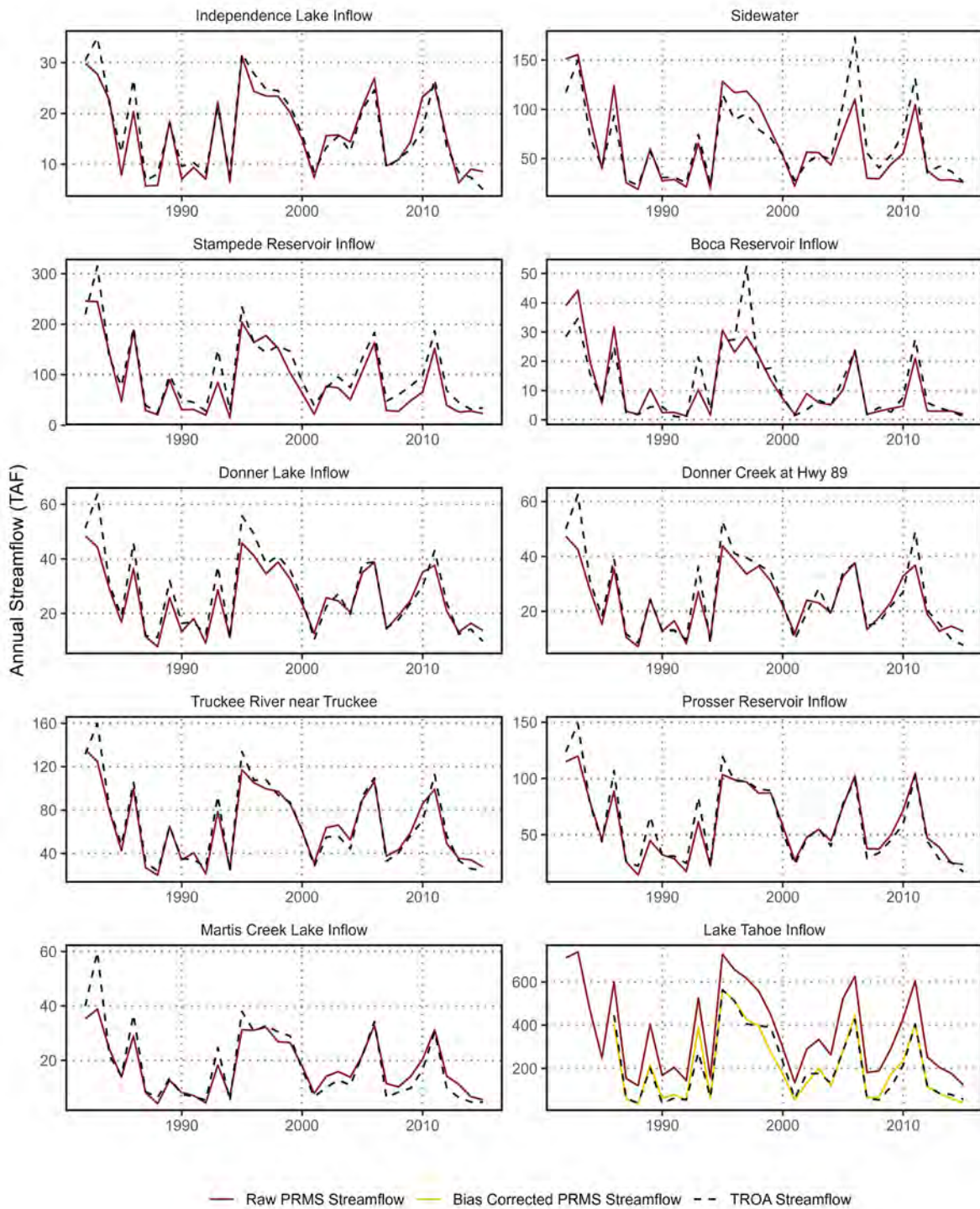


Figure 20.—Time series of annual streamflow at each location (TAF = thousand acre-feet).

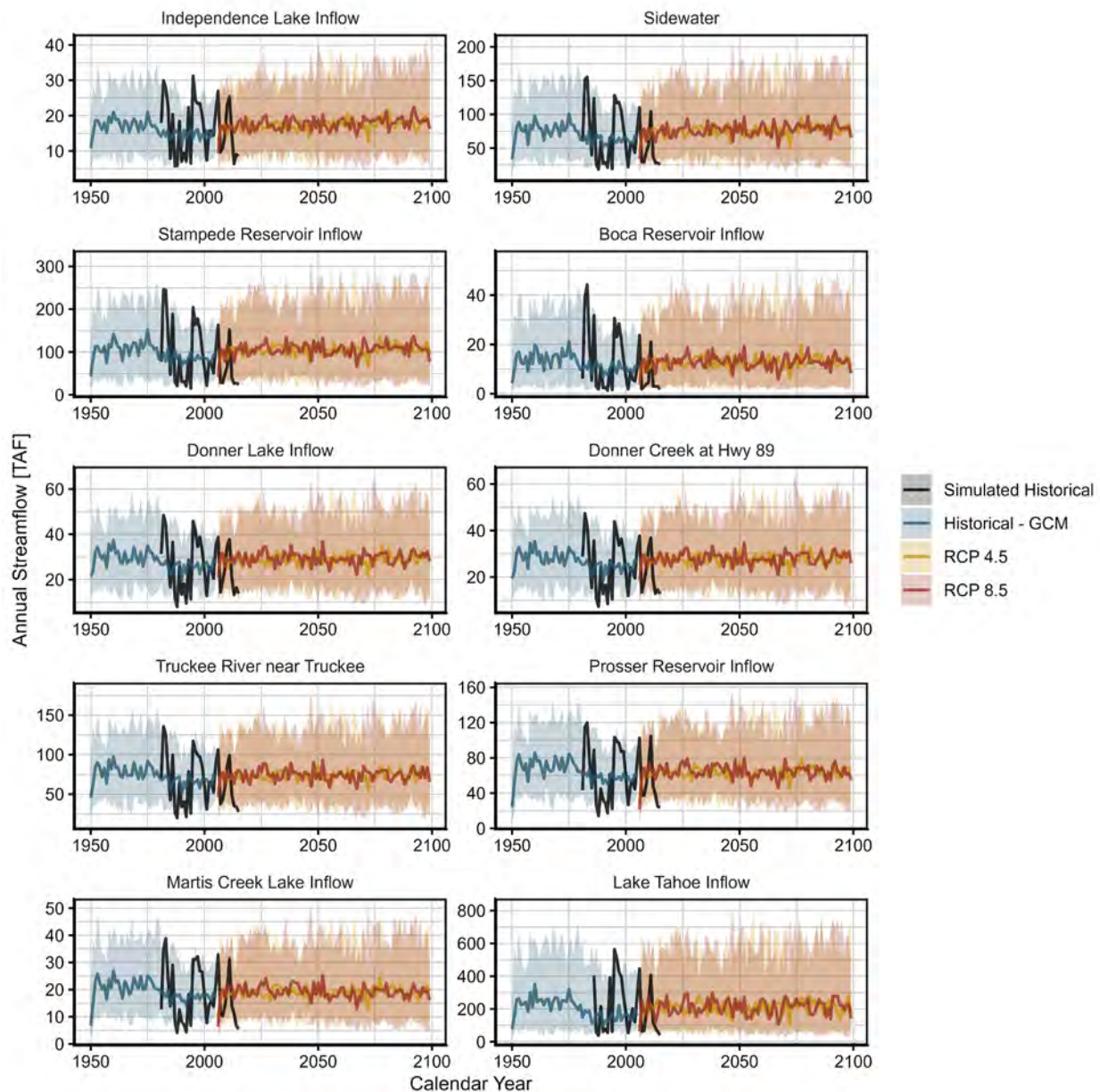


Figure 21.—Time series of general circulation model historical (blue) and LOCA-CMIP5 projected future (yellow = RCP 4.5 and red = RCP 8.5) annual streamflow compared to the Precipitation Runoff Modeling System simulated historical streamflow (black).²²

²² Dark colored lines indicate the respective ensemble median value, while shading indicates the 5th and 95th percentile ensemble values. TAF = thousand acre-feet.

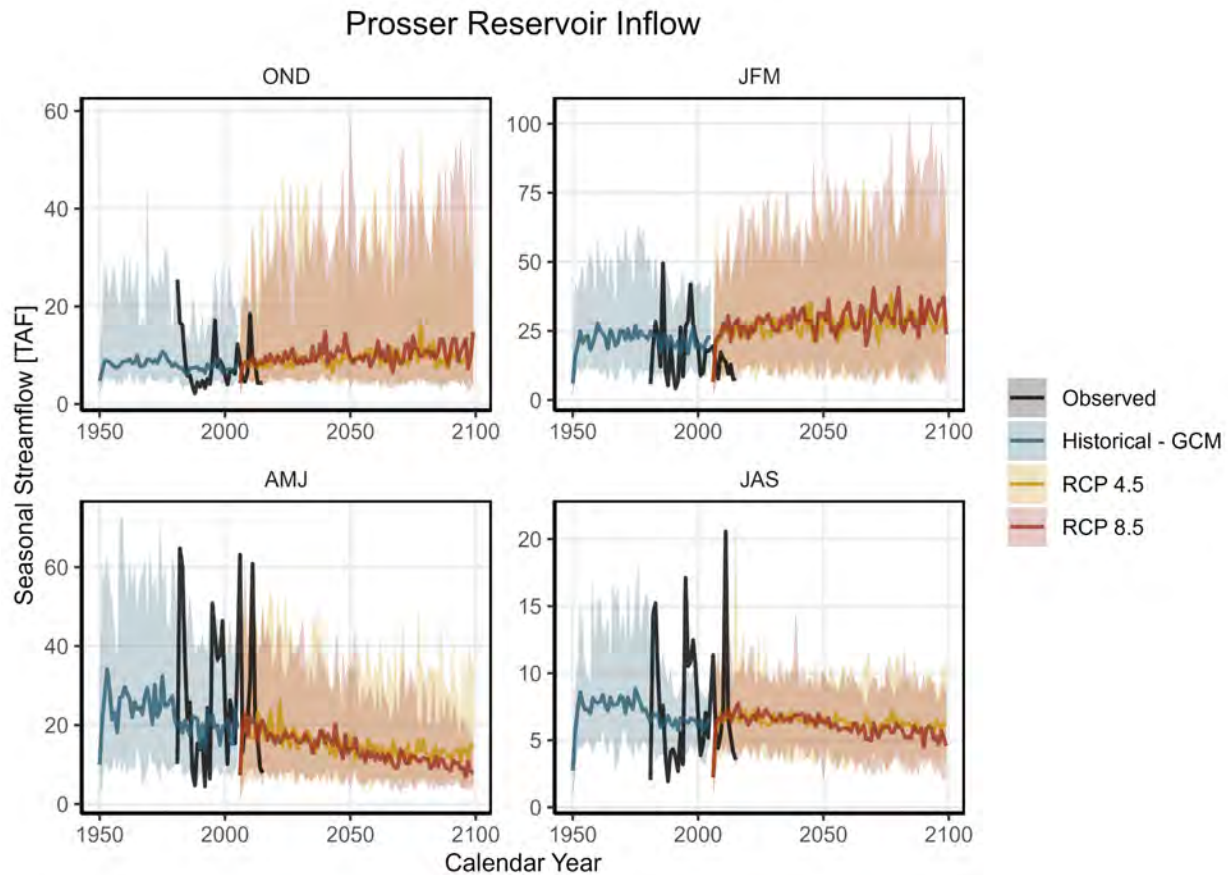


Figure 22.—Time series of general circulation model historical (blue) and LOCA-CMIP5 projected future (yellow = RCP 4.5 and red = RCP 8.5) seasonal streamflow into Prosser Reservoir compared to the Precipitation Runoff Modeling System simulated historical streamflow (black).²³

²³ Dark colored lines indicate the respective ensemble median value, while shading indicates the 5th and 95th percentile ensemble values. TAF = thousand acre-feet. OND = October, November, and December; JFM = January, February, and March; AMJ = April, May, and June; JAS = July, August, and September.

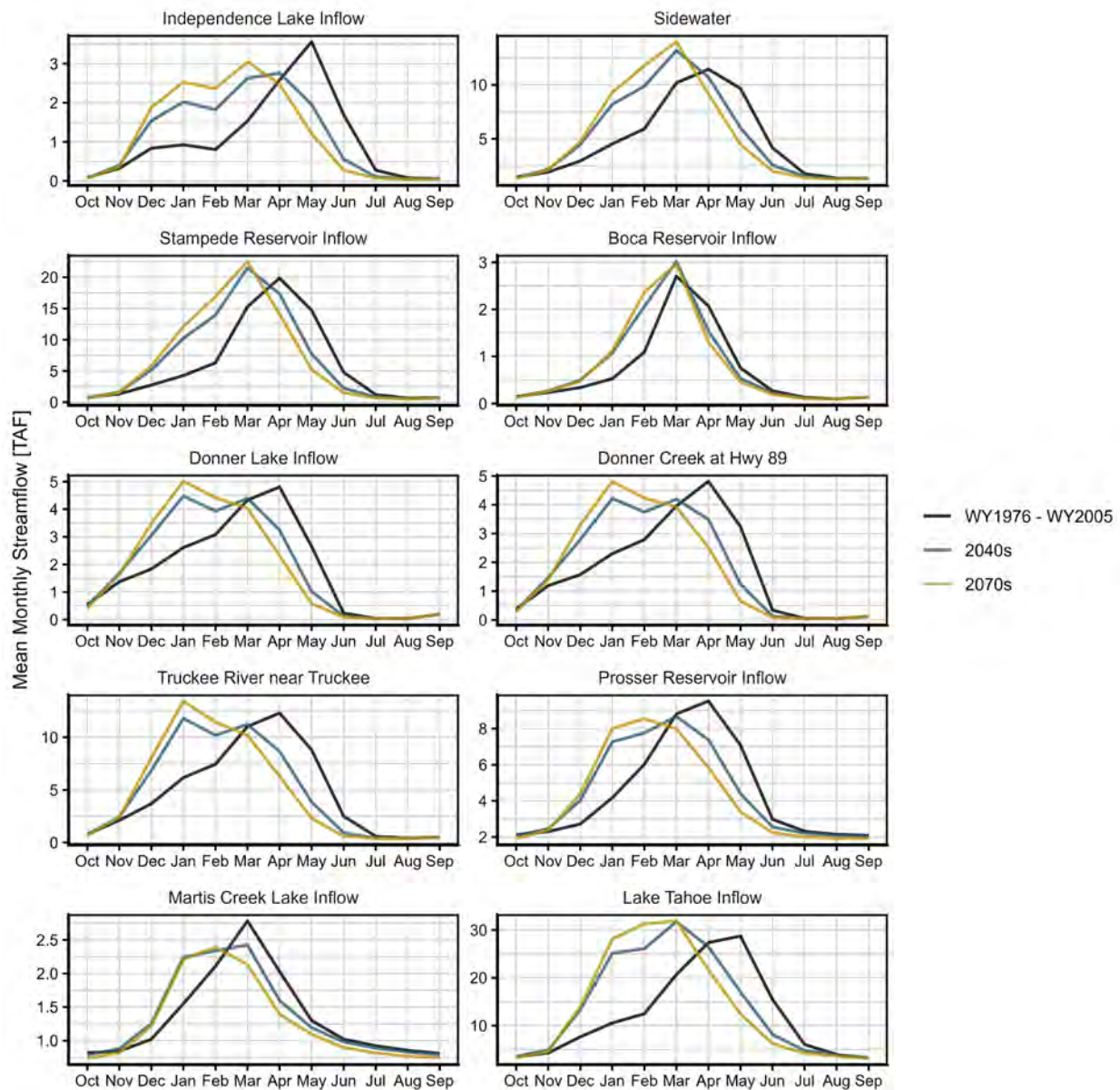


Figure 23.—Time series of 30-year Precipitation Runoff Modeling System simulated mean monthly streamflow at each location, including historical and LOCA-CMIP5 future projections.²⁴

²⁴ The black line represents the PRMS simulated historical period (WY 1976 through WY 2005), the blue line represents the near future period (WY 2031 through WY 2060), and the gold line represents the far future period (WY 2061 through WY 2090). TAF = thousand acre-feet. NOTE: Boca Reservoir Inflow represents the local inflow portion of the lake and excludes releases from upstream Stampede Reservoir.

Table 13.—Projected change in the 30-year median seasonal streamflow between the historical period (WY 1976–WY 2005) and the far future period (WY 2061–WY 2090)*

Location**	Projected Change (%) in 30-year Median Seasonal Streamflows (WY 2061 and WY 2090) minus (WY 1976–WY 2005)							
	RCP 4.5				RCP 8.5			
	OND***	JFM	AMJ	JAS	OND	JFM	AMJ	JAS
Donner Creek at Highway 89	64.7	45.8	-58.2	9.3	77.1	57.2	-69.9	-6.8
Truckee River near Truckee	74.4	44.8	-54.8	-13.0	103.4	54.3	-70.7	-18.1
Boca Reservoir inflow	30.9	58.0	-32.0	2.9	21.7	48.4	-36.8	-9.4
Donner Lake inflow	54.9	40.7	-56.6	23.7	62.2	46.4	-64.2	3.1
Independence Lake inflow	86.8	120.1	-45.5	-50.0	92.2	177.5	-60.0	-61.0
Martis Creek Lake inflow	5.1	12.5	-13.8	-6.2	6.4	12.2	-24.9	-12.4
Prosser Reservoir inflow	28.5	36.0	-39.0	-5.4	39.3	34.8	-44.3	-12.6
Sidewater	35.9	70.2	-35.4	-5.4	34.2	79.5	-46.6	-10.0
Stampede Reservoir inflow	77.2	118.0	-42.7	-17.9	59.5	129.1	-56.8	-29.0
Lake Tahoe inflow	56.1	123.8	-35.7	-5.8	44.3	103.2	-47.9	-19.1
Fort Churchill Streamflows	24.1	86.9	-16.1	-6.3	19.6	130.4	-31.8	-9.8

* Comparisons are between the median of the 64 LOCA-CMIP5 projected streamflow and the median of the 32 GCM historical streamflow. Color represents the magnitude of change, with blue indicating an increase in flows and orange indicating a decrease in flows. The darker the color, the larger the magnitude of change.

** Fort Churchill streamflow is regressed, and the results are described below.

*** OND = October, November, and December; JFM = January, February, and March; AMJ = April, May, and June; JAS = July, August, and September.

Projected streamflow at Fort Churchill was generated using the LOESS model for LOCA-CMIP5 historical and future streamflow projections generated by the PRMS Carson River hydrology models. Figure 24 summarizes the historical and future traces and historical observations. Future traces are represented in green, with shaded regions encompassing the 25–75 percent range of all ensembles, including RCP 4.5 and RCP 8.5 (medium green), the 5–95 percent range of all ensembles (light green), and the median (50th percentile) across ensembles in dark green.

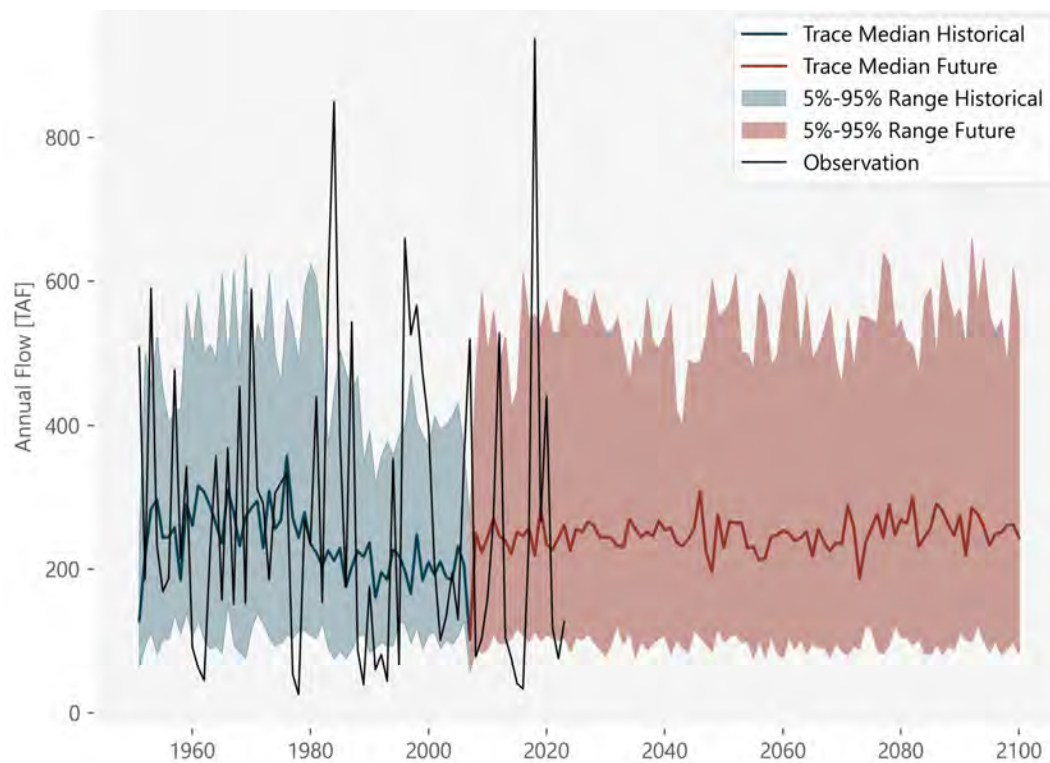


Figure 24.—Simulated Fort Churchill streamflow for historical and future climate scenarios for the period 1950–2099.

Figure 25 shows median monthly Carson River near Fort Churchill streamflow, with the median computed across all future projections, including RCP 4.5 and RCP 8.5. The timing of peak streamflow shifts earlier, with both 2040s and 2070s peak streamflow arriving in April as opposed to May for the historical period. Winter period streamflow increases under future climate scenarios, and late spring and early summer streamflow significantly decreases.

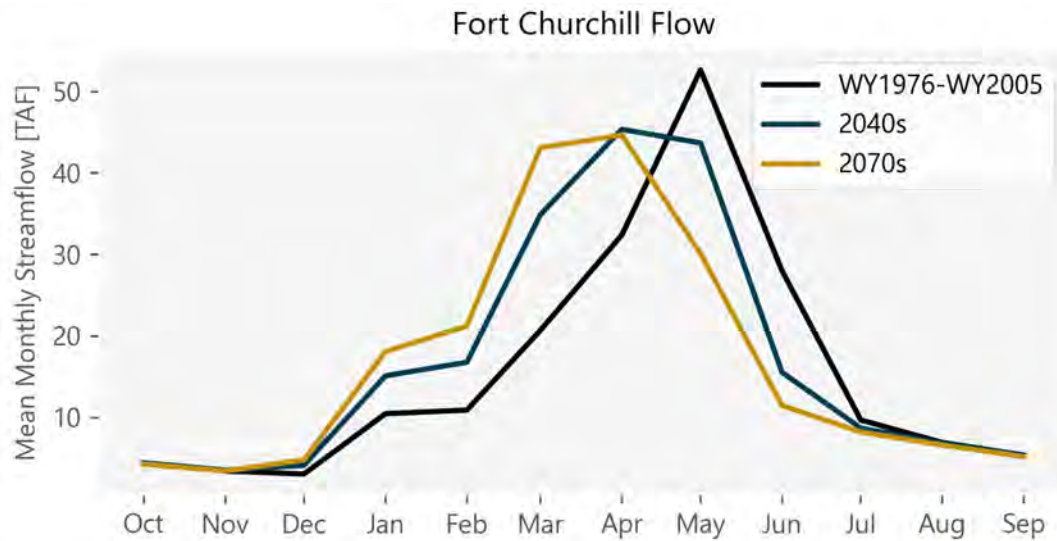


Figure 25.—Median monthly Fort Churchill flows by period.

4.4 Lake Tahoe Evaporation

Monthly evaporation from Lake Tahoe was estimated using CRLE for the PRMS model period (October 1980 to December 2015), for each of the historical (1950–2005) and future (2006–2099) LOCA-CMIP5 projections.

Future projections of surface water evaporation from Lake Tahoe indicate an increase in the median annual evaporation rate of approximately 0.2 feet per year (RCP 4.5) to 0.5 feet per year (RCP 8.5) by 2100. Results from the Lake Tahoe evaporation modeling are shown on figure 26. Historically, evaporation from Lake Tahoe exhibited a considerable amount of interannual variability (shown in the black line on figure 26), with evaporation from the lake ranging from approximately 2.5 feet per year to 3.1 feet per year.

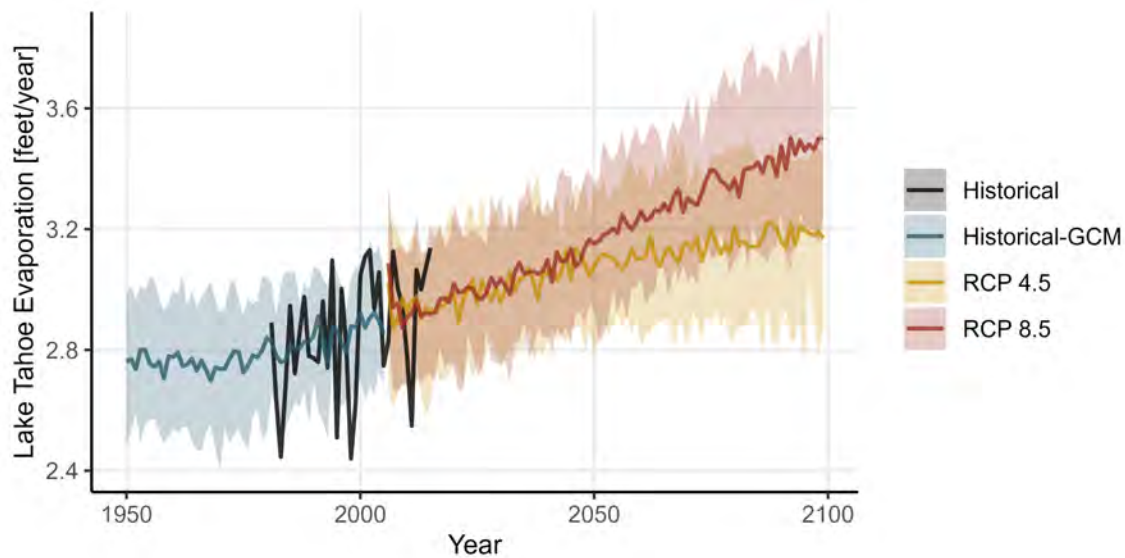


Figure 26.—Lake Tahoe annual evaporation for the 32 general circulation model historical runs (1950–2005), the observed calculated unimpaired historical (1980–2015), and the 64 LOCA-CMIP5 projections (2005–2099) (red = RCP 8.5, and yellow = RCP 4.5).²⁵

4.5 Water Planning Modeling

The PRMS streamflow output, TROA Planning Model historical dataset, and paleo reconstruction datasets were used as inputs to the TROA Planning Model to assess OCAP performance under drought and projected future conditions relative to the historical and paleo-periods. First, the study compared the impact of paleo and historical droughts on Lahontan Reservoir and Lake Tahoe storage elevations and select water supply metrics to identify if paleo droughts were more impactful than those from the observed period (Section 4.5.1 Drought Performance). Secondly, the study calculated and compared the observed historical period and the LOCA-CMIP5 dataset in the near future (2031–2060, 2040s) and the far future (2061–2090, 2070s), based on a set of metrics addressing water supply, environmental flows and conditions, and flood risk (Section 4.5.2 Future LOCA-CMIP5 Performance).

4.5.1 Drought Performance

One of the objectives of the paleo modeling was to identify whether paleo droughts were more impactful than those in the recent historical period. More severe droughts in the paleo-reconstructed period indicate a larger range of natural climate variability than observed historically and under plausible future conditions. Alternatively, more severe droughts in the historical period may indicate drying trends from the paleo-period through modern times.

²⁵ Colored shading indicates the 5th and 95th percentile of the respective ensemble.

The three largest paleo and the two largest historical rule-based drought events based on annual average and cumulative deficit were identified with the rule-based drought definition (table 6 and table 8 for LCD droughts and table 7 and table 9 for LAD droughts for the Carson and Truckee River, respectively) were used to examine whether paleo droughts were more impactful than those from the observed period and from average historical conditions. Drought events identified through the rule-based definition, as opposed to the zero-crossover definition, were selected because they align with existing literature and the common experience of historical drought over this period. The study examined the impact of these droughts on Lahontan Reservoir and Lake Tahoe storage using four similar metrics for each supply source, as described subsequently.

For the Carson Basin, the study examined the Lahontan elevation below the Lahontan Storage Objective Current Month (LSOCM), percent of years with refill to top of active storage, percent of capacity at the end of water year, and percent of days below conservation pool, described subsequently, during the historical and future period.

An important water supply metric for the Lahontan Reservoir is whether the LSOCM is met each month. This is particularly important at the end of June, when storage is at its highest to meet irrigation demands. This objective is met when the Lahontan Reservoir elevation (solid black line on figure 27) exceeds the LSOCM (dashed blue line on figure 27). **During the drought periods, Lahontan Reservoir storage is consistently, with a few exceptions, below the LSOCM, indicating that storage objectives are not met throughout the WY during the most severe droughts.**

The paleo-period LCD droughts identified on the Carson River are significantly longer than the historical droughts. All three of the paleo-period LCD droughts are longer than the longest historical LCD drought (2007 to 2016, 10 years), with the most significant LCD in the paleo-period lasting 32 years from 1569 to 1600. This results in a significantly longer drought period when the Lahontan Reservoir storage is below the LSOCM during the paleo-period relative to the historical droughts.

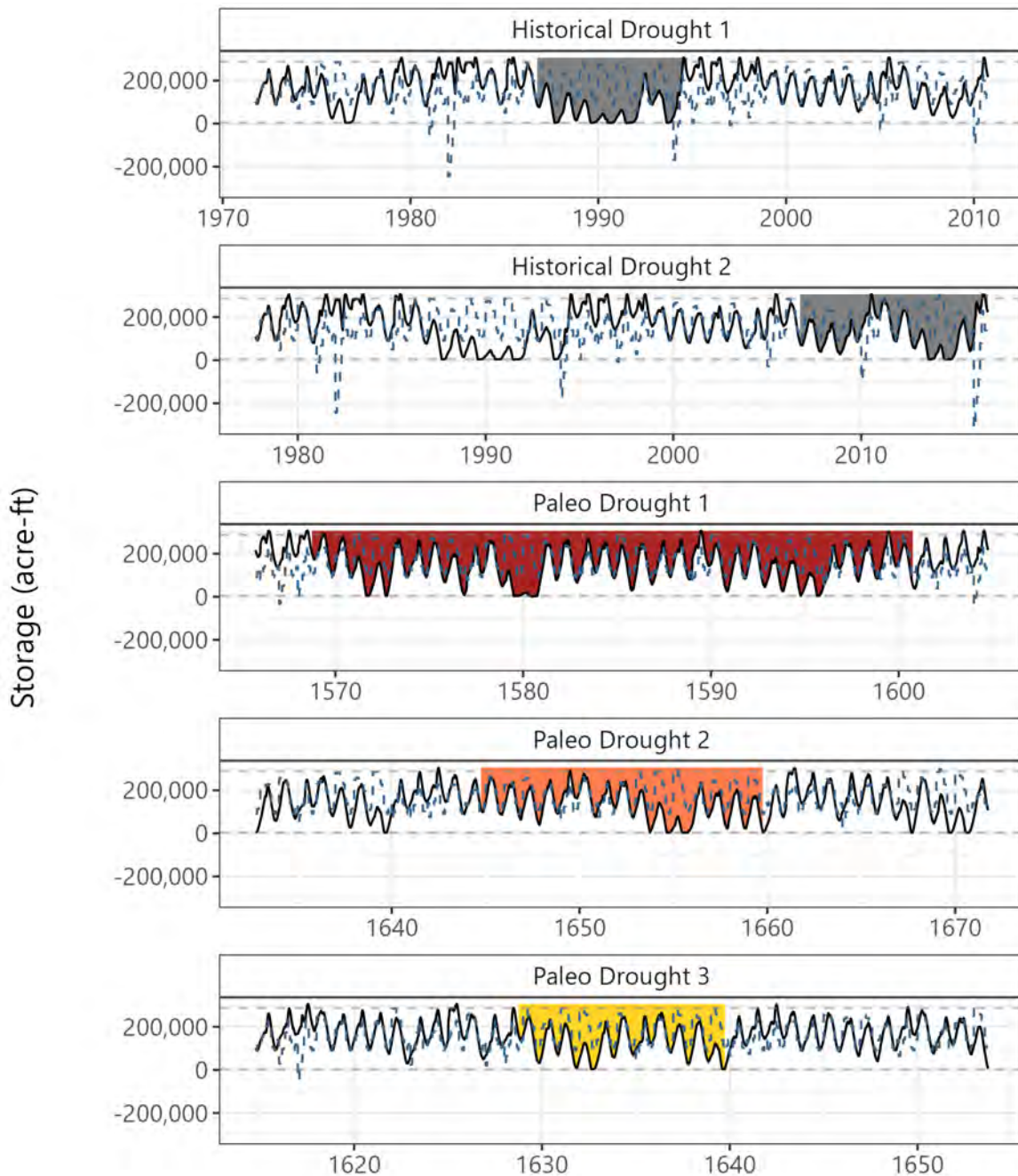


Figure 27.—Daily modeled storage for Lahontan Reservoir for each drought event (panels).²⁶

²⁶ The two LCD droughts in the historical period are presented in gray in the top two panels (table 6). The three LCD rule-based drought events identified on the Carson River. The horizontal lines show the top of active storage (dashed, upper at 286,978 acre-feet) and bottom of conservation pool (dashed, bottom at 4,000 acre-feet) storages. The dark blue dashed line indicates the LSOCM. Drought events are shaded.

The study examines four additional metrics related to Lahontan Reservoir storage during drought (figure 28). April 1 storage provides insight into the water supply around the start of the irrigation season. The LAD droughts have a slightly larger impact on April 1 storage relative to the LCD droughts, decreasing from an average of 199 TAF during the historical period to 116 during the historical LAD drought from 1987 to 1994.

The Lahontan end-of-WY storage (on September 30) is significantly impacted by both historical and paleo-period droughts. The relative impact of paleo versus historical droughts is variable. **The LAD droughts in the paleo and historical period have the most severe impacts on the end-of-WY storage, which decreased from an average of 38 percent capacity over the historical period to 8 percent during the 1843 to 1847 paleo drought.**

Over the historical baseline and paleo-periods, Lahontan Reservoir refill exceeded the top-of-active storage in approximately 25 percent of years. During half of the selected droughts, the Lahontan Reservoir storage never reached the top-of-active storage. In addition to not reaching full capacity, reservoir storage also falls below the conservation storage more frequently during the drought periods, with up to 14 percent of days below the conservation pool level in the 1843 to 1847 paleo-period drought relative to only 2 percent in the historical baseline period.

Overall, the Lahontan metrics are most impacted by the LAD droughts identified in both the paleo and historical periods. The LAD droughts had the most significant impacts on the Lahontan water supply, with the largest decreases in water supply in Lahontan at the end of the WY, more days below the conservation pool, and fewer years with refill to the top of active storage. These results indicate that the Lahontan water supply is most impacted by intense, shorter-duration droughts.

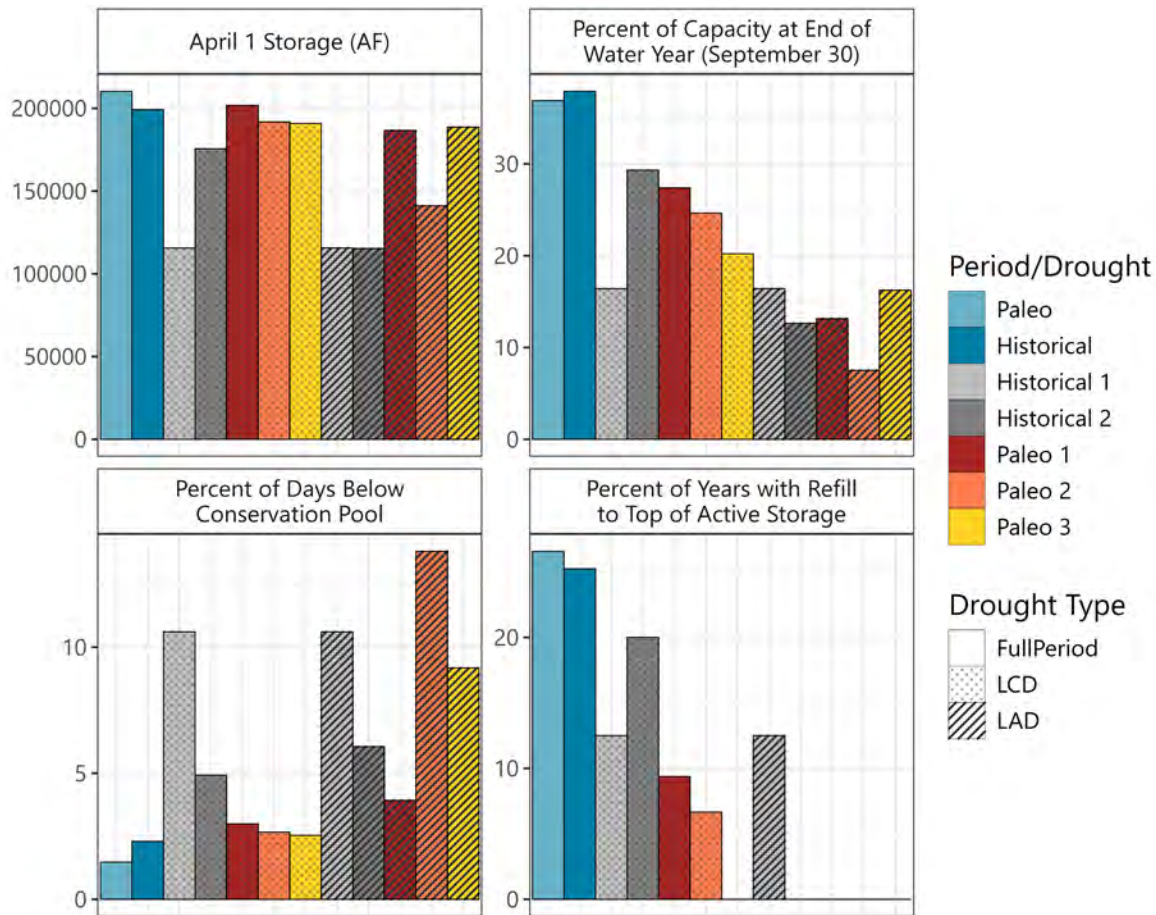


Figure 28.—Operating Criteria and Procedures metrics at Lahontan showing mean distant past paleohydrology and historical period conditions (light blue, blue), historical droughts (gray), and for the top two historical and top three paleohydrology largest annual deficit (stripes, table 7) and largest cumulative deficit (dots, table 6) rule-based paleohydrology drought events identified on the Carson River (red, orange, and yellow).

For the Truckee Basin, the study examined the Lake Tahoe pool elevation compared to the legal filling limit (6229.1 feet) and natural lake rim (6223.0 feet; figure 29), the percent of days the CDD is met, the percent of days exceeding the Truckee River at Reno daily average flow target (5,500 ft³/s), the percent of days Floriston Rates are met, and the average annual number of days Lake Tahoe is below the natural rim of the lake (figure 30).

Lake Tahoe pool elevation declines during all presented drought events to below the natural rim of the lake. Below the natural rim of the lake, streamflow cannot be released, and additional storage losses occur due to lake evaporation. **Lake Tahoe pool elevations are significantly impacted by the LCD paleo-period drought events, which show more rapid and longer declines in Lake Tahoe pool elevations relative to the historical droughts.** This impact was the most severe during the 1651 to 1680 paleo-period drought, where Lake Tahoe pool elevations decreased by more than 37 feet.

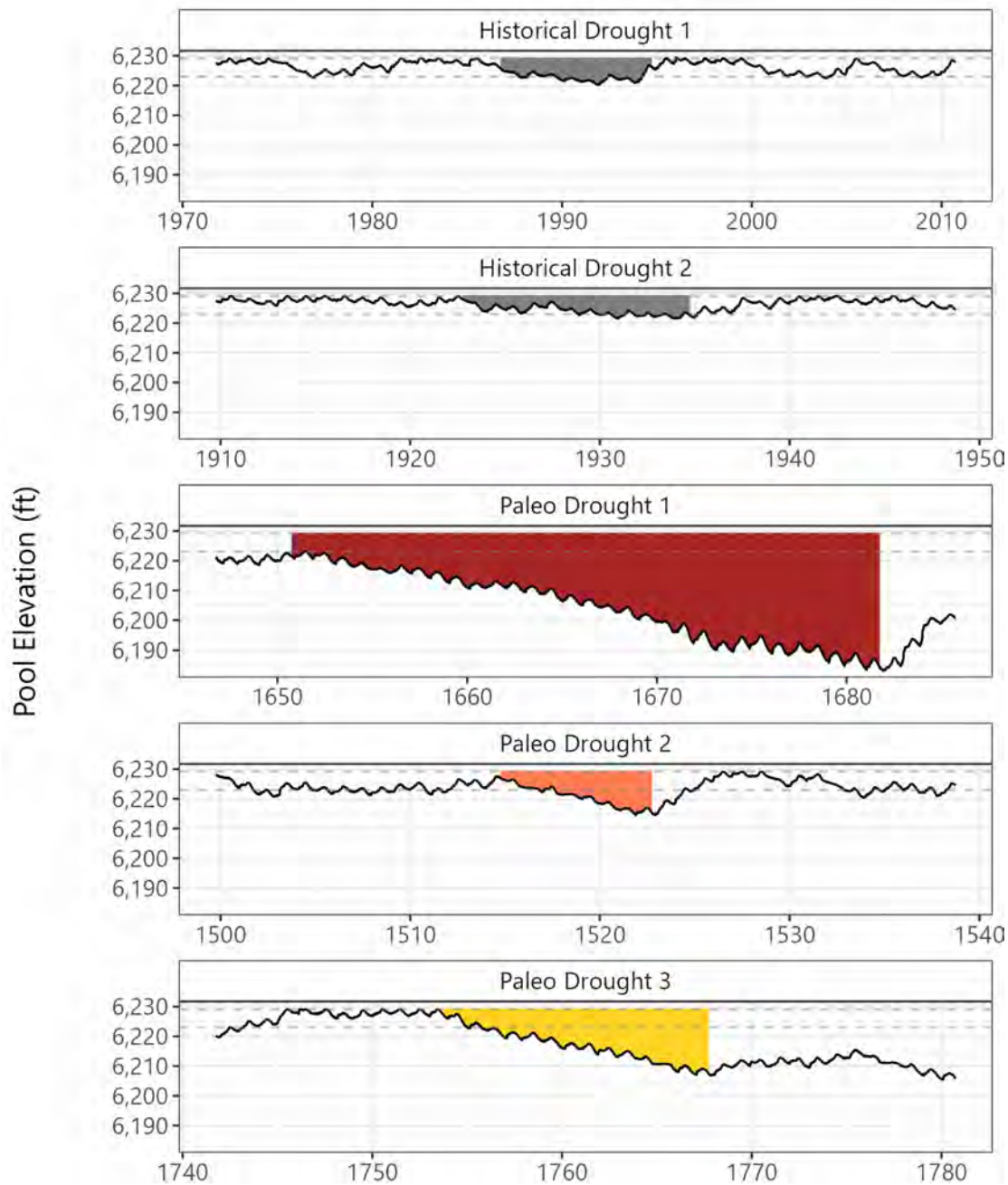


Figure 29.—Daily modeled pool elevation for Lake Tahoe for each drought event (panels).²⁷

²⁷ The two LCD droughts in the historical period are presented in gray in the top two panels (table 9). The three LCD rule-based droughts events identified on the Truckee River for the paleo-period are presented in red, orange, and yellow (table 9). The horizontal lines show the legal filling limit (upper) and natural lake rim (bottom) storages.

The percent of days the CDD is met is high during the baseline historical and paleo-periods, at around 97 and 98 percent on average, respectively. However, the frequency that the CDD demand is met decreases for all historical and paleo droughts, with the most significant decrease occurring in the historical droughts, dropping to 81 percent of days the CDD is met in both the 1928 to 1935 and 1987 to 1994 droughts.

Both paleo and historical period droughts significantly reduce the number of days that Truckee flows at Reno exceed the flow target. For most droughts, the flow target is never exceeded during the drought period, and there is no clear difference between the impacts of the paleo and historical period droughts.

The Floriston Rates are met for 45 and 82 percent of days during paleo and historical baseline periods, respectively (figure 30). Historical period droughts show mostly declines in the percent of days the Floriston Rates are met, with the lowest at 28 percent in the 1987 to 1994 drought. **The Floriston Rates are most impacted during the paleo droughts, relative to the historical droughts, with the largest impacts occurring during highest ranked LCD drought from 1651 to 1681 where the percent of days the Floriston Rates were met fell to just 11 percent.**

Over the baseline historical period, the Lake Tahoe pool elevation falls below the rim for an average of 45 days per year. This value is significantly higher over the paleo-period, 195-day average, indicating that the paleo-period may be significantly drier overall for the Truckee Basin when compared to the historical. **The LCD droughts over the paleo-period have the most significant impact on the average number of days below the Lake Tahoe natural rim, where the 1651 to 1681 paleo drought falls below the rim almost the entire length of the drought.**

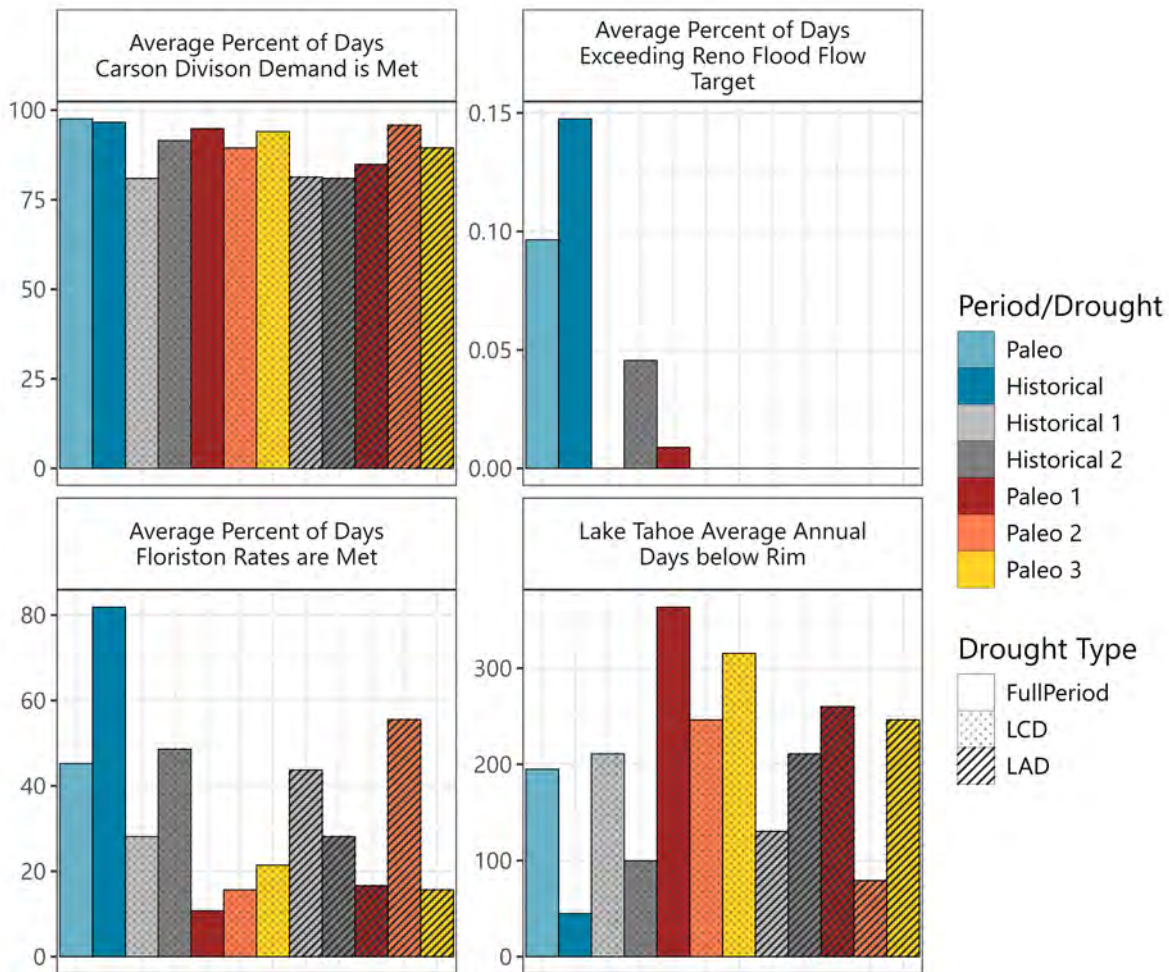


Figure 30.—Basin wide metrics showing mean distant past paleohydrology and historical period conditions (light blue, blue), historical droughts (gray), and for top two historical and top three paleohydrology largest annual deficit (stripes, table 9) and largest cumulative deficit (dots, table 8) rule-based paleohydrology drought events identified on the Truckee River (red, orange, and yellow).

Overall, **metrics related to Lahontan storage are more impacted by the LAD drought events, while metrics involving Lake Tahoe water supply are more impacted by the longer duration paleo-period LCD droughts.** Metrics such as the average percent of days the CDD are met are impacted by water supplies along the Truckee and Carson rivers, resulting in mixed results. Evaluating the impacts of a larger variety of paleo and historical drought conditions is critical to evaluate the vulnerabilities of these more complicated metrics.

4.5.2 Future LOCA-CMIP5 Performance

Results from the TROA Planning Model simulations using the future LOCA-CMIP5 (future scenarios) are evaluated in the following sections using the water resources metrics identified in table 4. Results are presented for the 61 future scenarios, out of a total of 64, that successfully ran through the TROA Planning Model. Future scenarios are grouped into distributions over two periods, the near future (2031–2060, 2040s) and the far future (2061–2090, 2070s) for each emissions scenario (RCP 4.5 and RCP 8.5) and compared to both the recent historical and paleo-periods.

4.5.2.1 Water Supply

Multiple metrics were selected to evaluate water supply (table 4). Results are presented on figure 30 and table 14, with the future scenarios combined into four groups based on emissions scenario and period and presented as distributions. Historical and paleo-period averages are also presented for comparison.

From the near to far future periods for both emissions scenarios, the percent of days Lake Tahoe falls below the rim increases while the percent of years where Lake Tahoe reaches the legal filling limit begins to decline (high emissions) or remains the same (medium emissions), indicating potential declines in water supply. The percent of days Lake Tahoe is below the natural rim decreases from the paleo-period average of over 53 percent to the historical period average of around 12 percent. Future simulations show an increase in the percent of days Lake Tahoe is below the natural rim, compared to the historical period, ranging from 13.1 to 28.5 percent (median values across future scenarios), with the most significant increases in the Far Future RCP 8.5 scenario. The average percent of years Lake Tahoe reaches the filling limit increases from the paleo to the historical period but decreases into the 2040s and 2070s future periods. The paleo-period had a lower percentage of years in which Lake Tahoe reached the filling limit at just 13.5 percent compared to filling 32.5 percent of the years in the historical period. Future periods saw decreases in the average percent of years Lake Tahoe reached the filling limit compared to the historical period, with median values for future simulations ranging from 13.3 percent in the far future, high emissions scenario to 30 percent in the near future, high emissions scenario.

Lake Tahoe pool elevations over the future periods for each emissions scenario are presented on figure 32. **Future Lake Tahoe pool elevations remain similar to the historical period median at the beginning of the future period; however, over time, Lake Tahoe pool elevations decline, with the most significant decreases and largest variability in the higher emissions scenarios.**

The range of future Lake Tahoe pool elevation increases over time in the future scenarios and is most variable in the RCP 8.5 emissions scenarios, with significant differences between the 2031–2060 and 2061–2090 periods and the RCP 4.5 and RCP 8.5 scenarios (figure 32). The 2031–2060 period pool elevations are generally consistent with the historical daily pool elevation distribution, but higher than the paleo-period. The mean pool elevations for both emissions scenarios decline across the entire future period simulation, with more rapid pool elevation declines for the high emissions scenario in the far future period. Average pool elevations in both emissions scenarios remain above the mean elevation in the paleo-period during the 2031–2060 period but fall below in the 2061–2090 period.

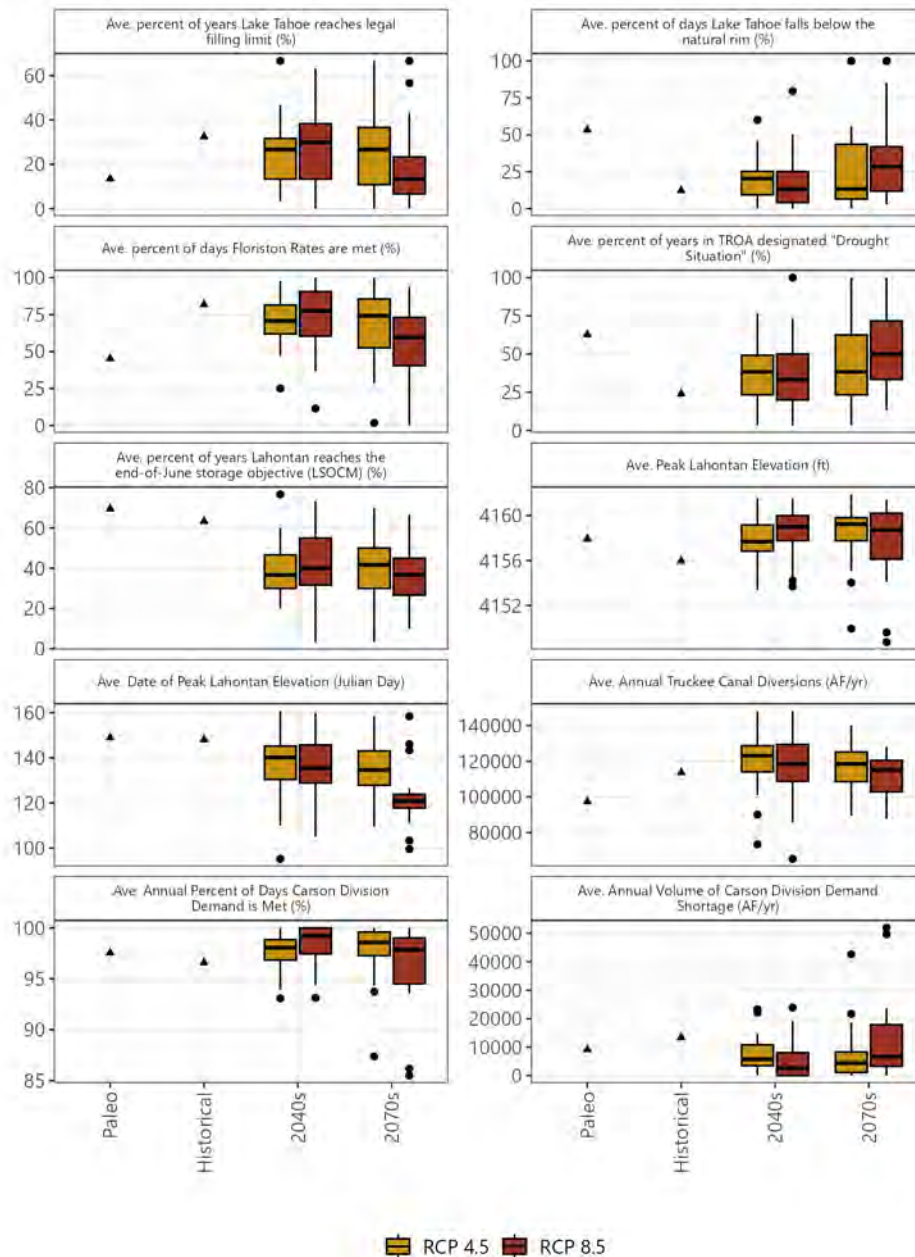


Figure 31.—Water Supply metrics for evaluating basin-wide water supply reliability.²⁸

²⁸ Mean values for each metric over the full paleo (1500–1900) and historical (1901–2017) periods are represented by a single, triangular, point. Future scenarios are shown as box plots demonstrating the range of the values calculated for each simulation, delineated by the near future (2031–2060) and far future (2061–2090) periods and by RCP emissions scenarios. The boxes delineate the 25th to 75th percentile values outside that range shown as points and the median is shown as a horizontal black line.

The average percent of days the Floriston Rates are met increases from the paleo-period to the historical period, while the medians for the future emissions scenario decrease compared to the historical period. However, several scenarios, 12 in the near future and 6 in the far future, meet Floriston Rates for more than 90 percent of days of that period, and two scenarios at 100 percent of days. Trends between the near and far futures vary between the two emissions scenarios, with the median percentage of days Floriston Rates are met increasing from the near to far future for the lower emissions scenario and decreasing for the high emissions scenario.

The same trend is observed in the average percent of years TROA is designated as a “Drought Situation,” with initial declines in the metric moving from the paleo-period to the historical period but increasing in the future scenarios, indicating a decrease in water supply reliability, but less severe than the paleo-period. The average percentage of years designated as a “Drought Situation” increases from the near to the far future in the high emissions scenario but remains steady between the two future periods in the medium emissions scenario.

Table 14.—Water resources metrics for evaluating Truckee-Carson Project water supply reliability*

	Average Percent of Years Lake Tahoe Reaches Legal Filling Limit (%) – W01	Average Percent of Days Lake Tahoe Falls Below the Natural Rim (%) – W02	Average Percent of Days Floriston Rates are Met (%) – W03	Average Percent of Years in TROA Designated "Drought Situation" (%) – W04	Average Percent of Years Lahontan Reaches the End- of-June Storage Objective (LSOCM) (%) – W05	Average Peak Lahontan Elevation (ft) – W06	Average Date of Peak Lahontan Elevation (Julian day) – W07	Average Annual Truckee Canal Diversions (AF/yr) – W08	Average Annual Percent of Days CDD is Met (%) – W09	Average Annual Volume of CDD Shortage (AF/yr) – W10
Paleo (1500–1900)	13.5	53.4	45.2	62.8	69.5	4,158	148.9	97,402	97.5	9,148
Historical (1901–2017)	32.5	12.3	81.8	23.9	63.2	4,156	148.0	113,690	96.6	13,373
Near future (2031–2060) RCP 4.5	26.7	20.4	70.7	37.0	51.7	4,158	140.1	123,142	98.1	5,720
Near future (2031–2060) RCP 8.5	30.0	13.1	77.5	38.3	56.7	4,159	135.3	118,569	99.2	2,608
Far future (2061–2090) RCP 4.5	26.7	13.3	74.2	33.3	55.0	4,159	134.6	118,522	98.6	4,405
Far future (2061–2090) RCP 8.5	13.3	28.5	59.4	50.0	50.0	4,159	120.8	115,065	97.9	6,660

* Mean values for each metric are presented over the full paleo and historical periods. Mean values for each individual future scenario are calculated over the near future and far future period, and a median value for each group of future scenarios is presented in the table.

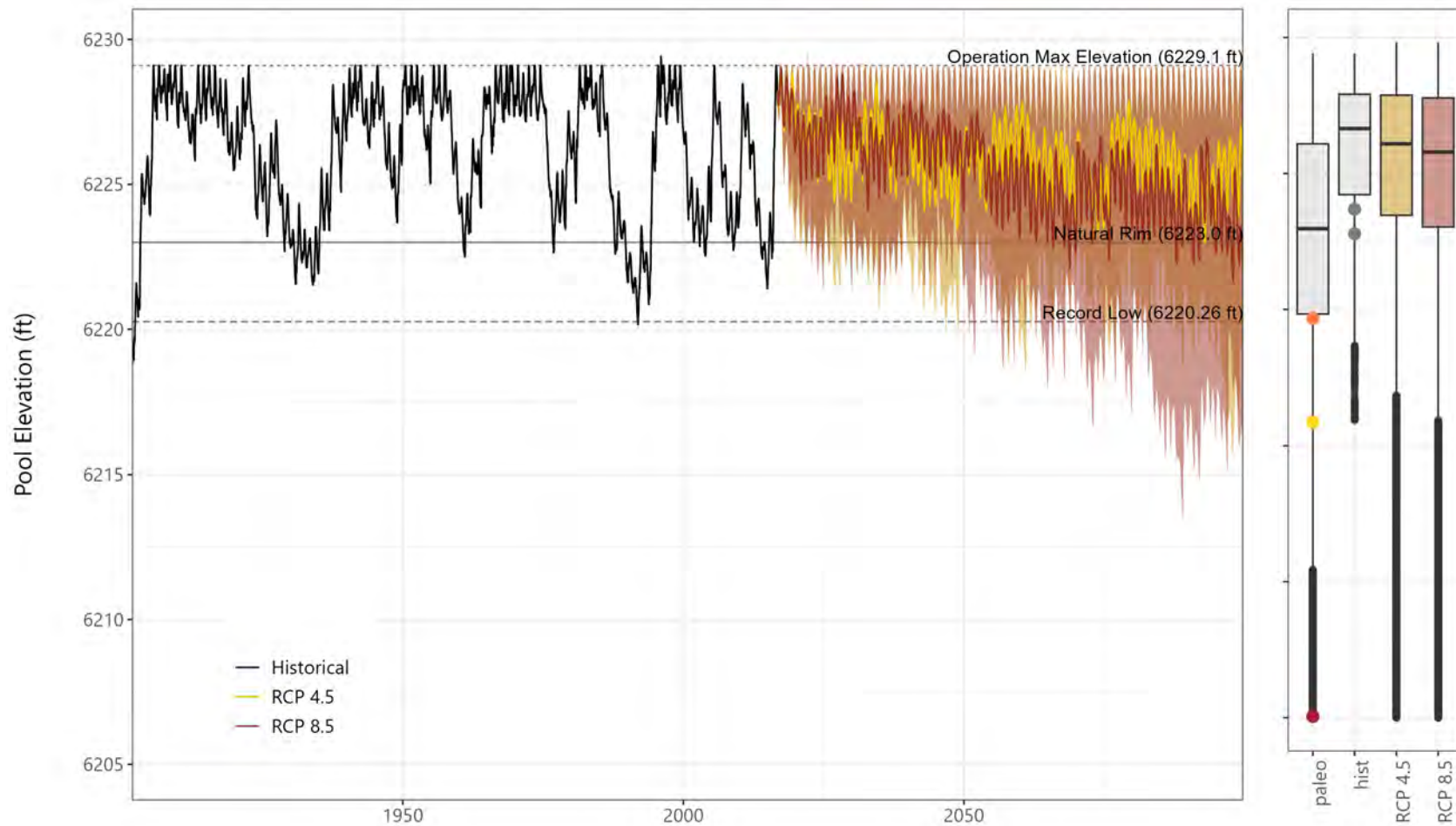


Figure 32.—Daily modeled pool elevation for Lake Tahoe over the near future and far future periods (left panel).²⁹

²⁹ Results are grouped by emissions scenario, where the shaded region indicates the 10th to 90th percentiles and the solid line indicate the median of the respective scenario groups. Results are compared to the distributions of daily modeled Lake Tahoe pool elevations over the historical and future periods (right panel) and the average Lake Tahoe Pool elevation over the largest LCD droughts in the paleo and historical periods (table 8).

Three metrics are presented to evaluate Lahontan supply reliability: the average percentage of years that Lahontan reaches the end-of-June LSCOM³⁰, the average peak Lahontan pool elevation, and the average Julian day the peak is reached. Overall, there is a decline in the percent of time the end-of-June LSOCM is met from the paleo-period to the historical period and into the future scenarios. The trend in the peak Lahontan pool elevations is more complex; the annual average peak elevation decreases from the paleo-period to the historical period but increases in the future. This contradiction is due to the change in timing of this peak pool elevation, as the average date of the peak Lahontan pool elevation is earlier in future scenarios.

Lahontan storage over future periods is generally consistent with the range of recent historical and paleo reservoir storage (figure 33). While end-of-June Lahontan storage values across climate scenarios show a small decline from the historical average, end-of-September Lahontan storage values generally show greater decreases from the historical average, with periods of lower storage reaching the bottom of the conservation pool frequently in the 2061–2090 period. These results together indicate an increase in variability, which is also contributing to the higher variability in how often the CDD is met in the far future. The low future storage values are similar to the average end of water year Lahontan storage during the most significant Carson rule-based LAD droughts.

³⁰ The end-of-June LSOCM varies each year based on the irrigated acreage in the Newlands Project. For simplicity, this study used the base June LSOCM of 229,000 acre-feet.

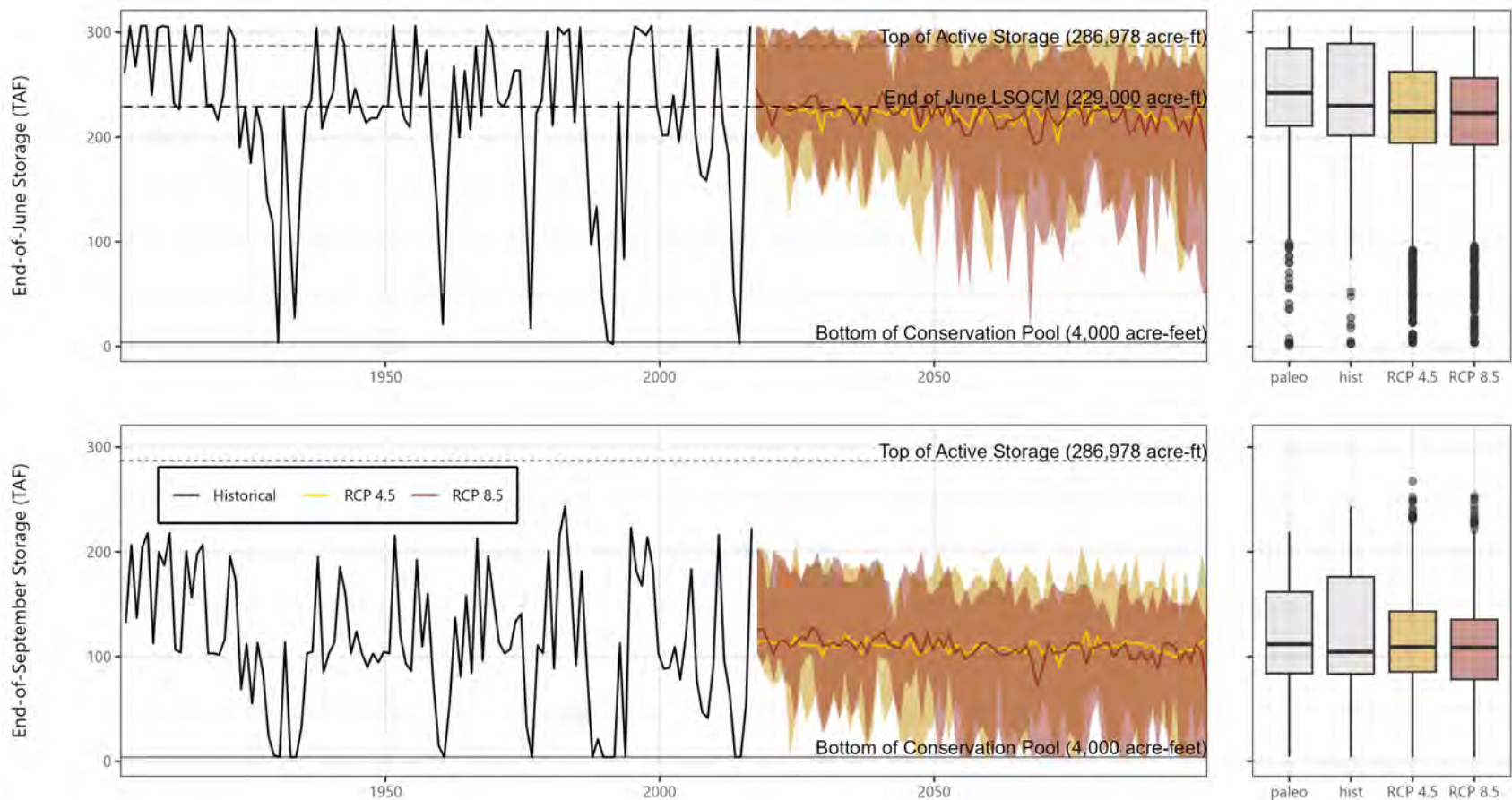


Figure 33.—Maximum June (top) and end-of-September (bottom) modeled reservoir storage for Lahontan over the near future and far future periods (left panel).³¹

³¹ Results are grouped by emissions scenario, where the shaded region indicates the 10th to 90th percentiles and the solid line indicate the median of the respective scenario groups. Results are compared to the distributions of daily modeled Lake Tahoe pool elevations over the historical and future periods (right panel) and the average end-of-WY Lahontan storage over the largest LAD droughts in the paleo and historical periods (table 8).

The Project delivers water to two divisions, the Truckee Division, which receives water directly from the Truckee Canal, and the Carson Division, which receives water from Lahontan Reservoir on the Carson River. Project water supply reliability is evaluated using three metrics: the average annual Truckee Canal diversion, the average annual percent of days the CDD is met, and the average annual volume of the CDD shortage.

Two metrics evaluate the water supply to meet the CDD: **The historical period has a lower average percent of days where the CDD is met and a higher average annual volume of CDD shortage relative to the paleo-period** (figure 31). The future results show a higher average percentage of days where the CDD demand is met in the future, up to 100 percent in 13 of the near future scenarios and 8 of the far future scenarios, and lower average annual shortage volumes, down to 0 acre-feet. Like other metrics, the highest variability in model results occurs in the far future and highest RCP scenarios.

To assess the OCAP's ability to meet its objective to minimize the use of water from the Truckee River as a supplemental Project supply, the study examined changes in the average annual diversion into the Truckee Canal at Wadsworth under differing hydrologic conditions. Average annual diversions into the Truckee Canal over the recent historical period were greater than the average annual diversions over the paleo-period. Future scenario results indicate initial increases in diversions into the Truckee Canal at Wadsworth during the near future; however, results show a decrease from the near future period to the far future period and from RCP 4.5 to RCP 8.5. This increase in diversions into the Truckee Canal is driven by an increase in Truckee River flows above Derby, discussed further in the following section.

Overall, trends in water supply are different for the Truckee and Carson River Basins. **Metrics for Lake Tahoe** (figure 31) **indicate an initial decrease in water supply reliability from the historical period to the near future; however, trends are variable from the near to far future periods, with the higher emissions scenario generally showing further declines in water supply reliability metrics and some lower emissions scenarios showing increases in water supply in the far future. Metrics for the Lahontan reservoir show more variability, where an overall increase in water volume in conjunction with a change in streamflow timing results in more variable trends in water supply reliability.** This is illustrated by variable metric trends across all future scenario groups, indicating an increase in the median peak Lahontan elevation, contrasted with a decrease in the median percent of years the LSOCM is met and an increasingly earlier date of peak Lahontan elevation.

4.5.2.2 Environmental

Water supply metrics for Truckee River flows at Nixon into Pyramid Lake are presented in figure 34 to evaluate system environmental considerations. **From the paleo-period to the recent historical period and near future period, on average, the environmental metrics indicate increased streamflow into Pyramid Lake and an increased lake elevation, which levels out in the far future** (bottom left and top left graphs on figure 34, respectively). Pyramid pool elevations rise faster in the higher emissions scenario but begin to decline and then level out

in the far future, as opposed to the lower emissions scenarios. Median future Pyramid Lake elevations for the two future emissions scenarios are higher than the historical and paleo pool elevation distribution medians, but within the historical range (figure 35).

The variability of average pool elevation at Pyramid Lake increases from the near to far future and from RCP 4.5 to 8.5, as demonstrated by the wide range of elevations on figure 35. These results may indicate that wetter future conditions, in combination with increased Nixon flows resulting from the enactment of the 1997 OCAP and TROA, may be able to reverse some of the decline in Pyramid Lake levels experienced after the enactment of the Project in the early 1900s.

However, it should be noted that the existing model runs do not consider changes to reservoir evaporation, with the exception of Lake Tahoe evaporation, and water demands over the future period, which are likely to increase (figure 26). Inclusion of these changes would likely decrease the volume of water that reached and remained in Pyramid Lake.

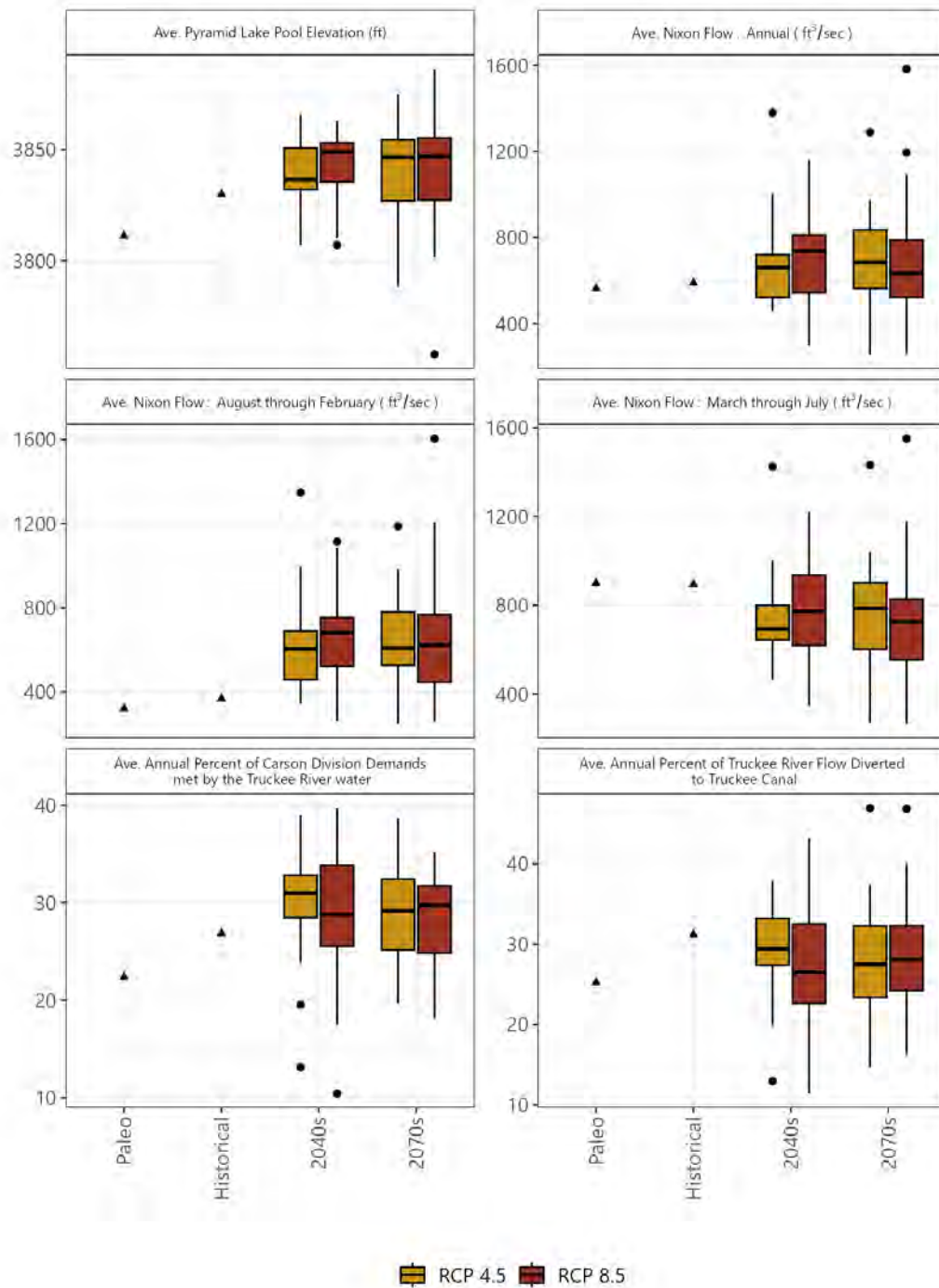


Figure 34.—Water Resource metrics for environmental considerations.³²

³² Mean values for each metric over the full paleo (1500–1900) and historical (1901–2017) periods are represented by a single, triangular, point. Future scenarios are shown as box plots demonstrating the range of the values calculated for each simulation, delineated by the near future (2031–2060) and far future (2061–2090) periods and by

Average flow rates at Nixon, NV are broken into three different categories: the annual average, the August to February average, and the March to July average, to assess conditions during different life stages of the threatened Lahontan cutthroat trout (LCT) (*Oncorhynchus clarkii henshawi*) and endangered Cui-ui (*Chasmistes cujus*) fish species under the Endangered Species Act (ESA) (USFWS 2003). August through February average Nixon, NV flows for the historical period are higher than the paleo but lower than the median of the future scenarios for all RCP and future periods. Nixon flow rates over the full year show a similar, but less extreme, pattern.

Results for March to July Nixon flows for both emissions scenarios show decreases in streamflow from the historical period, but opposite trends from the near to far future, with March to July Nixon flows continuing to decrease in the high emissions scenario but beginning to rebound and increase into the far future in the medium emissions scenario group. These results indicate that changes in March to July Nixon flows are more uncertain, likely due to the combined effects of precipitation variability and warming into the future and shift toward earlier snowmelt timing. These results warrant more in-depth analysis in future studies.

Table 15.—Environmental metrics related to Pyramid Lake elevation and inflow, as measured at Nixon*

	Average Pyramid Lake Pool Elevation (ft) – E01	Average Nixon Flow: Annual (ft³/s) – E02	Average Nixon Flow: August– February (ft³/s) – E03	Average Nixon Flow: March–July (ft³/s) – E04	Average Annual Percent of CDD Met by the Truckee River Water – E05	Average Annual Percent of Truckee River Flow Diverted to Truckee Canal – E06
Paleo (1500–1900)	3,811	563.6	321.4	899.7	22.4	25.2
Historical (1901–2017)	3,830	589.0	368.4	895.0	26.9	31.2
Near future (2031–2060) RCP 4.5	3,836	660.2	604.0	693.1	31.0	29.4
Near future (2031–2060) RCP 8.5	3,849	737.2	682.2	773.9	28.8	26.5
Far future (2061–2090) RCP 4.5	3,846	684.7	608.9	786.0	29.1	27.5
Far future (2061–2090) RCP 8.5	3,847	633.1	622.8	725.8	29.7	28.1

* Mean values for each metric are presented over the full paleo and historical periods. Mean values for each individual future scenario are calculated over the near future and far future period, and a median value for each group of future scenarios is presented in the table.

RCP emissions scenarios. The boxes delineate the 25th to 75th percentile values outside that range shown as points and the median is shown as a horizontal black line.

Two additional metrics were added to evaluate the impact of these scenarios on water diverted through the Truckee Canal: the average percent of CDD met by the Truckee River diversions, and the annual percent of the Truckee River streamflow that is diverted into the Truckee Canal. The average percent of the CDD met by the Truckee River increases from the paleo-period through the historical period and into the future periods, this is consistent with the previous section result, indicating that Truckee River canal diversions increase in the future scenarios. Despite this increase, **the average annual percent of the Truckee River streamflow diverted to the Truckee canal decreases from the historical period to all future scenario groups due to increased Truckee River flows above Derby Dam.** There is little change in these metrics between the near and far future periods.

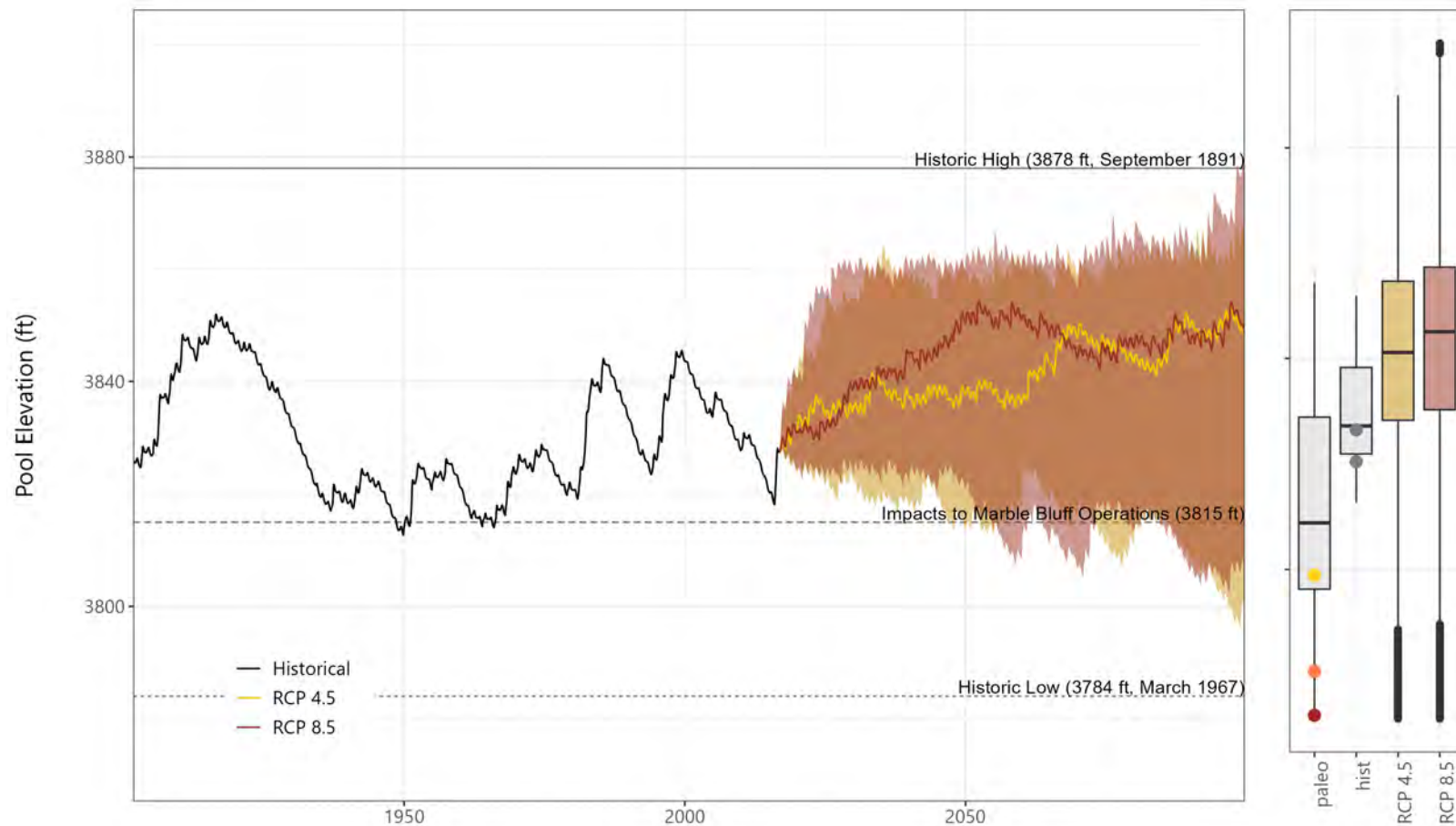


Figure 35.—Daily modeled pool elevation for Pyramid Lake over the near future and far future periods (left panel).³³

³³ Results are grouped by emissions scenario (Representative Concentration Pathways [RCP]), where the shaded region indicates the 10th to 90th percentiles and the solid lines indicate the median of the respective scenario groups (left panel). Results are compared to the distributions of daily modeled Pyramid Lake pool elevations over the historical and future periods (right panel) and the average Pyramid Lake pool elevation over the LAD droughts in the paleo and historical periods (right panel, colored dots, table 9).

4.5.2.3 Flood Risk

While flood risk management is not an OCAP objective, high flows that force precautionary releases or spills can impact the performance of the OCAP. Additionally, increases in flood risk pose an overall challenge for water management in the Truckee-Carson Basins. Several flood risk metrics were selected to evaluate Truckee River flows at Reno against a series of flood levels from previous studies, including the daily flow target, 10- and 100-year unregulated rain flood flows, and 10- and 100-year unregulated snowmelt flood flows. Of note, the modeled flows represent streamflow regulated by flood control and other dams, yet these were compared to the exceedance probabilities of unregulated flows.

On average, the flood metrics on the Truckee River exhibit an increasing trend toward greater flood probability from the paleo-period to the historical period and into the future periods. The mean of the future scenarios' average annual number of days with flows above the Reno flood flow target increases from the paleo-period (9 days) to the historical period (21 days) and into the near and far future periods (scenario median values of 19 to 26 days, respectively).

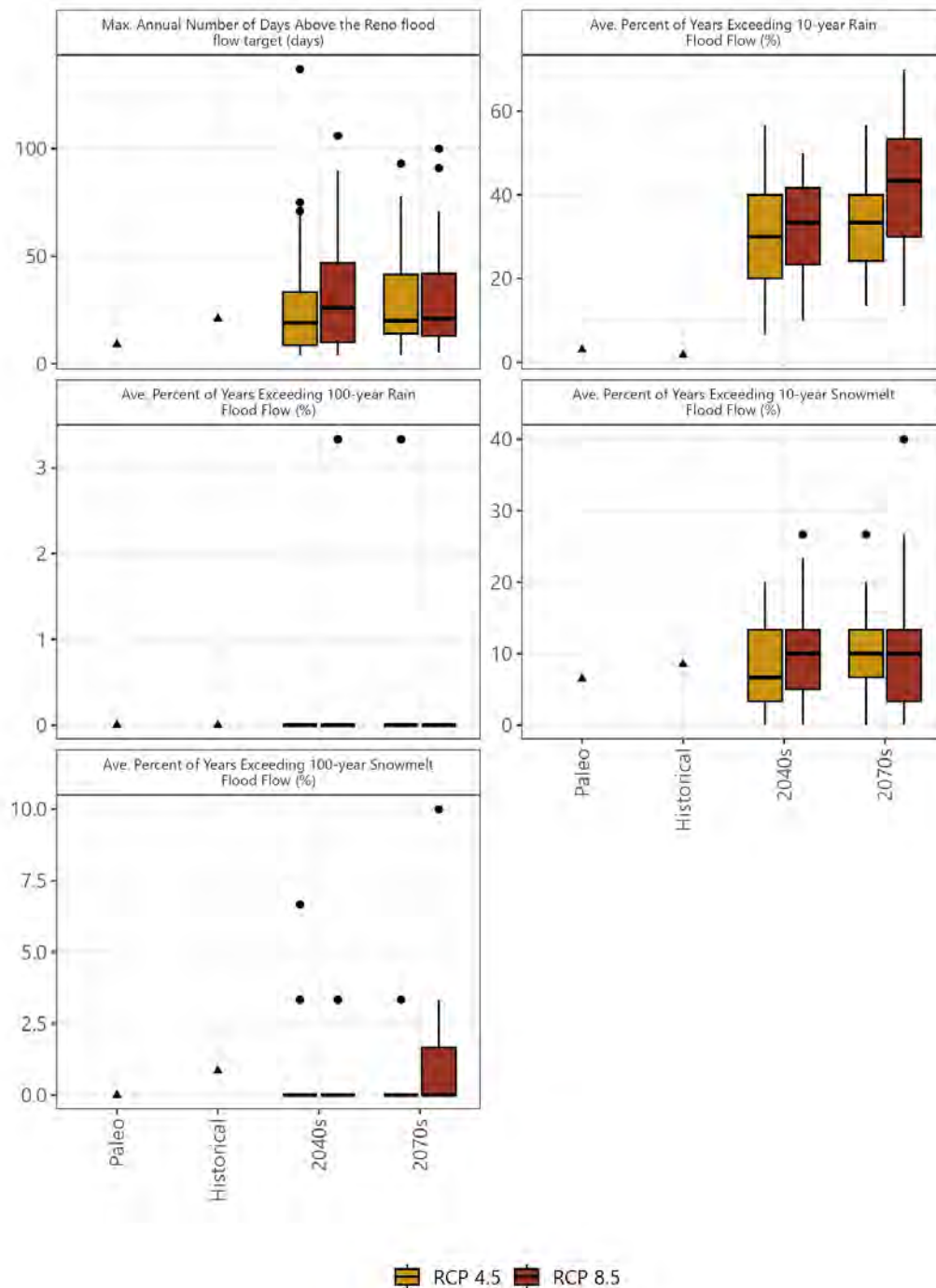


Figure 36.—Water Resources metrics for evaluating flood considerations.³⁴

³⁴ Water Supply metrics for evaluating basin-wide water supply reliability. Mean values for each metric over the full paleo (1500–1900) and historical (1901–2017) periods are represented by a single, triangular, point. Future scenarios are shown as box plots demonstrating the range of the values calculated for each simulation, delineated by the near future (2031–2060) and far future (2061–2090) periods and by RCP emissions scenarios. The boxes delineate the 25th to 75th percentile values outside that range shown as points and the median is shown as a horizontal black line.

The results show significant increases in the average percent of years exceeding the unregulated 10-year rain flood flow event from the historical to future scenarios, increasing from only 2 percent in the historical period to a median value of over 30 percent in all future scenario groups, with the most extreme result in the far future higher emissions scenario, with a median value of 43 percent. Only one event in the entire paleo and historical period would have exceeded the unregulated 100-year flood flow; however, three individual future scenarios include 3 events that exceed the 100-year rain flood flow, and one scenario includes 10 events that exceed the 100-year snow flood flow.

Increases in snowmelt flood flows show generally consistent trends, with a small increase in the average percent of years exceeding the 10-year snowmelt flow from the paleo and historical period to the future periods, except for the medium emissions scenario, which shows a decline from the historical period to the near future. Results show a small increase in the percent of years exceeding the 100-year snowmelt flood flows from the paleo-period to the historical period, from 0 to 1 percent, respectively; however, there is no notable change from the historical to future periods.

Overall, flood risk metrics in the future scenarios show a significant increase relative to the historical and paleo-periods, with the most significant increase occurring in the far future, high emissions scenario.

Table 16.—Flood risk metrics*

	Maximum Annual Number of Days Above the Reno Flood Flow Target (days)	Average Percent of Years Exceeding 10-year Rain Flood Flow (%)	Average Percent of Years Exceeding 100-year Rain Flood Flow (%)	Average Percent of Years Exceeding 10-year Snowmelt Flood Flow (%)	Average Percent of Years Exceeding 100-year Snowmelt Flood Flow (%)
Paleo (1500–1900)	9	3.0	0.0	6.5	0.0
Historical (1901–2017)	21	1.7	0.0	8.5	0.9
Near future (2031–2060) RCP 4.5	19	30.0	0.0	6.7	0.0
Near future (2031–2060) RCP 8.5	26	33.3	0.0	10.0	0.0
Far future (2061–2090) RCP 4.5	20	33.3	0.0	10.0	0.0

	Maximum Annual Number of Days Above the Reno Flood Flow Target (days)	Average Percent of Years Exceeding 10-year Rain Flood Flow (%)	Average Percent of Years Exceeding 100-year Rain Flood Flow (%)	Average Percent of Years Exceeding 10-year Snowmelt Flood Flow (%)	Average Percent of Years Exceeding 100-year Snowmelt Flood Flow (%)
Far future (2061–2090) RCP 8.5	21	43.3	0.0	10.0	0.0

* Mean values for each metric are presented over the full paleo and historical periods. Mean values for each future scenario are calculated over the near future and far future period, and a median value for each group of future scenarios is presented in the table.

5.0 Discussion

This Pilot Study produced a wealth of climate and hydrology data along with a modeling workflow to process that data through existing models used in the Truckee-Carson Basins, with applications far beyond the current study. The data and modeling results produced in the Pilot Study were used to evaluate distant past and recent historical drought conditions and to evaluate plausible projected future climate and hydrologic conditions. Modeling using the existing TROA Planning model also facilitated investigations into the performance of the OCAP if distant past conditions were to recur or if LOCA-CMIP5 project climate projections were to materialize. Results presented in this study are preliminary; however, they offer a view into future hydrologic conditions and water management challenges.

5.1 Key Takeaways

The following key takeaways highlight new information developed in this Pilot Study that will benefit future water management and planning in the Truckee-Carson Basins and future OCAP Updates. They also highlight new or broader understanding of the variability of climate and hydrologic conditions in the region.

5.1.1 Dataset and Workflow Innovations

- The dataset produced in the Pilot Study will contribute significantly to modeling and planning efforts in the Truckee-Carson Basins. The dataset components include:
 - Paleo (WY 1500–1900) hydrology in the Truckee and Carson Basins on a daily timestep at all RiverWare input locations of the TROA Planning Model. The paleo time series is an expansion of previous efforts, such as the 2021 SECURE Water Act West-wide Climate and Hydrology Assessment, in that it extends

further back in time to encompass periods of well-documented mega droughts that occurred in the region, and it leverages the Truckee River at Farad, CA, streamflow reconstruction that had not previously been evaluated in a water management context.

- o LOCA-CMIP5 climate data (1950–2099) for all 32 GCMs over the historical and 2 future emissions scenarios developed as input to existing PRMS models. The LOCA-CMIP5 climate data were bias-corrected using novel techniques that, compared to previous applications, better capture extremes and better accommodate seasonality shifts.
 - o PRMS simulated unregulated streamflow (1950–2099) in the Truckee-Carson Basins at all TROA Planning Model input locations using the full ensemble of LOCA-CMIP5 climate projections (highlighted above). The full ensemble of streamflow will allow for testing of management strategies under this full range of plausible hydrologic conditions, not just a subset as in previous studies.
 - o Lake Tahoe simulated evaporation (1950–2099) developed on a monthly timestep using the full ensemble of LOCA-CMIP5 climate projections (highlighted above). The full ensemble of monthly estimates over the period of record is an improvement over previously available, one-value-per-month estimates.
 - o Simulated streamflow at Fort Churchill based on an updated regression approach (1950–2099), resulting in improved fit compared to historical observations. These time series fill a gap in the dataset by providing estimated regulated inflows to the TROA Planning Model at Fort Churchill.
 - o A full ensemble of daily inputs to the TROA Planning Model spanning WY 1500–2099. To the study team’s knowledge, no other study has combined paleo, recent historical, and projected future hydrologic data in this manner in the Truckee-Carson Basins.
 - o TROA Planning Model outputs spanning WY 1500–2099, including a range of computed metrics that encompass water supply, environmental concerns, and flood risk.
- The datasets and modeling workflow developed, tested, and validated in this Pilot Study provide a pathway for future studies. For example, the framework now exists to perform a vulnerability assessment of Truckee-Carson Basins’ operations and serve as a test bed for management alternatives under the greatest range of plausible climate and hydrologic conditions to-date.

5.1.2 Changes in Climate Over Time

- Extending the paleo back to 1500 revealed long-lasting droughts, up to 32 years, indicating that the droughts experienced in the recent historical period may not represent the range of natural variability in the system, even without considering climate change.
- The future climate projections developed in this Pilot Study generally align with findings from previous studies that indicate warmer, year-round conditions; earlier peak spring runoff due to warmer winter temperatures; and the potential for wetter winters and drier summers.

5.1.3 Operating Criteria and Procedures (OCAP) Performance under Different Hydrologic Scenarios

- Most metrics used to evaluate the OCAP performance under climate change show increases in Newlands Project water supply reliability and Truckee River flows to Pyramid Lake from the paleo and historical periods into the near-future period (2040s). These trending improvements level off or slightly decrease in the far-future (2070s).
- Metrics related to Lahontan Reservoir storage show more variability under future climate conditions due to the combined impacts of an overall increase in water supply and a significant change in earlier spring streamflow into the reservoir.
- Metrics impacted by water supplies along the Truckee and Carson rivers, such as the average percent of days the CDD is met, show mixed results. Evaluating the impacts of a large variety of paleo and historical drought conditions is critical to evaluate the vulnerabilities of these more complicated metrics.
- Water supply metrics related to Lahontan storage for the paleo and historical droughts were more impacted by the LAD droughts, with no significant difference in impacts between the droughts identified in the historical and paleo-period.
- Water supply metrics related to Lake Tahoe are most severely impacted by paleo-period LCD droughts, which are longer in duration than LAD droughts or the historical LCD droughts.
- Trends from the historical period into the far future indicate a median decrease in water supply storage at Lake Tahoe across climate scenarios, along with a median decrease in the average percentage of days Floriston Rate is met and a median increase in days in a TROA-designated drought. However, the ranges of changes encompass increases and decreases in these metrics. Concurrently, approximately half of the scenarios indicate an increase in days above the Reno flood flow target. Combined with the increase in downstream Truckee River flows, these results indicate that more water is flowing through the systems as flood flows rather than flows regulated to meet Floriston rates year-round.

5.2 Recommendations for Future Work

This Pilot Study accomplished its objectives to develop a robust climate and hydrology dataset to demonstrate how well the 1997 OCAP can meet water rights demands under a changing hydrologic regime; at the same time, it revealed opportunities to improve upon this dataset and the use of the dataset in the evaluation of OCAP performance under climate change, as follows.

- Paleo information
 - The study team recommends that paleo streamflow reconstruction for the Carson River near Fort Churchill be reviewed and potentially redeveloped using methods that preserve the variance in streamflow observed in the recent historical period.
 - A potential complement to tree rings informing understanding of distant past drought and wet events is using paleo-lake level information from the pluvial lakes in the Truckee-Carson Basins (Adams and Rhodes 2019). This information could potentially inform the characterization of distant past wet events, in particular.
- Recent historical information
 - The study team recommends revisiting the methods underlying the TROA Planning Model dataset before 1986.
- Future climate and OCAP performance assessment
 - The produced hydrologic dataset does not include projected evaporation at water bodies beyond Lake Tahoe, nor does it include projected future demands. The study team recommends developing projections of evaporation at all major water bodies within the Truckee-Carson Basins, as well as developing future demand scenarios to provide a more complete picture of climate change impacts on water availability and OCAP performance.
 - The study team encountered TROA Planning Model limitations resulting from pushing the model beyond the historical conditions within which it was developed to operate; modifications were developed to successfully run 61 out of 64 LOCA-CMIP5 projections, and the study team recommends reviewing the TROA Planning and Operations model that is currently (at the time of this report) under development and intended to replace the TROA Planning Model to ensure that it is capable of operating under the range of plausible future conditions.
 - The assessment methods used in this study focused on the mean/median, variance, and long term trends associated with the selected metrics to provide a preliminary overview of OCAP performance under climate change; the study team recommends using these results to dive deeper into the identified conditions which could most impact OCAP performance (for example, earlier spring runoff and lower April through July forecast) by examining time-series results for specific GCMs and emissions scenarios.

- o The metrics used in this study were selected by the Reclamation study team and were derived from metrics used in previous studies. To ensure that the OCAP performance results reflect the values and concerns of basin stakeholders and effectively inform the OCAP Update, the study team recommends working with stakeholders to refine and update the metrics list and assessment process.
- o To complement the top-down workflow developed in this Pilot Study, the study team recommends applying a bottom-up vulnerability assessment that uses information developed in this Pilot Study, as well as stakeholder input, to identify management concerns around which sensitivity and vulnerability of the OCAP to climate change are then characterized over a large plausible range of future conditions.
- o To further stress test OCAP performance under climate change, the study team recommends using a weather generator to develop and test plausible future conditions targeted towards stakeholders and OCAP vulnerabilities identified through the analysis conducted in this study and the recommended future studies.

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Appendix A

Historical and Projected Climate

Appendix A: Historical and Projected Climate

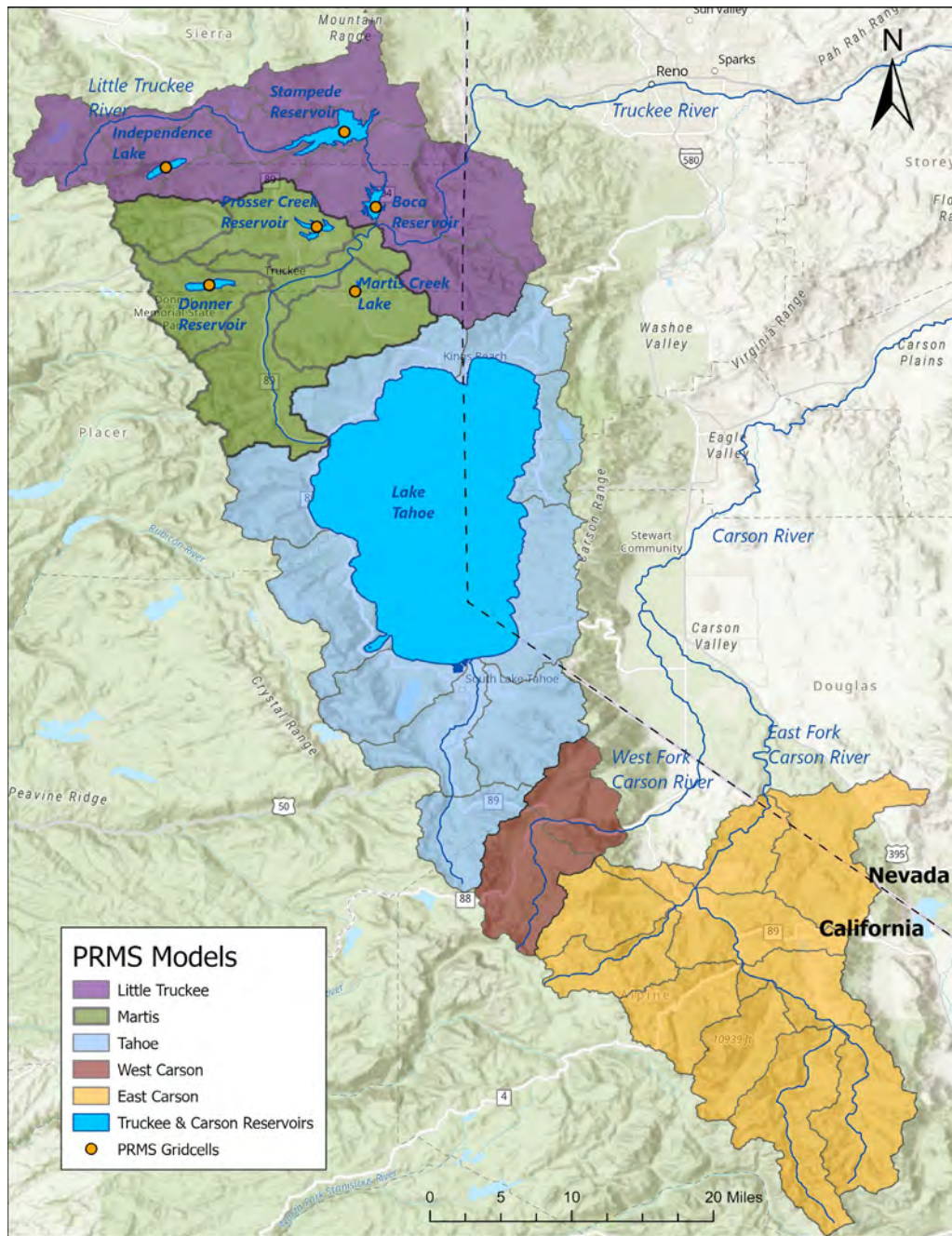


Figure A-1.—The Precipitation Runoff Modeling System grid cell overlaying each reservoir from which daily projected precipitation was extracted for input into the Truckee River Operating Agreement Planning Model.³⁵

³⁵ The Pilot Study used an area-weighted average for Lake Tahoe.

Little Truckee Precipitation Runoff Modeling System (PRMS) Model

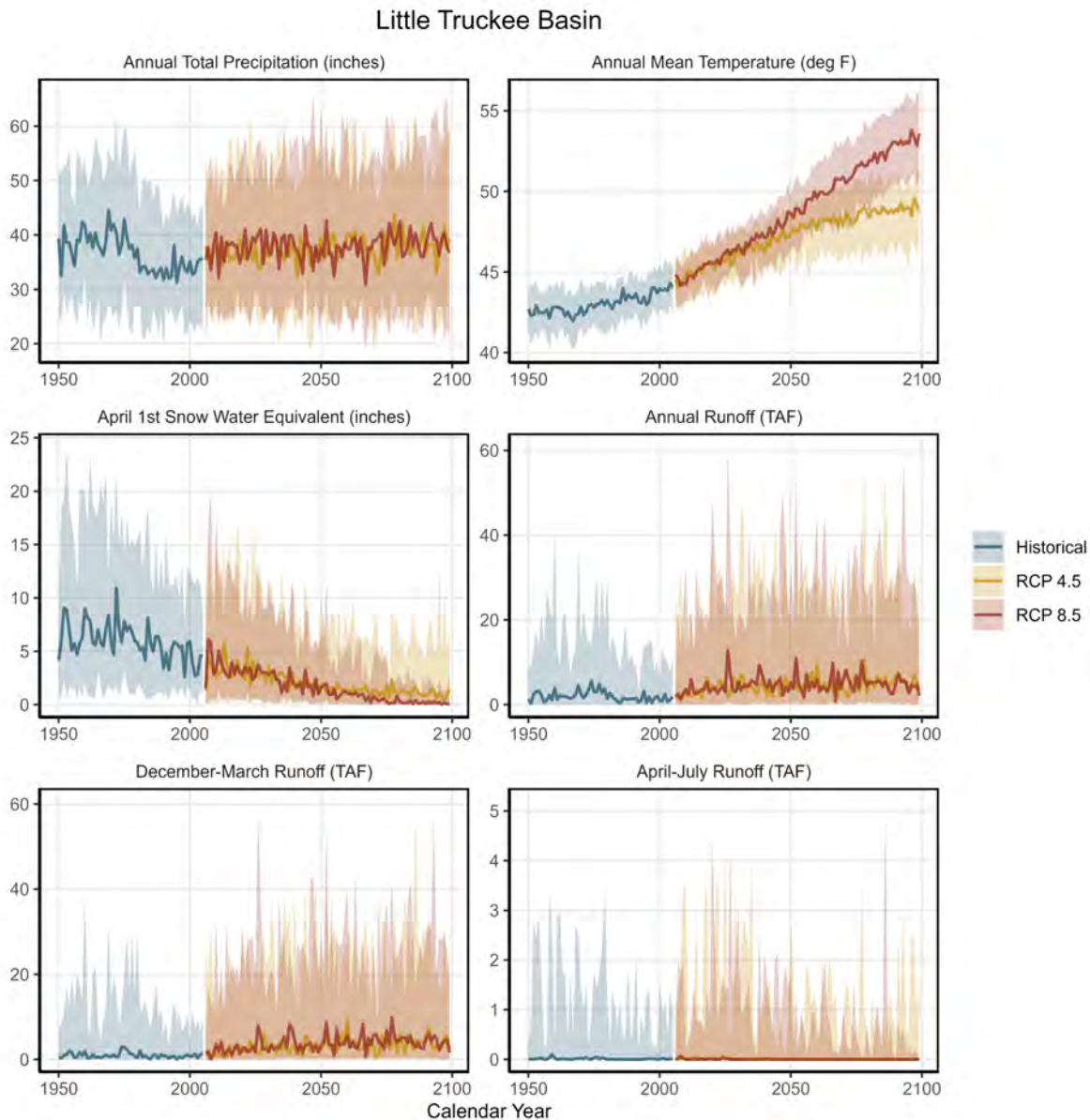


Figure A-2.—Time series of basin-averaged, bias-corrected, LOCA-CMIP5 historical (blue) and LOCA-CMIP5 projected (yellow = RCP 4.5 and red = RCP 8.5) hydroclimate indicators for the Little Truckee River Basin.³⁶

³⁶ Dark colored lines indicate the respective ensemble median value, while shading indicates the 10th and 90th percentile ensemble values. It should be noted that the visual gap in the data in the transition from recent historical period to projected future is only an artifact of the visualization and does not indicate a gap in the data itself.

Lake Tahoe Precipitation Runoff Modeling System (PRMS) Model

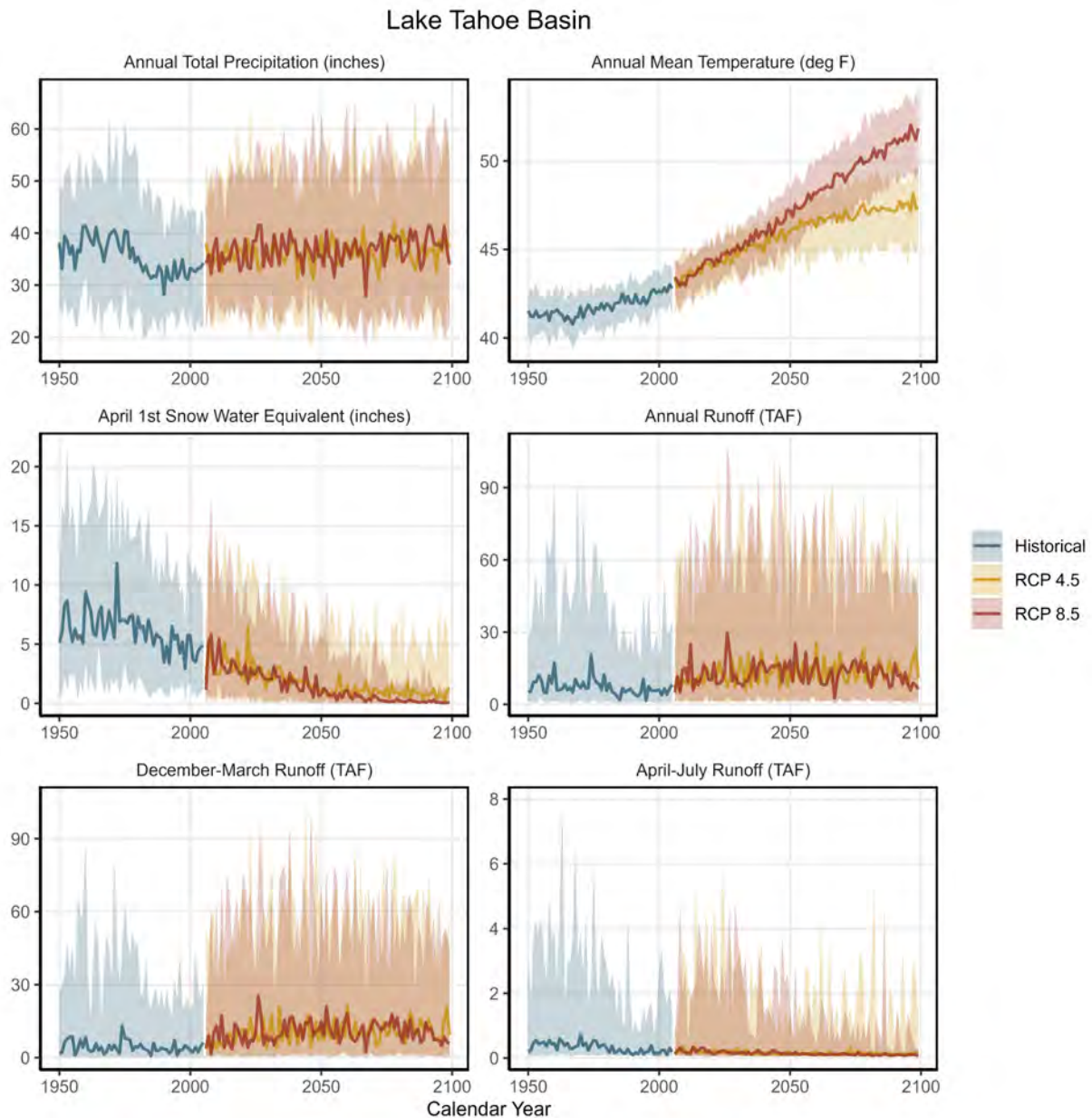


Figure A-3.—Time series of basin-averaged, bias-corrected, LOCA-CMIP5 historical (blue) and LOCA-CMIP5 projected (yellow = RCP 4.5 and red = RCP 8.5) hydroclimate indicators for the Lake Tahoe Basin.³⁷

³⁷ Dark colored lines indicate the respective ensemble median value, while shading indicates the 10th and 90th percentile ensemble values.

East and West Carson Precipitation Runoff Modeling System (PRMS) Models

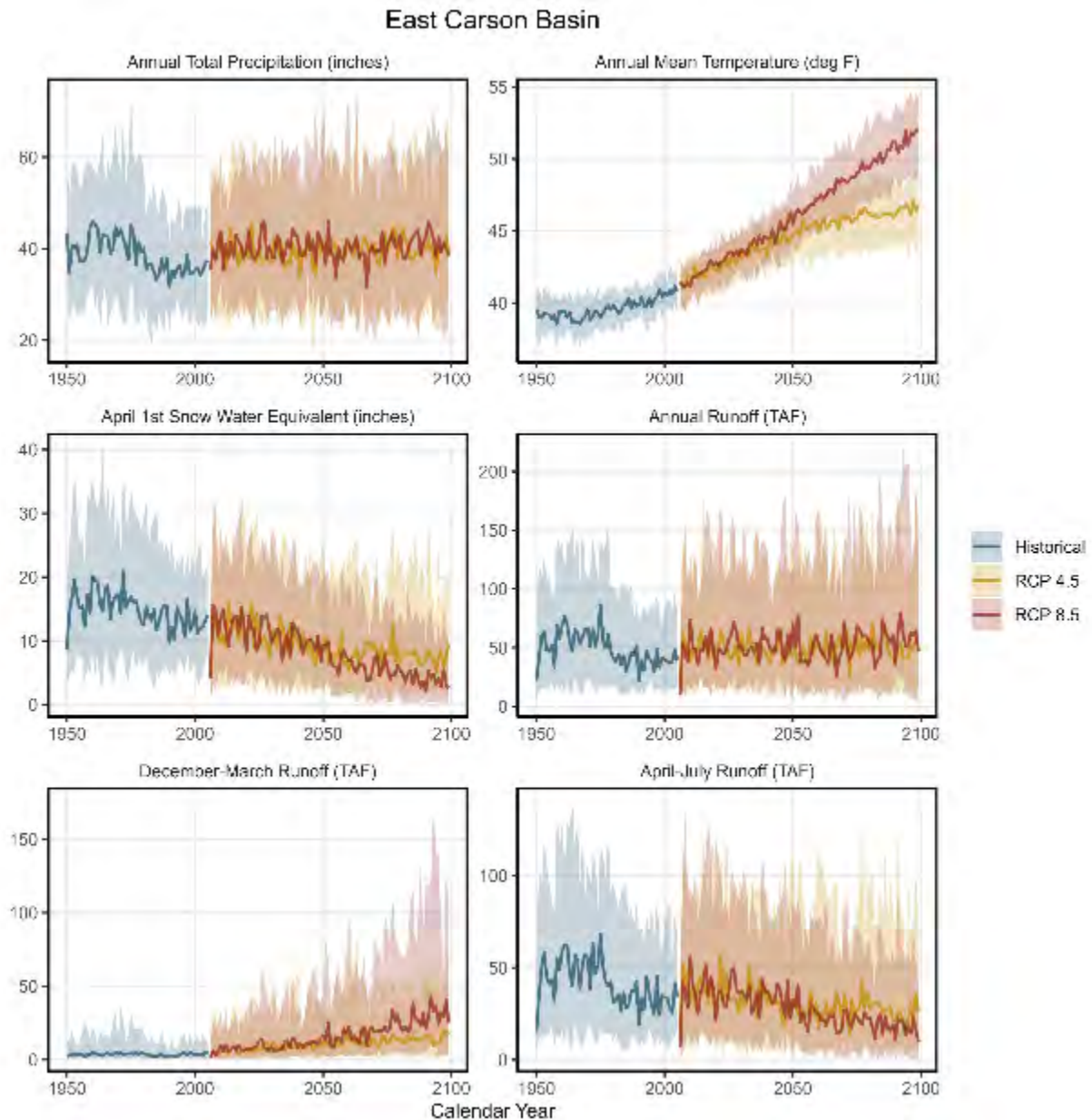


Figure A-4.—Time series of basin-averaged, bias-corrected, LOCA-CMIP5 historical (blue) and LOCA-CMIP5 projected (yellow = RCP 4.5 and red = RCP 8.5) hydroclimate indicators for the East Carson Basin.³⁸

³⁸ Dark colored lines indicate the respective ensemble median value, while shading indicates the 10th and 90th percentile ensemble values.

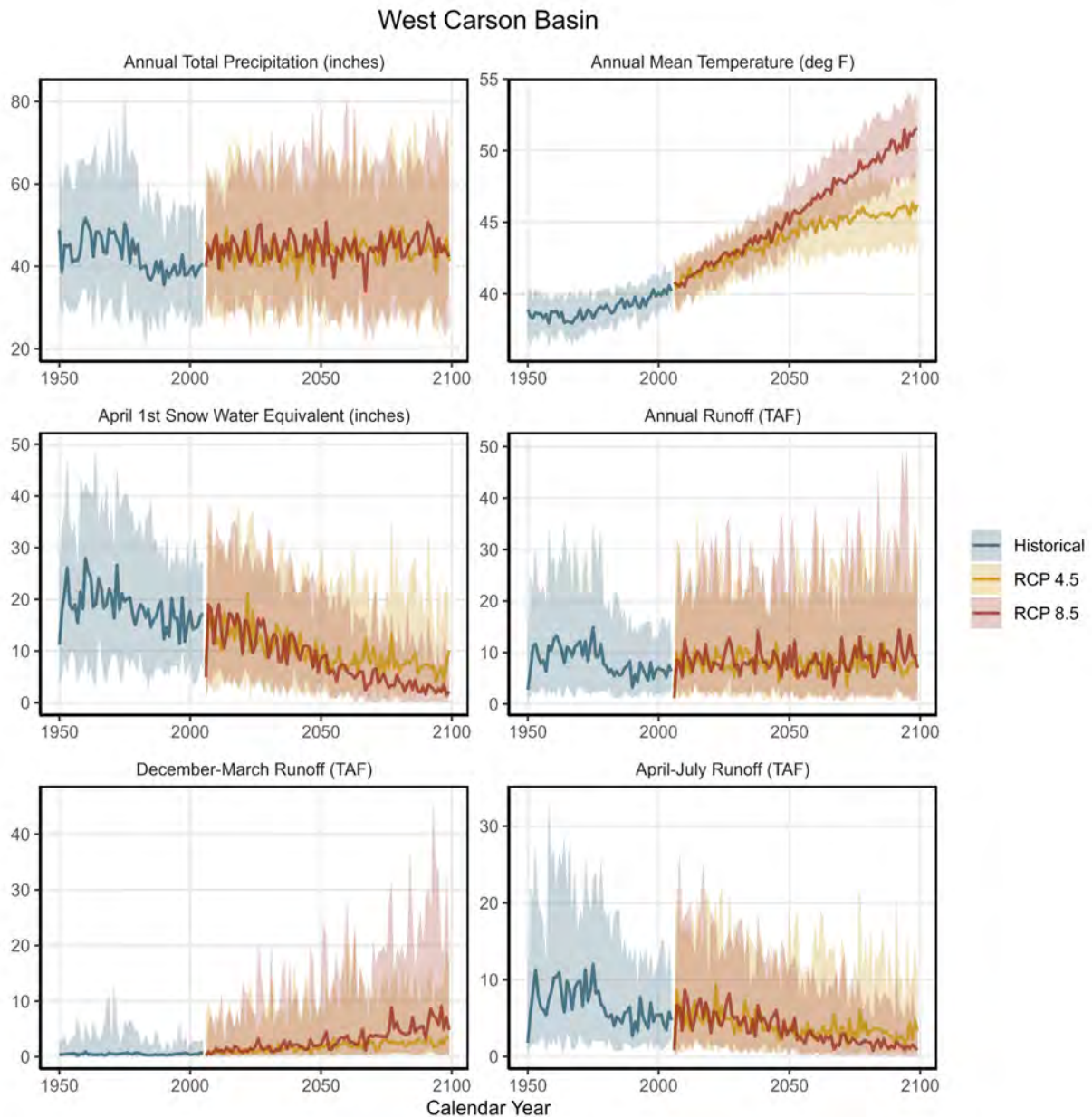


Figure A-5.—Time series of basin-averaged, bias-corrected, LOCA-CMIP5 historical general circulation model (GCM) (blue) and LOCA-CMIP5 projected (yellow = RCP 4.5 and red = RCP 8.5) hydroclimate indicators for the West Carson Basin.³⁹

³⁹ Dark colored lines indicate the respective ensemble median value, while shading indicates the 10th and 90th percentile ensemble values.

Appendix B

Literature Review: Truckee and Carson River Basins Climate Studies

Appendix B: Literature Review – Truckee and Carson River Basins Climate Studies

Several studies in the last 15 years have examined the impacts of a changing climate on hydrology in the Truckee and Carson River Basins (Truckee-Carson Basins). Most of the previous climate studies followed a similar workflow to the Pilot Study. However, differences in the methodologies, models, and data sources yield different results. This section describes the modeling framework, inputs, and results from previous studies, and compares these to the current study.

All climate studies took advantage of existing hydrologic and operational models in the basin, yielding significant overlap in model selection. The Truckee Basin Study (Reclamation 2015), Water for the Seasons (DRI 2019), USGS Carson River Climate Study (Kitlaster et al. 2021), and TMWA Water Resources Plan (2024) all ran climate scenarios through the same Precipitation Runoff Modeling System (PRMS) surface water models. The more recent studies, then ran the PRMS output through the RiverWare Truckee River Operating Agreement (TROA) Planning Model, used to guide operations in the basin since 2015. Without the benefit of the TROA Planning Model, the Truckee Basin Study developed hydrologic regressions to describe hydrologic conditions at several key locations downstream of Farad, CA, while the Carson River climate study ran the PRMS output through a Groundwater and Surface-water Flow (GSFLOW) model of the Carson River Valley coupled with a MODSIM network flow model. Lastly, Reclamation’s West-wide Climate Assessment (2021) ran climate scenarios through a Variable Infiltration Capacity (VIC) hydrological model and the TROA Planning Model.

Previous climate studies differed most significantly in the climate data used as input to the PRMS or VIC models, including whether GCM traces were used directly or whether the study developed synthetic climate scenarios; which GCMs were used; which emissions scenarios were used; how the climate data was downscaled; how the climate or streamflow data was bias-corrected; what historical data was used to establish a baseline; and much more. Due to the wide-range of GCM and other modeled climate data, data selections within the plausible range of climate yield a similarly wide-range of hydrologic projections produced by the climate studies in the Truckee-Carson Basins. Importantly, although the results differ amongst studies, it does not mean that some studies are “wrong” and others are “right”; rather, the results represent different spectrums of the plausible range of future conditions.

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Appendix B

Table B-1.—Summary of data and methods used in previous climate studies in the Truckee-Carson Basins and the current Pilot Study

	Truckee Basin Study (2015)	TMWA Water Resources Plan (2020)	Water for the Seasons (2020)	Climate Change in the Carson Valley (2021)	West-Wide Climate Assessment (2021)	Pilot Climate Dataset (2024)
Climate data version	CMIP3	CMIP5	CMIP5	Synthetic temperature	CMIP5	CMIP5
Emissions scenario	SRES A2 SRES A1B SRES B1	RCP 4.5 RCP 8.5	RCP 4.5 RCP 8.5	N/A	RCP 4.5 RCP 8.5	RCP 4.5 RCP 8.5
GCMs	16 GCMs	8 GCMs	16 GCMs	N/A	32 GCMs	32 GCMs
GCM downscaling	BCSD	LOCA and MACA	LOCA and MACA	N/A	LOCA	LOCA
GCM bias correction	BCSD; Quantile mapping of temperature and precipitation	Not reported.	Bias-corrected precipitation – method unknown	N/A	LOCA frequency- dependent correction	Modified quantile mapping - temperature and precipitation
Rainfall runoff model	PRMS	PRMS and GSFLOW	PRMS, GSFLOW, and MODFLOW	PRMS and GSFLOW	VIC	PRMS
Streamflow bias correction	None	Annual Tahoe basin volume to match historical volume	None	N/A	None	Annual Tahoe basin volume to match historical volume using CDFs
Tahoe evaporation	CRLE 2015	CRLE 2015	CRLE 2015	N/A	CRLE 2021	CRLE 2023, future evaporation estimates only at Lake Tahoe
Tahoe surface area	Unknown	120,583 acres	Unknown	N/A	Unknown	143,000 acres
Operations model	Regression	TROA Planning Model	TROA Planning Model	MODSIM	None	TROA Planning Model

Notes: :

BCSD Bias Correction and Spatial Disaggregation
CDF Cumulative Distribution Function
CRLE Complementary Relationship Lake Evaporation model
GCM General Circulation Model
GSFLOW Coupled Groundwater and Surface-Water Flow model
LOCA Localized Constructed Analogs
MACA Multivariate Adaptive Constructed Analogs
CMIP3 Coupled Model Intercomparison Project phase 3

CMIP5 Coupled Model Intercomparison Project phase 5
MODIS Moderate Resolution Imaging Spectroradiometer
PRMS Precipitation Runoff Modeling System
SRES A1B Special Report on Emissions Scenario A1B – Medium emissions scenario
SRES A2 Special Report on Emissions Scenario A2 – High emissions scenario
SRES B1 Special Report on Emissions Scenario B1 – Low emissions scenario
TROA Truckee River Operating Agreement
VIC Variable Infiltration Capacity model

Truckee Basin Study (2015)

The Truckee Basin Study (Reclamation 2015) was one of the first studies to investigate how future climate and hydrological conditions might impact water management decisions within the basin.

Climate Data

The Truckee Basin Study used a scenario-based approach where future scenarios informed by climate projections, demand conditions, and water management conditions were used to explore the range of plausible future water supply conditions within the Truckee Basin. Five future water supply scenarios were compared to a historical supply condition that was based on gage data and a reference supply condition that was based on simulations. The historical supply condition was based on stream gage records dating back to 1901. This historical dataset, the Truckee-Carson Data File (TCDATFIL), was disaggregated from monthly to daily flows at key river system points and is a predecessor to the current TROA dataset used in the TROA Planning Model. The reference scenario was developed by running Livneh historical data (Livneh et al. 2013) from 1915 through 2003 through a Precipitation Runoff Modeling System (PRMS) surface water model that was developed for the Truckee Basin Study. The five future climate scenarios were developed through a hybrid-delta ensemble approach that combined 112 future climate projections selected as part of the Coupled Model Intercomparison Project phase 3 (CMIP3; (Meehl et al. 2007)). Before using the 112 CMIP3 projections to develop future scenarios, Reclamation downscaled these projections to 1/8th degree resolution.

Rainfall-runoff Modeling

The five developed climate scenarios and reference scenarios were run through the PRMS models (Markstrom et al. 2008) to project streamflow at various locations in the Truckee Basin. Three PRMS models were developed using 300-meter by 300-meter grid cells to represent three different sub-basins within the Truckee River Basin: the Martis Creek Basin, the Lake Tahoe Basin, and the Little Truckee River Basin. The three models combine to simulate hydrology above Farad, CA, which represents 90 percent of the contributing surface runoff in the entire Truckee Basin. Climate data was distributed to each grid cell based on mean monthly precipitation patterns from PRISM and daily temperature and precipitation recorded at multiple climate monitoring stations across the basin. Calibration of the PRMS models was performed from 1980 to 2010 using 20 gaging stations in addition to Moderate-resolution Imaging Spectroradiometer snow-covered area and measured snow-telemetry (SNOTEL) snow-water equivalent. Some of the gaged stations did not represent naturalized streamflow and instead of naturalizing the streamflow by subtracting out things like diversion, the calibration relied upon the TCDATFIL dataset which represents a back-calculated naturalized streamflow.

Operational Modeling

The PRMS models did not encompass any area below the Farad gage. As such, hydrologic regressions were developed for the Truckee Basin Study to describe hydrologic conditions at several key locations downstream from Farad. These regressions were developed by extrapolating from modeled hydrologic conditions on the Truckee River upstream of Farad.

Summary of Results

The future scenarios modeled in the Truckee Basin Study demonstrate a wide range of uncertainty surrounding future water supply and greater certainty in the expectation for the region to warm. Warming temperatures will shift the timing of runoff earlier in the spring and will increase evaporation at all Truckee Basin lakes and reservoirs, particularly the vast Pyramid Lake and Lake Tahoe. Pyramid Lake elevations end the hotter scenario 20 to 30 feet lower than their warmer scenario counterparts. Pyramid Lake elevations also illustrate the wide range of projects, with end-of-century elevations spanning an approximately 100-foot decrease in lake elevation to a 100-foot increase in elevation among the scenarios examined. Similarly, future projections suggest that inflows into other lakes and reservoirs would decrease or increase, with slightly higher inflows under the Central Tendency of the climate projections.

Water for the Seasons (2020)

The Water for the Seasons was a 5-year collaborative research project between an interdisciplinary research team and local stakeholders to assess the climate resiliency of the Truckee-Carson River System (Singletary and Sterle 2020).

Climate data

The team of researchers and stakeholders worked together to develop four climate scenarios that explored a range of potential projected changes in climate (Singletary and Sterle 2020; Albano 2019). These four scenarios were defined by: (1) extended drought conditions, (2) increased temperature, (3) increased precipitation variability, and (4) an ensemble of water level projections for Lake Tahoe.

The four future climate scenarios were developed using historical gridded CMIP5 data downscaled by LOCA. The study noted a precipitation bias in the LOCA downscaled projections. The study found an increase in small precipitation events or ‘drizzle’ recorded with the downscaled projections when compared to actual historical recorded precipitation. To account for this bias, the projected precipitation was adjusted using a relationship between the historical and projected precipitation.

The Water for the Seasons project developed the following scenarios using a combination of GCM, historical, and synthetic hydrology.

- **Extended drought scenario:** The extended drought scenario investigated how water supplies would be altered if droughts were extended as compared to historical. This scenario took the 2012–2015 drought and combined it with the 1987–1994 drought, creating a 12-year drought sequence. Then the single wet year (1995) was added to the end of it to explore how much one wet year could improve drought conditions. These drought conditions were based on gridded daily PRISM data. A climate-change scenario was then formed by increasing temperature by 2.5 degrees Celsius (°C) to reflect mid-century conditions.
- **Increased temperature scenario:** The increased temperature scenario was built by first determining the 30-year mean average temperature increase projected in the study domain by 2080 using 15 select climate projections that represented both RCP 4.5 and RCP 8.5 emission scenarios.
- **Variability scenario:** The variability scenario represented increases in precipitation variability and their impact on water resources. This scenario was developed from 30 of the LOCA downscaled CMIP5 projections which were screened and reduced down to two projections that exhibited similar average temperature as the increased temperature scenario above and had either low (approximately 5 year) or high (approximately 2–3 year) variations in precipitation frequency.
- **Tahoe storage scenario:** The Tahoe storage scenario was developed to explore how projected changes in climate might impact Lake Tahoe water surface elevation. Lake Tahoe storage occurs between the natural level of the lake and the height of the dam, which is only 6 feet higher than the natural level. Once the lake rises 6 feet above the natural rim of the lake, water must be released downstream. Lake levels can fall below the natural rim of the lake in times of drought by tens of feet or more. The Lake Tahoe scenario was developed using 16 Multivariate Adaptive Constructed Analogs (MACA) downscaled projections that included temperature, precipitation, solar radiation, and wind speed as this scenario was also applied to a lake evaporation model in addition to a surface water model. All 16 projections were used to estimate probabilities that the Lake will reach various levels under projected climate change.

Rainfall-runoff Modeling

The Water for the Seasons project developed an integrated model comprised of multiple hydrologic and operations models. The future scenarios were first run through PRMS models of the Carson and Truckee Basins. The study developed a GSFLOW coupled surface-groundwater model for the middle and lower portions of the basin by combining the PRMS model with a MODFLOW groundwater model.

Operational Modeling

The future scenarios were run through the RiverWare-based TROA Planning Model and/or a MODSIM decision support model of the Carson Valley. In the Truckee Meadows, RiverWare's groundwater objects were calibrated to MODFLOW to more accurately depict pumping impacts on surface water flows.

Summary of Results

The scenarios developed and modeled in the Water for the Seasons Project yielded the following key takeaways regarding climate impacts:

- Climate projections across the river system generally show warmer temperatures and increased precipitation variability. Mountain snowpack will decline, and dry years will become more frequent.
- Scenarios of a warmer climate demonstrate measurable snowpack changes that affect the timing and availability of water supply. With 4.3 degrees of warming, annual streamflow volumes were similar to historical, but earlier snowmelt shifts streamflow peaks by approximately 45 days. In addition, the study found that Lake Tahoe more frequently exceeded the legal water elevation limit of 6,229 ft and lake evaporation increased by 14 percent.
- The sequencing of wet and dry years has a significant impact on water supply and river system operations. The scenario with longer periods (approximately 5 years) of sustained dry and wet years resulted in more adverse effects on reservoir storage and water supply.

Uniquely, the Water for the Seasons project included a collaborative stakeholder component. Ninety percent of the 66 local water managers interviewed believe that climate change is important to the Truckee-Carson Basins (Sterle 2020).

Truckee Meadows Water Authority Water Resource Plan (2020)

The Truckee Meadows Water Authority drafts a water resource plan every 5 years with the latest published in 2020⁴⁰ (Truckee Meadows Water Authority 2020). These plans analyze future water resource conditions and outline strategies to meet the region's projected drinking water needs. The future water resource modeling for the 2020 water resource plan built upon the Truckee Basin Study and Water for the Seasons modeling described above.

⁴⁰ TMWA produced a subsequent report in 2025, after earlier drafts of this paper were completed.

Climate Data

The TMWA analyzed eight GCMs with RCP 4.5 and RCP 8.5 emission forcing from the CMIP5 dataset. The eight GCMs were selected based on existing climate change research completed for the northern Sierra Nevada (Lynn et al. 2015). These 16 projections were divided into two scenarios consisting of an 8-projection ensemble described by emission scenario (low and high emission). In addition, TMWA developed a historical ensemble of nine different hydrologic patterns that were used to test current river and reservoir operations under future demand projections.

Rainfall-runoff Modeling

The 16 projections were run through the Truckee GSFLOW and PRMS models developed during the Water for the Seasons project.

Operational Modeling

Output from the GSFLOW and PRMS models was input to the TROA Planning Model to determine if TMWA could meet the changing supply and demand needs of its customers.

Summary of Results

Results from the historical ensemble runs show that TMWA's water supply is resilient enough to withstand a repeat of any of the major droughts on record without any shortages, even under increased projected demand. In the RCP 4.5 moderate emission scenario, model results show that there would be no shortages in any of the 8 GCMs until the year 2083. In comparison, the RCP 8.5 high emission scenario shows shortages occurring first in 2070 and then more often after that through 2098 with the last 14 years showing shortages in at least one of the 8 GCMs.

Climate Change in the Carson Valley (2021)

The "Integrated Hydrology, Operations Modeling and Climate Change in the Carson River Valley" (Kitlaster et al. 2021) study applied an integrated groundwater-surface water model and hydrologic river operations model to the Carson Valley to evaluate the impacts of climate change on the snow-fed agricultural systems. The study explicitly models the conjunctive use of surface water and groundwater and accounts for feedback between the natural hydrology and anthropogenic responses. This allows for shifting to groundwater use to offset diminished surface water deliveries and changing river diversions in response to earlier snowmelt runoff and water availability.

Climate Data

Climate change was simulated by superimposing an increase in temperature of 1 to 5 °C on the historical climate data. All other climate parameters were held constant at historical values.

Rainfall-runoff Modeling

The study linked an operations model to a hydrologic model to explore the impacts of climate change on water rights in the Carson River Valley (Kitlasten et al. 2021). It developed Groundwater and Surface-water FLOW (GSFLOW) models of both the East and West Fork of the Carson River run in ‘PRMS-only’ model. The operations model used is MODSIM and it is coupled to the GSFLOW model of the Carson River Valley. The Carson River Valley GSFLOW model simulates both surface and groundwater dynamics using the linked PRMS and USGS modular hydrologic models.

The two upper watershed GSFLOW models that were run in ‘PRMS-only’ mode were calibrated by adjusting parameters controlling solar radiation, temperature, and evapotranspiration in the watersheds to match the annual water balance. After water balance calibration, parameters impacting snow processes were calibrated using the Moderate-resolution Imaging Spectroradiometer (MODIS) dataset that estimates the fractional snow-covered area within the watersheds. Finally, additional calibration of parameters that impact overland runoff and subsurface storm streamflow were adjusted using the daily time series from two USGS gages (USGS ID 10309000 and 10310000).

Operational Modeling

Streamflow from the two PRMS models was applied as inflows to the Carson River Valley GSFLOW-MODSIM simulation. The Carson Valley integrated model was calibrated using a combination of USGS streamflow gages, 14 gaging stations maintained by the Federal Water Master, annual pumping totals for irrigation wells, and basin-wide pumpage totals. Transient water level records were used to constrain groundwater levels, irrigation rates, efficiency factors, and model parameters controlling evapotranspiration calculations.

Summary of Results

Results from the integrated model runs suggest that earlier snowmelt will decrease annual surface water deliveries to all water rights in the Carson Valley as there is minimal storage available to catch earlier runoff. This could result in a regional shift toward greater reliance on groundwater for irrigation. Alternatively, downstream water users in the Newlands Project benefit from earlier snowmelt due to the Project’s access to storage in Lahontan Reservoir. Overall crop consumption (a common surrogate for crop yield) decreases due to spatiotemporal changes in water supply that preferentially impact a subset of growers in the region.

West-Wide Climate and Hydrology Assessment (2021)

The 2021 West-Wide Climate and Hydrology Assessment (Reclamation 2021b) is the technical companion document to the 2021 SECURE Water Act Report to Congress (Reclamation 2021a). The assessment investigated projected changes in climate and hydrology across key watersheds in the Western United States.

Climate Data

The 2021 West-Wide Assessment used LOCA statistically downscaled CMIP5 climate and streamflow projections to assess projected changes to hydroclimate across the West at a 1/6-degree (approximately 6 km) grid resolution. The 64-projection ensemble included 32 GCMs run at both the RCP 4.5 and RCP 8.5 emission scenarios. The same 64 LOCA-CMIP5 projections are used in the Pilot Study.

Rainfall Runoff Modeling

The 2021 West-Wide Assessment developed hydrology projections by running the LOCA-downscaled climate projections through the Variable Infiltration Capacity (VIC v4.2c; (Liang et al. 1996) hydrological model. The analysis reported on six hydroclimate variables: annual mean temperature, annual total precipitation, April 1 snow-water equivalent, annual runoff, December–March runoff, and April–July runoff. Routed streamflow was also developed for five locations in the Truckee and Carson River Basins.⁴¹

Streamflow Reconstructions

The report also investigated drought events through a reconstructed and projected drought index. The Palmer Drought Severity Index (PDSI) (Palmer 1965) was used to define drought events from 1473 to 2005, as it focuses on droughts driven by hydroclimate variability. The PDSI dataset provides tree-ring based reconstructions of average June through August PDSI on a 0.5-degree grid resolution. Future projections of PDSI were developed from 1950 to 2099 using the Wells (2003) model for computing PDSI using LOCA-CMIP5 climate projections. Drought duration for the historical and projected periods was then spatially-aggregated to 8-digit Hydrologic Unit Codes across the Western United States.

Further analyses in the report use water-year annual streamflow reconstructions based on tree-rings. Tree ring reconstructions can go back over 1,000 years and help characterize long-term patterns of variability that influence drought and flood risk. Tree-ring reconstructions are developed using a statistical correlation of tree growth patterns to an observed streamflow

⁴¹ Little Truckee River below Boca Dam; West Fork Carson River at Woodfords; Truckee River at Farad gage; Truckee River at Nixon gage; Carson River at Fort Churchill gage.

record. There was one available tree-ring reconstruction of anomaly streamflow on the Carson River near Fort Churchill, NV (“Fort Churchill gage”, USGS ID 10312000) with the data available from TreeFlow (www.treeflow.info/). The anomaly streamflow was then translated into a streamflow reconstruction for use in the Assessment. The annual streamflow reconstruction was then disaggregated to a daily time series using the pattern of observed streamflow.

Operations Modeling

This daily streamflow reconstruction was then used to inform all inflows for all necessary locations to run through the TROA Planning Model. This daily distant past paleohydrology (paleo)-reconstructed streamflow time series will also be used in the Pilot Study.

Summary of Results

Results from the 2021 West-Wide Assessment focus on time series of the six hydroclimate variables at the Nixon gage on the Truckee River. Total annual precipitation is projected to be fairly constant over time, although it appears that interannual variability might also be increasing over time. Annual mean temperature is projected to increase by approximately 7 degrees Fahrenheit (°F) from 2000 to 2099. April 1 snow-water equivalent, annual runoff, and April through July runoff all show a decrease over time while December through March runoff show an increase over time. Overall, the median basin snowpack is projected to decrease with increasing temperatures throughout the basin and a slight projected increase in basin precipitation. Streamflow projections show noticeable shifts in the distribution of monthly streamflow, although a significant shift in the peak runoff does not occur until the 2070s.

Results of the PDSI drought analysis for the 8-digit Hydrologic Unit Codes located in the Carson and Truckee River Basins first compared observed and simulated (projections) mean drought duration and drought severity over a common period. Simulated drought duration and severity for the projections is biased high compared to the observed record. This is important to take into consideration when looking at what projected drought simulations might suggest. When comparing historical mean drought duration to projected mean drought duration, it appears the mean drought duration will increase from approximately 2–3 years to 3–4 years (RCP 4.5 ensemble) or 3–5 years (RCP 8.5 ensemble).

Results from the tree-ring streamflow reconstruction suggest that the largest drought on record occurred over 14 years from 1923 to 1936. After running select paleo-droughts through the TROA operations model, water supply metrics related to Lake Tahoe were investigated. During most of the recorded droughts, lake level dropped below the natural rim of the lake (6,223 feet) which means that storage can no longer be released for downstream use. These estimated lake levels likely occur due to evaporation and reduced inflows. After a paleo drought in the 1700s, it took lake levels approximately 7 years to return to operable ranges.

The April 1 pool elevation of Lake Tahoe is also an important metric for distributing seasonal water supply to downstream users. On average, the April 1 pool elevation from 1901 to 2017 was 6,226 feet, which is 3 feet above the natural rim of the lake. Over the course of the two historical droughts during that same period, the April 1 pool elevation was 6,221 feet (14-year drought) and 6,225 feet (5-year drought). Over the paleo droughts, the average April 1 pool elevation was found to be 6,223 feet and 6,225 feet.

Another important water operations metric in the basin is the number of days the Floriston Rates are met, a designated flow rate required to flow past Floriston, CA, daily. Over the historical period, the Floriston Rates are met 83 percent of the days. However, during the 14-year drought period Floriston Rates were only met 38 percent of the days.

The last metric that was evaluated was the average number of days during a drought that the Carson Division of the Newlands Project experienced a shortage and did not receive its full allocation. Over the historical period Carson Division Demand is met about 93 percent of the time. Interestingly, the number of days Carson Division Demand is met is not significantly altered during any of the historical or paleo droughts.

Flood events were also considered using this long reconstructed time series; however, the percentage of flood days over the course of the 117-year historical period and the paleo-period was very low and much less of a concern than droughts.

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Appendix C

TROA Planning Model Ruleset Changes

Appendix C: TROA Planning Model Ruleset Changes

LT Releasable Floriston Rate Inflow – Function

This function was updated to limit releases from Boca Reservoir (specifically the “BocaData.LTReleasableFRInflow” variable) to the maximum possible release from the reservoir given the inflow.

Updated Code

```
1 BocaData.LTReleasableFRInflow []
4 = Min (Boca.Hydrologic Inflow [],
10 + # Changed This to Net Precip. -HG 11/22/13
11 Max (VolumeToFlow (Boca, "Precipitation Volume" [], ),
18 - VolumeToFlow (Boca, "Evaporation" [], ),
19 0.00 "cfs"
24 + Stampede.Hydrologic Inflow []
26 + Max (VolumeToFlow (Stampede, "Precipitation Volume" [], ),
29 - VolumeToFlow (Stampede, "Evaporation" [], ),
36 0.00 "cfs"
42 + IF (IndependenceHasStored3000 ()) THEN
43 Independence.Hydrologic Inflow []
46 + Max (VolumeToFlow (Independence, "Precipitation Volume" [], ),
49 - VolumeToFlow (Independence, "Evaporation" [], ),
56 0.00 "cfs"
57 ELSE
58 0.00 "cfs"
59 END IF
60 GetMaxOutflowGivenInflow (Boca,
61 NaNToZero (Boca.Inflow [@"t"] ),
71 @@"t")
```

Original Code

```

1 BocaData.LTReleaseableFRInflow []
4 = Boca.Hydrologic Inflow []
9 + # Changed This to Net Precip. +HG 11/22/13
10 Max ( VolumeToFlow ( Boca . "Precipitation Volume" [], ) )
17 - VolumeToFlow ( Boca . "Evaporation" [], ) ,
23 @ "t"
24 0.00 "cfs"
25 + Stampede.Hydrologic Inflow []
28 + Max ( VolumeToFlow ( Stampede . "Precipitation Volume" [], ) )
35 - VolumeToFlow ( Stampede . "Evaporation" [], ) ,
36 @ "t"
41 0.00 "cfs"
42 + IF ( IndependenceHasStored3000 ( ) ) THEN
43 Independence.Hydrologic Inflow []
45 + Max ( VolumeToFlow ( Independence . "Precipitation Volume" [], ) )
48 - VolumeToFlow ( Independence . "Evaporation" [], ) ,
51 @ "t"
52 0.00 "cfs"
53 ELSE
54 0.00 "cfs"
55 END IF

```

"CalPreferredAvailableReleaseChange" Function

This function can trigger additional Stampede releases which must pass through Boca Reservoir. When storage is unusually low in Boca, the reservoir may not be able to pass these additional releases. The MaxOutflow calculation was adjusted (only for Stampede Reservoir) to limit additional release to the remaining possible Boca Reservoir release volume.

Updated Code

```

296 STOP_RUN TargetProcess CONCAT " is not a valid Borrow reservoir target for the Cal Preferred flow logic"
297 END IF
300 END IF
301 # If reservoir is
302 # stampede,
303 # make sure
304 # Boca has
305 # additional
306 # capacity to
307 # release pass
308 # through
309 IF ( reservoir == Stampede ) THEN
310 CheckThisResPhysicalConstraints ( Boca ,
311 99,999.00000000 "cfs" ) - GetTotalTheoreticalOutflow ( reservoir ,
312 @ "t" )
313 ELSE
314 99,999.00000000 "cfs"
315 END IF
316 0.00000000 "cfs"

```

“WaterAvailableforFR” Function

This function can increase Stampede Reservoir releases which must pass through Boca Reservoir. If Boca Reservoir storage is low, these additional releases may exceed its release capacity. The authors updated the limit the release capacity calculation for Independence and Stampede Reservoirs to the remaining amount of release available at Boca Reservoir.

Updated Code

```

( "ALL" )
WITH NUMERIC remainingReleaseCapacity = IF ( reservoir == Independence ) THEN DO
( OR reservoir == Stampede )
Min ( CheckThisResPhysicalConstraints ( reservoir ,
999,999,999.00000000 "cfs" )
- ( STRINGIFY reservoir ) CONCAT "ReleaseComponents.TheoreticalOutflow" [ ] ,
# Check to ensure Boca can
# release any more
CheckThisResPhysicalConstraints ( Boca ,
999,999,999.00000000 "cfs" )
- ( Boca CONCAT "ReleaseComponents.TheoreticalOutflow" [ ]
+ Boca CONCAT "ReleaseComponents.TotalPassThru" [ ] )
)
ELSE
CheckThisResPhysicalConstraints ( reservoir ,
999,999,999.00000000 "cfs" )
- ( STRINGIFY reservoir ) CONCAT "ReleaseComponents.TheoreticalOutflow" [ ]
END IF

```

Original Code

```

WITH NUMERIC remainingReleaseCapacity = CheckThisResPhysicalConstraints ( reservoir ,
999,999,999.00000000 "cfs" )
- ( STRINGIFY reservoir ) CONCAT "ReleaseComponents.TheoreticalOutflow" [ ] DO

```

“IdentifyHoldbackAndTransferSupplies” Function

The function “SupplyNamesFromIntra” returned a supply name that doesn’t exist (the “holdbackPartyOrExchangeName” was “IndependenceFRPassThruLTAbvStpFRPassThru_FR.Supply”). This function was updated to check the length of the returning supply names, if it is empty, it will move on to the next item in the loop. PWRE is further evaluating the model to determine how it returned a supply name that does not exist.

Updated Code

```
WITH LIST transferSupplylist = SupplyNamesFromIntra ( { { reservoir , SupplyList <1> } } , holdbackPartyOrExchangeName , "ALL" ) DO
# L. Thatch added 1/7/2024 - Problem if 'SupplyNamesFromIntra' Doesn't Returns an empty list. If
# transferSupplylist is empty, return previous result
IF ( transferSupplylist == { } ) THEN
    result
ELSE
    WITH STRING transferSupply = # This takes the source account to the outflow supply and finds the appropriate transfer supply for the current scheduling party.
                                # It assumes that there is only one transfer supply from each source account for each scheduling party, that is why the index is zero here.
                                transferSupplylist <0>
    WITH STRING transferSupplyName = transferSupply CONCAT ".Supply" DO
        APPEND { outflowSupplyName , reductionAmount , transferSupplyName , reductionStillNeeded - reductionAmount } ONTO result
    END WITH
END WITH
END IF
```

Original Code

```
WITH STRING transferSupply = # This takes the source account to the outflow supply and finds the appropriate transfer supply for the current scheduling party.
                             # It assumes that there is only one transfer supply from each source account for each scheduling party, that is why the index is zero here.
                             SupplyNamesFromIntra ( { { reservoir , SupplyList <1> } } , holdbackPartyOrExchangeName , "ALL" ) <0> DO
WITH STRING transferSupplyName = transferSupply CONCAT ".Supply" DO
    APPEND { outflowSupplyName , reductionAmount , transferSupplyName , reductionStillNeeded - reductionAmount } ONTO result
END WITH
```

Appendix D

Discussion of Streamflow Bias Correction

Appendix D: Discussion of Streamflow Bias Correction

Introduction – Bias Correction of Streamflow

Bias correction of streamflow refers to the statistical adjustment of streamflow outputs from hydrological models to reduce systematic discrepancies relative to observed records. Raw streamflow simulations driven by climate model outputs often exhibit persistent biases in magnitude, variability, and extremes. As such, bias-correction methods—such as quantile mapping or distribution-based scaling—can be applied to align modeled and observed flow distributions over a historical reference period. In climate change studies, this process is used to improve the reliability of impact assessments, under the assumption that correcting historical biases enhances the credibility of projected future changes when the same correction is applied to scenario simulations.

This study bias-corrected the climate model outputs (temperature and precipitation) before inputting these into the PRMS hydrological model. Analyses were then conducted on PRMS output to determine whether systemic biases existed and whether bias-correction methodologies could decrease identified biases before inputting the streamflow data into the RiverWare nodes, described in the following sections.

While streamflow bias correction using the combined cumulative distribution function (CDF) method (refer to Section 3.3.1 Bias Correction of Climate Data) appears promising for reducing streamflow biases, the inflows to most of the reservoirs in the Truckee-Carson Basins that are part of the Truckee River Operating Agreement (TROA) dataset contain negative values at the daily and monthly timescales. Negative inflows are problematic in bias-correction procedures and often inflate biases. This appendix contains an exploratory analysis to understand the extent of negative values in the TROA dataset reservoir inflows.

The exploration work shows that an annual CDF bias-correction approach is effective in removing systematic biases in Lake Tahoe inflows, but similar approaches at other reservoirs have little impact. As a result, the study team chose only to bias correct Lake Tahoe inflows and to use a CDF bias-correction of annual streamflow. The following discussion provides insights into this choice.

Lake Tahoe Basin

Climate/Water Balance (figure D-1)

- Precipitation increases in the future during the winter and spring months.
- Temperature increases in the future lead to less snow-water equivalent (SWE) in all months and more runoff in winter months.

- Lake Tahoe inflows thus increase in the future during the winter months and decreases during May–July. Tahoe inflows illustrated in figure D-1 are based on PRMS simulated inflows and do not incorporate corrections for bias.
- The future has a lot more outliers/extremes in precipitation during all months, SWE during most winter and spring months, runoff in all months except summer.

Negative Inflows (table D-1)

- Lake Tahoe has negative daily inflows and negative inflows sum to about 24 percent of the magnitude of the positive inflows.
- TROA still has negative inflows for Lake Tahoe on a monthly scale – but negative flows are less than 3 percent of the total positive streamflow.
- There are no negative Lake Tahoe inflows on an annual scale The study team developed a bias correction method based on annual CDFs, which is described later.

Bias-Correction (figure D-2, figure D-3, and table D-2)

- Lake Tahoe inflows in general appear to increase in the future during winter months but decrease in the future during spring months and stay relatively low/stable during summer months.
- Bias correction based on correction factors derived from annual CDFs improves statistics for Lake Tahoe inflows comparing daily, monthly, and annual flows to the TROA Planning Model dataset net inflows (table D-2).

Overall

It is apparent that bias-correcting Lake Tahoe inflows on a daily or monthly scale is not ideal given all the negative inflows within the TROA dataset. Bias-correction was performed on an annual scale using a quantile-mapping bias correction method based on comparing annual CDFs of PRMS simulated streamflow and natural streamflow from the TROA Planning Model dataset.

Table D-1.—Daily and monthly negative flows*

Location**	Count of Negative Flows		Fraction Comparing Negative Flow Total To Positive Flow Total	
	Daily (n = 12,875)	Monthly (n= 423)	Daily	Monthly
Boca Reservoir	1,554	48	0.029	0.025
Donner Reservoir	208	3	0.001	0.000
Independence Reservoir	157	4	0.001	0.001
Prosser Creek Reservoir	239	6	0.001	0.000
Stampede Reservoir	26	0	0.000	0.000
Lake Tahoe Inflow	3,895	118	0.242	0.025

* There are no negative flows on an annual scale. If a location is not listed, there are no daily negative flows at that location.

** Boca Reservoir and Lake Tahoe inflows are from 1986–2015 (daily n=11,049, monthly n=363); all other locations are from 1980-10-01 through 2015.

Table D-2.—Statistics comparing raw and bias-corrected Precipitation Runoff Modeling System streamflow to Truckee River Operating Agreement streamflow from 1986 through 2015

Location	Streamflow Data	Daily			Monthly			Annual		
		Percent Bias (%)	NSE (-)	RMSE (AF)	Percent Bias (%)	NSE (-)	RMSE (AF)	Percent Bias (%)	NSE (-)	RMSE (AF)
Lake Tahoe inflow	Bias-corrected	0	0.14	2399	0	0.73	17054	0	1.00	0
	Raw	68	0.09	2474	68	0.62	20258	68	0.16	146434

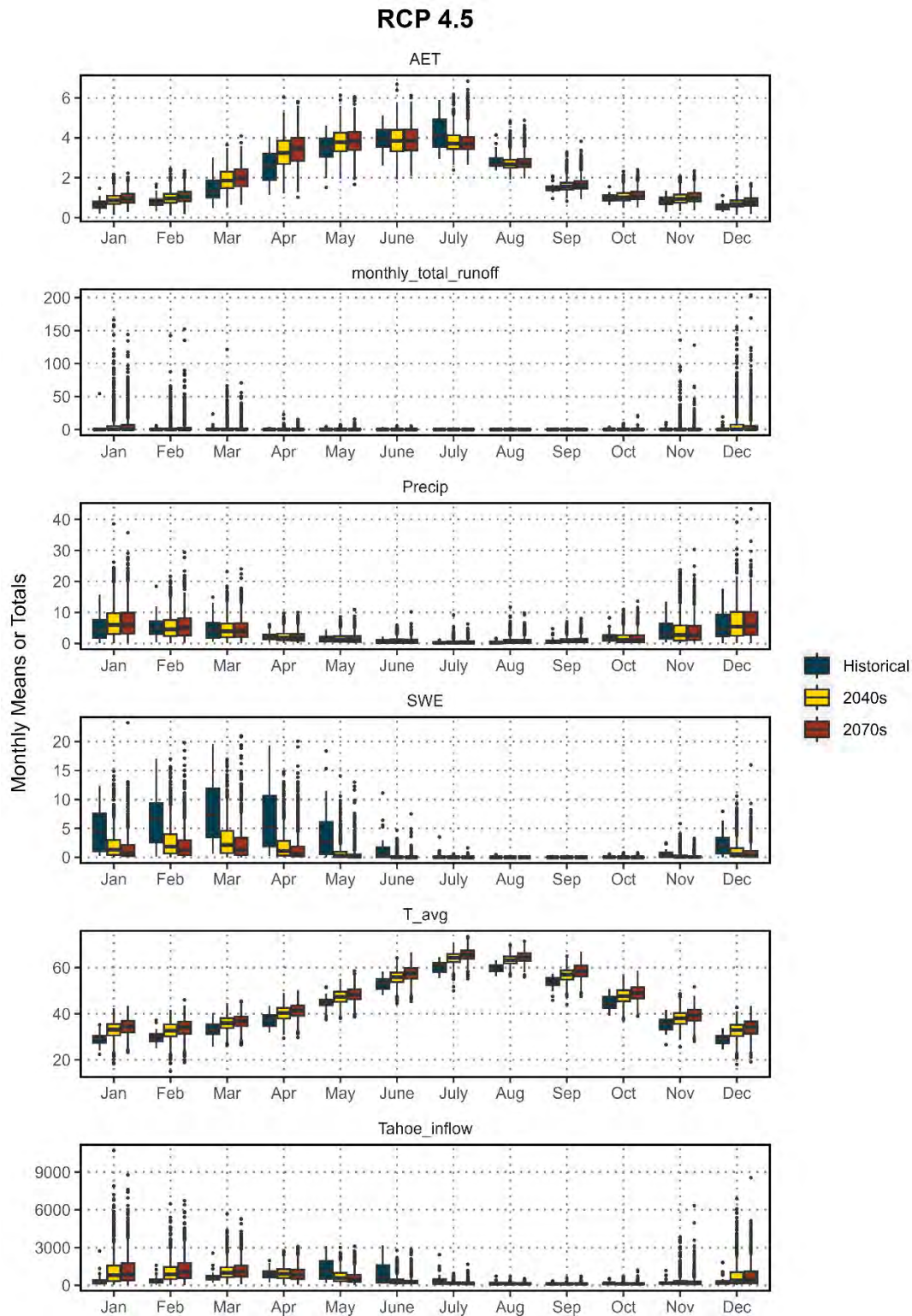


Figure D-1.—The distribution of water balance components monthly means or totals from the historical period (1986–2015), 2040s (2031–2060), and 2070s (2061–2090) over Lake Tahoe based on PRMS simulations (uncorrected).

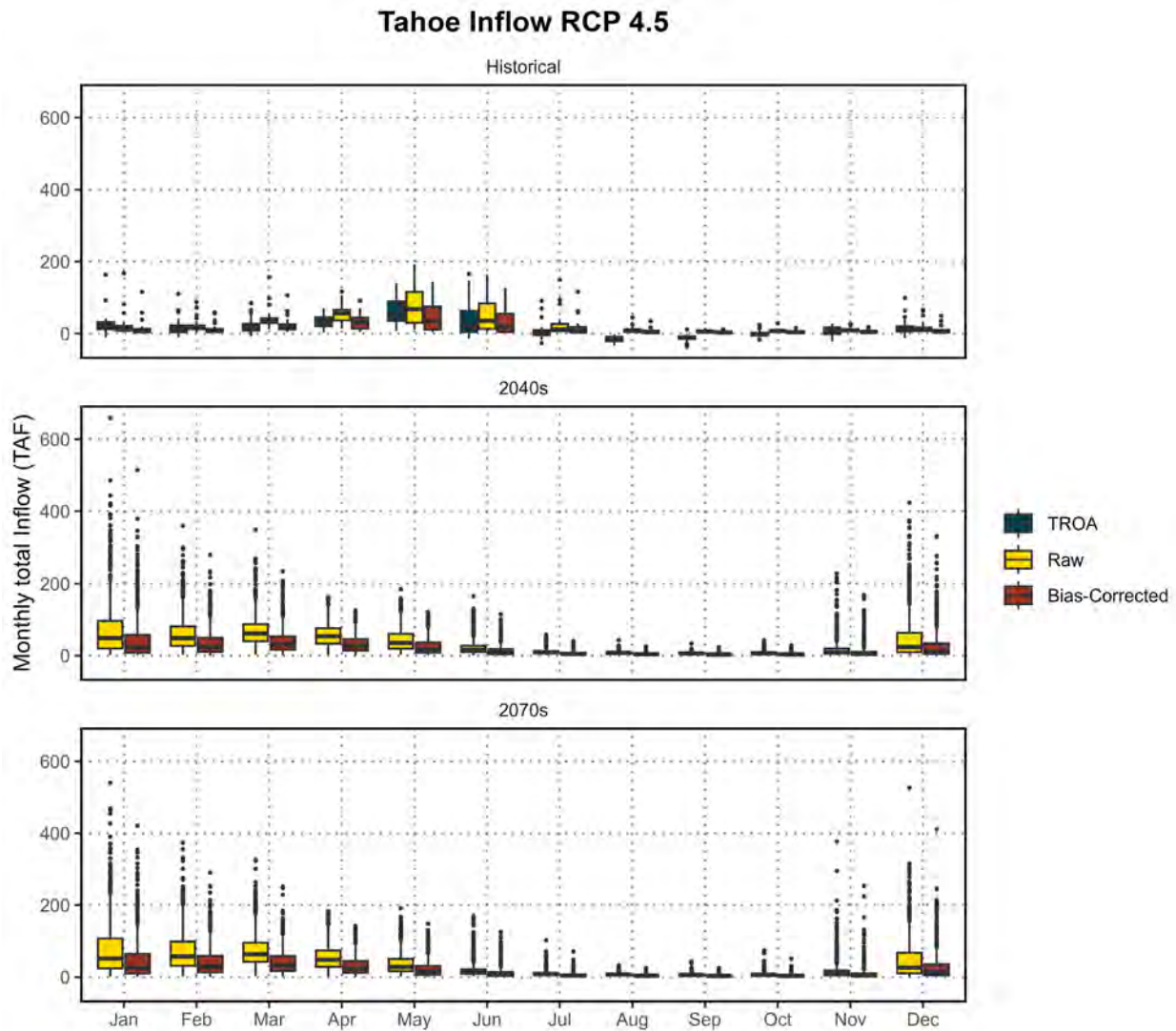


Figure D-2.—Monthly mean total inflows into Lake Tahoe: from the Truckee River Operating Agreement dataset (blue), raw Precipitation Runoff Modeling System inflows (yellow), and bias-corrected inflows (red) for three 30-year periods: historical period (1986–2015), 2040s (2031–2060), and 2070s (2061–2090) based on CMIP5 LOCA downscaled projections with RCP45.⁴²

⁴² Futures show monthly means from the 32 RCP 4.5 GCM ensemble.

Little Truckee River Basin – Boca, Independence, and Stampede Reservoirs, and Sidewater

Climate/Water Balance (figure D-3)

- Precipitation increases in the future during **most** winter and spring months
- Temperature increases in the future lead to a lot less SWE in all months and a lot more runoff in winter months
- Flows at all four locations are anticipated to increase during November–March (winter months) and decrease in the spring to early summer months (May–July). April flows look similar in future and historical simulations.
- The future has a lot more outliers/extremes in precipitation during all months, SWE during most winter and spring months, runoff in all months except summer and flows at all four locations.

Negative Inflows

- Boca Reservoir has the most negative inflows of the four locations in the Little Truckee River Basin with 2.9 percent of daily inflows being negative. Stampede and Independence Reservoirs only have 0.1 percent of daily flows being negative, while Sidewater has no negative flows in the TROA dataset.
- Both Boca and Independence Reservoirs have a few negative monthly flows.
- There are no negative inflows on an annual scale.

Bias-Correction

- These reservoirs have fewer negative inflows based on the TROA Planning Model dataset, which may support a form of streamflow bias correction; however, summary statistics (not reported here) were sufficient to support use of uncorrected simulated reservoir inflows (daily NSE greater than 0.4, monthly NSE greater than 0.4, annual NSE greater than 0.8, based on underrepresented streamflow as noted above).

Overall

- Overall, bias-correction for all four locations in the Little Truckee River Basin appears unnecessary based on negative inflows in the TROA Planning Model dataset and reasonably good, simulated streamflow statistics. Future streamflow trends seem to be represented well given the water balance trends.

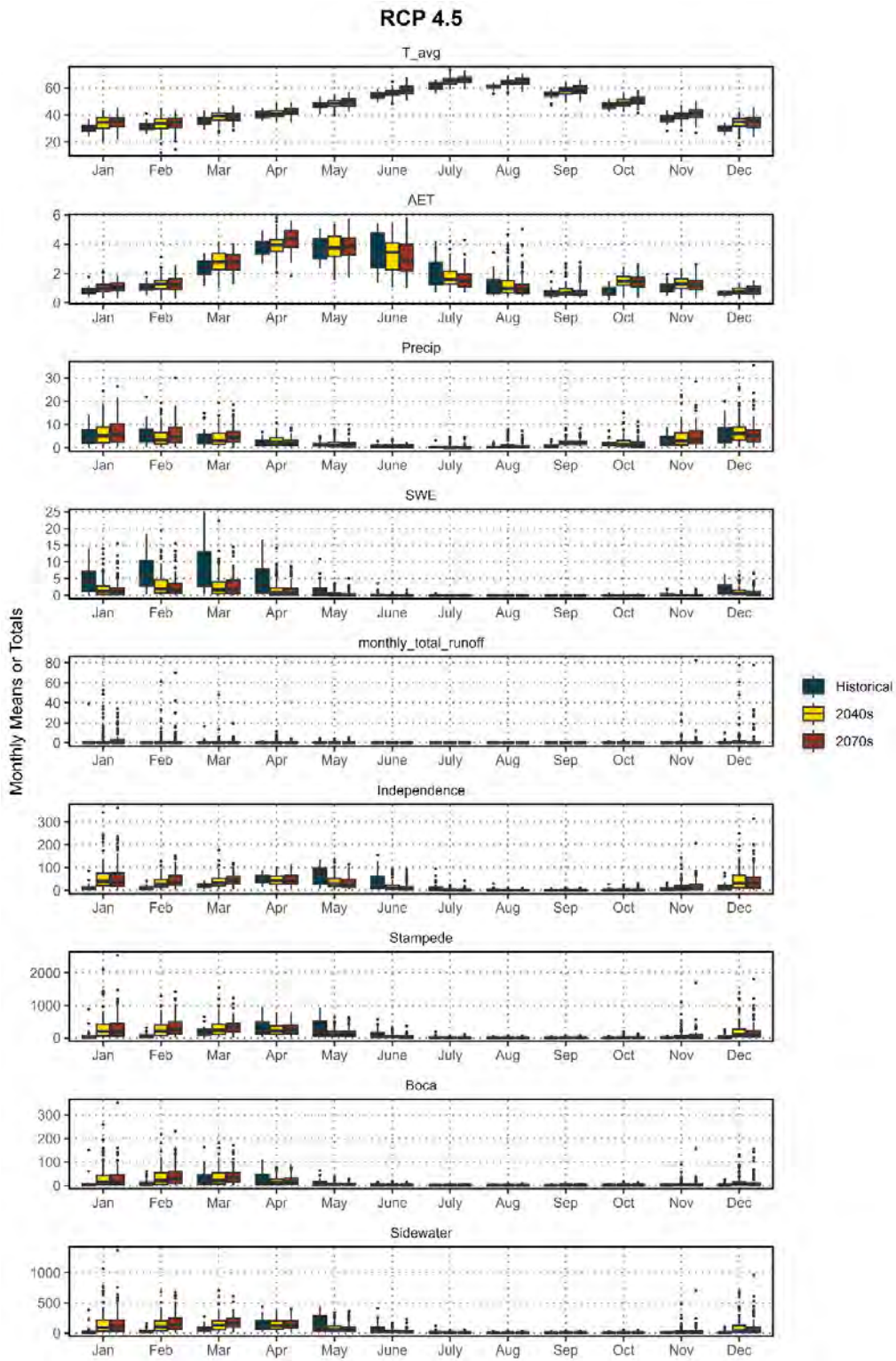


Figure D-3.—The distribution of water balance components monthly means or totals from the historical period (1986–2015), 2040s (2031–2060), and 2070s (2061–2090) for the Little Truckee River Basin.

Martis Creek Basin – Donner Lake, Martis Creek Lake, Prosser Creek Reservoir, BlwTahoe, and BlwDonner

Climate/Water Balance (figures D-4 and D-5)

- Precipitation increases in the future during the following months: January, April, May, August, October, November, and December.
- Temperature increases in the future lead to a lot less SWE in all months and a lot more runoff in winter months.
- Flows at all four locations are anticipated to increase during November–March (winter months) and decrease in the spring to early summer months (May–July). April flows look similar in future and historic.
- The future has a lot more outliers/extremes in precipitation during all months, SWE during most winter and spring months, runoff in all months except summer and flows at all four locations.

Negative Inflows

- Prosser Creek Reservoir and Donner Lake both have a similar number (0.1 percent) of daily inflows that are negative.

Bias-Correction

- These reservoirs have fewer negative inflows based on the TROA Planning Model dataset, which may support a form of streamflow bias correction; however, summary statistics (not reported here) were sufficient to support use of uncorrected simulated reservoir inflows (daily NSE greater than 0.3, monthly NSE greater than 0.7, annual NSE greater than 0.9).

Overall

- Overall, bias-correction for all locations in the Martis Creek Basin appears unnecessary based on negative inflows in the TROA Planning Model dataset and reasonably good, simulated streamflow statistics. Future streamflow trends seem to be represented well given the water balance trends.

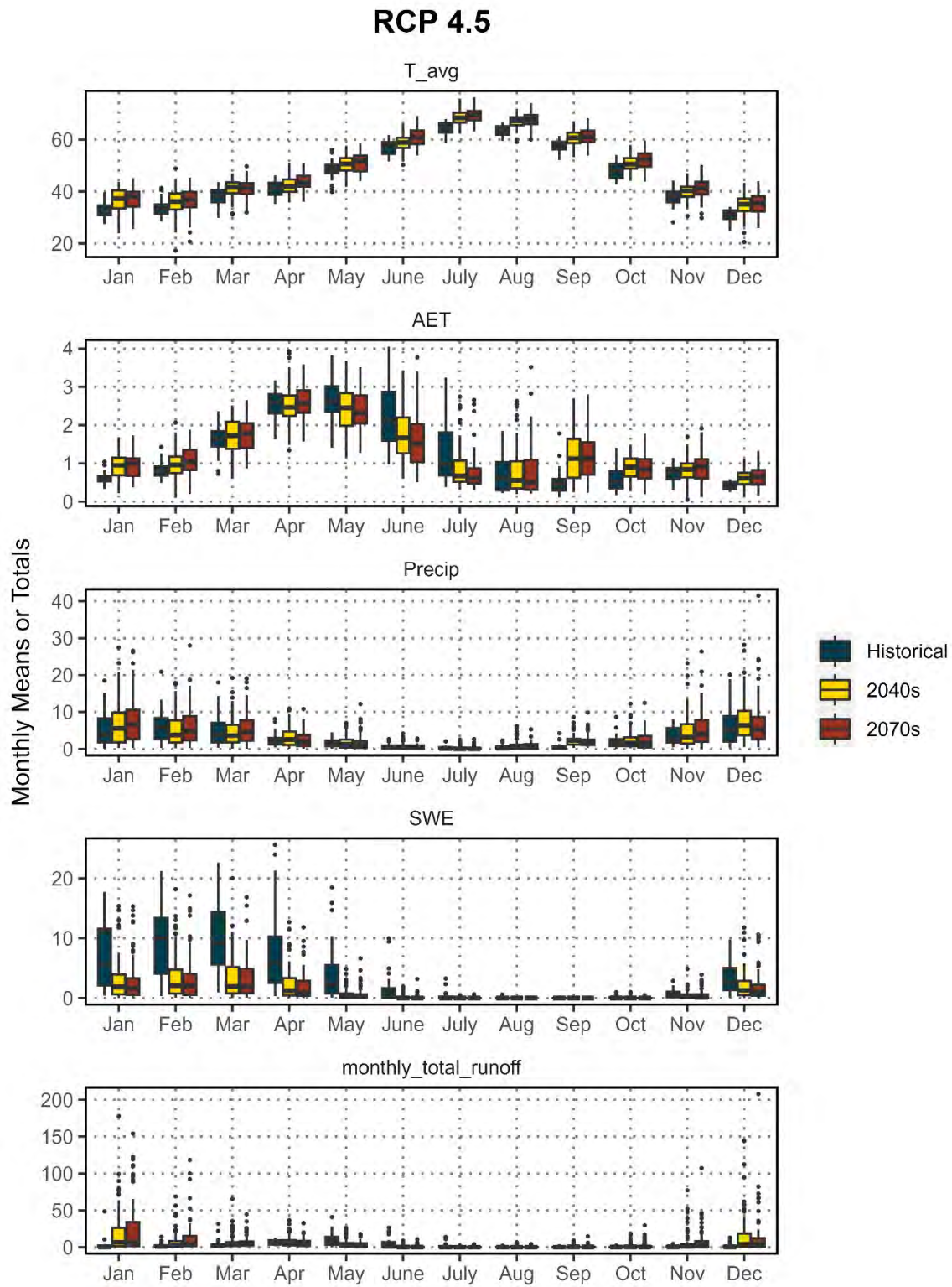


Figure D-4.—The distribution of water balance components monthly means or totals from the historical period (1986–2015), 2040s (2031–2060), and 2070s (2061–2090) for the Martis Creek Basin.

RCP 4.5 - Streamflows

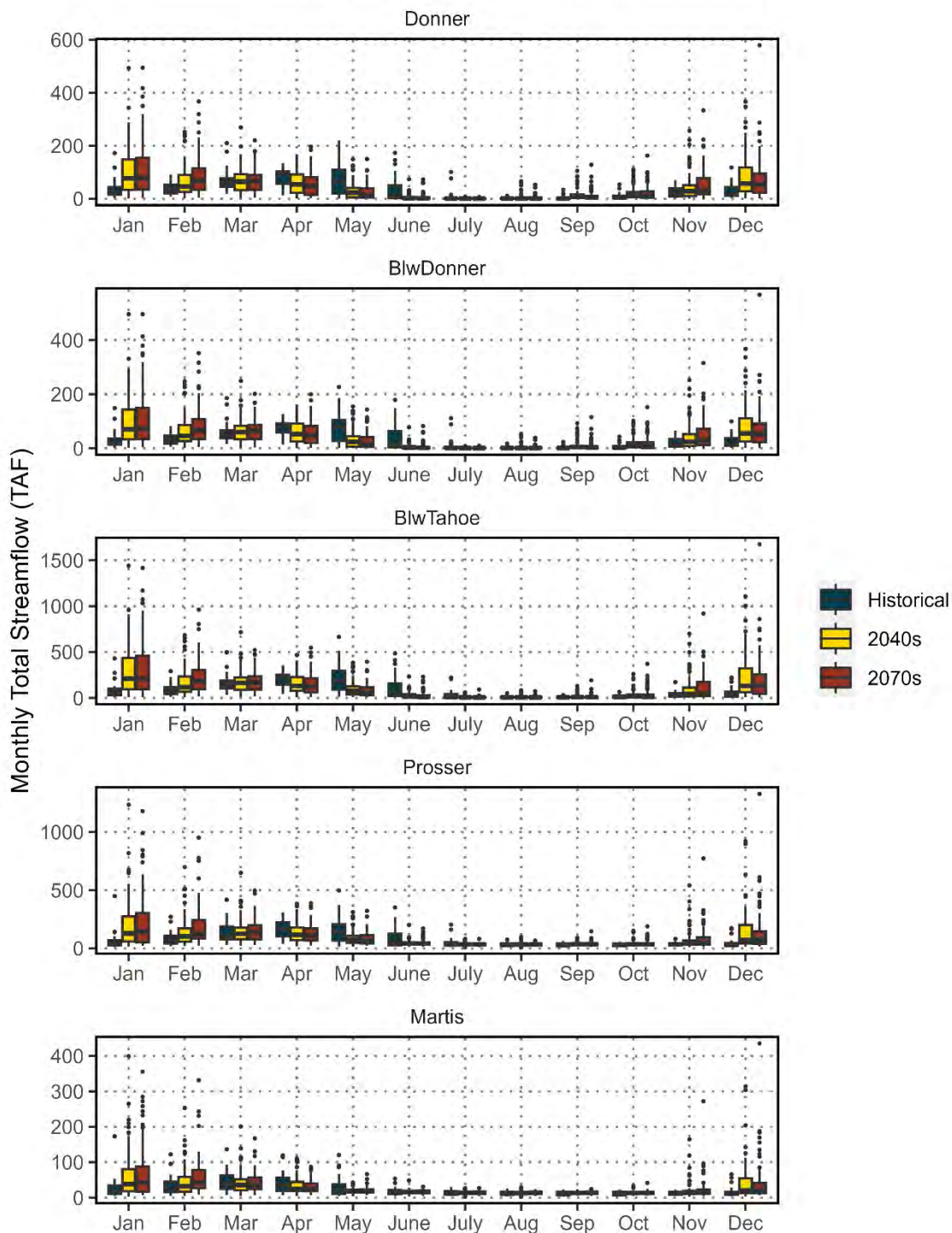


Figure D-5.—The distribution of streamflow in the Martis Creek Basin for the historical period (1986–2015), 2040s (2031–2060), and 2070s (2061–2090).

Annual Bias Correction of Streamflow

Given annual Lake Tahoe inflows are all positive, the study team first explored using an annual factor approach for bias correction. However, this approach was problematic because annual differences between the observed and modeled streamflow are not consistent across all years. The study team instead applied a CDF-based annual bias-correction approach for each location to bias-correct raw PRMS streamflow with the calculated Lake Tahoe inflows based on TROA Planning Model dataset net inflows (see section 3.5). Annual PRMS simulated Lake Tahoe inflow and TROA Lake Tahoe inflows based on the TROA Planning Model dataset have a Spearman correlation of 0.96 over the years 1986–2015. Figure D-6 illustrates annual CDFs for each dataset and consistent bias in PRMS simulated inflows. Highly correlated streamflow data with consistent rank correlation structure, which is illustrated by consistent bias in the CDF, lends itself to a CDF bias correction method.

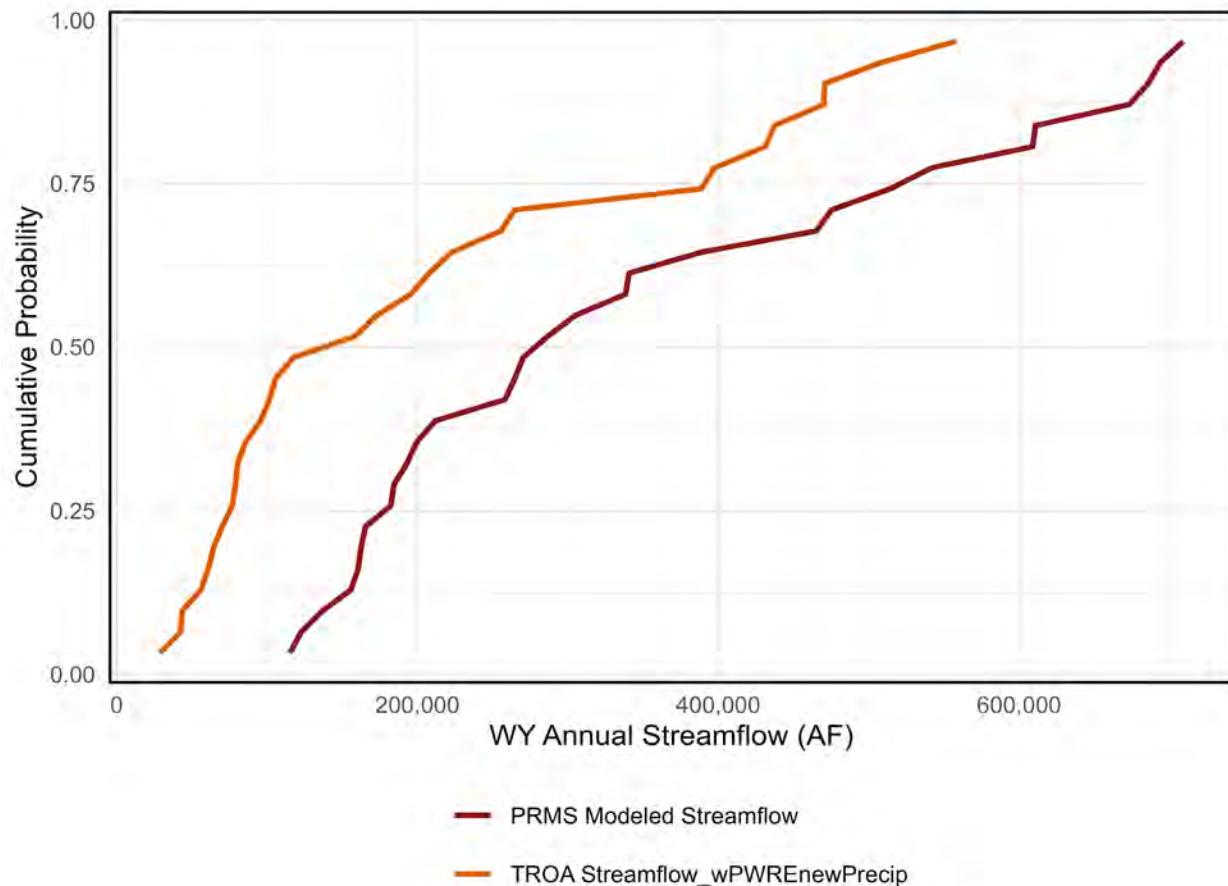


Figure D-6.—The cumulative distribution functions of annual PRMS simulated Lake Tahoe inflow (red) and annual reconstructed natural inflow based on the TROA Planning Model dataset (orange) for the historical period (1986–2015).

Rationale for Bias Correction of Lake Tahoe Inflows

From these analyses, the study team chose to bias-correct the annual Lake Tahoe inflow only. Then, using daily flow contributions to annual flow based on the TROA Planning Model dataset, daily inflows may be developed. The reasoning:

1. Bias-correcting using a CDF approach does not work when the observed dataset has negative inflows.
2. Bias-correcting using an annual factor approach does not work well when annual differences between the observed and modeled streamflow are not consistent across all years.
3. Raw PRMS streamflow compares well at all locations to TROA as it is.
4. Projected changes in streamflow are not stationary (figure D-7). This means historical trends may differ from future trends, and bias correction approaches limit future streamflow to historical distributions. This point is still not addressed in the annual CDF bias correction applied to Lake Tahoe inflows.

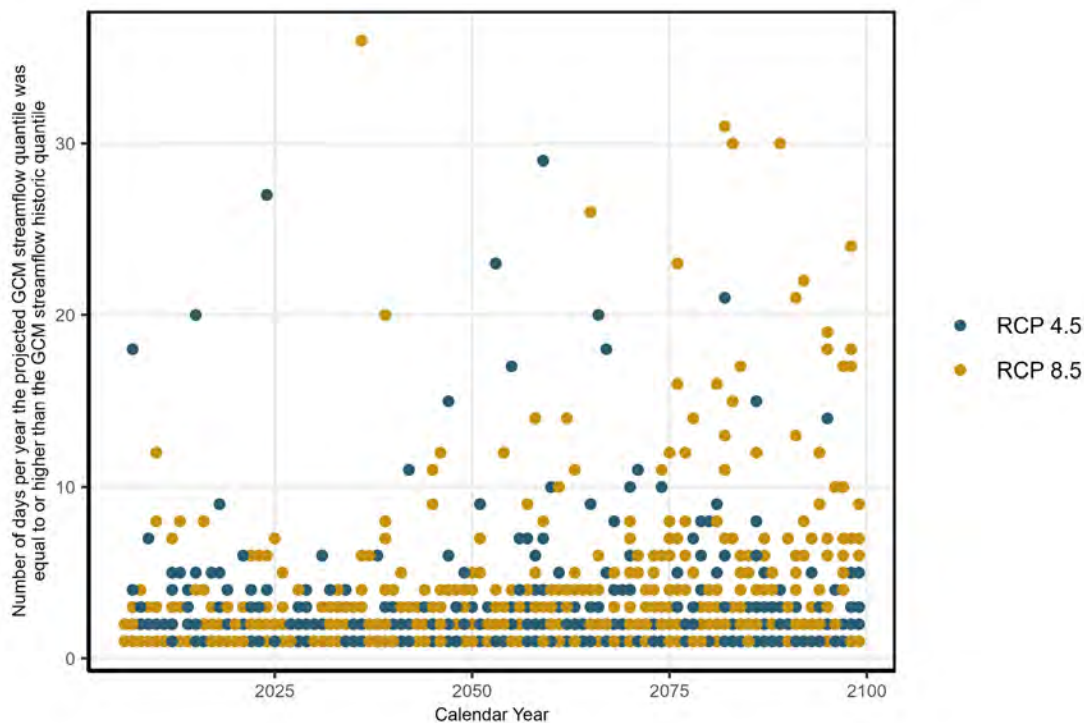


Figure D-7.—The number of days per year where the projected GCM streamflow quantile was equal to or above the historic GCM quantile for Independence Lake inflows using the combined-CDF bias-correction approach.

Appendix E

Data Source Comparisons

Appendix E: Data Source Comparisons

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Introduction

Choices of models and data processing methodologies in the Pilot Study have implications for study results. Examples of method choices discussed in the main report of this Pilot Study include, among others: the definition used to define droughts for drought event analysis (discussed in section 3.1.3); meteorological dataset selection, processing, and use (discussed in sections 4.3.2 and 4.5.2); and, methods for developing a naturalized streamflow dataset such as the TROA Planning Model dataset (discussed in appendix D). These choices can yield markedly different modeled streamflow and water management metrics results. To properly interpret the results, it is essential to understand the differences in climate and hydrologic model inputs and how methodological choices propagate through the modeling framework.

The Pilot Study team scrutinized various aspects of the modeling chain to understand uncertainties and implications of model and dataset choices. The study team speculated that the Precipitation-Runoff Modeling System (PRMS) simulations of Lake Tahoe inflow were biased high. Therefore, the team investigated a variety of variables that influence Lake Tahoe outflow, including precipitation inputs to the PRMS model, as well as precipitation and evaporation over Lake Tahoe. The study team also re-examined PRMS simulations and bias correction methods for PRMS-simulated Lake Tahoe inflows (discussed further in appendix D). This appendix documents comparisons made with models and datasets used in previous studies. Comparisons are organized by the following sections:

- Precipitation Dataset Comparison,
- Comparisons Related to Lake Tahoe Evaporation, and
- Modeled Lake Tahoe Inflow Comparisons.

Precipitation Dataset Comparison

The Pilot Study incorporated various sources of precipitation data. Station observations over a historical period of 1980–2015 were used as input for historical simulations of the PRMS model. The historical gridded precipitation dataset at 1/16-degree (approximately 6 km) spatial resolution developed by Livneh et al. (2015; hereafter called the Livneh dataset) was used as the training data for downscaling of CMIP5 climate projections (spanning 1950–2099) used in the Pilot Study. The historical gridded precipitation dataset called nClimGrid, developed by Durre et al. (2022) at 5-km spatial resolution, while not used by the Pilot Study, was included in a comparison of monthly precipitation alongside station data and the Livneh dataset. The purpose of the comparison was to identify differences between datasets and potential sources of bias in Pilot Study modeling components.

A comparison of monthly total precipitation from 1980 to 2015 was performed for 2 of the 19 climate stations used as input to the PRMS models for the Truckee and Carson River basins (see table 2 in the main report). Station 19k07s is the Mt Rose SNOTEL site located northeast of Lake Tahoe. Station 20I02s is the Rubicon No. 2 SNOTEL site located southwest of Lake Tahoe (see figure 1 in the main report).

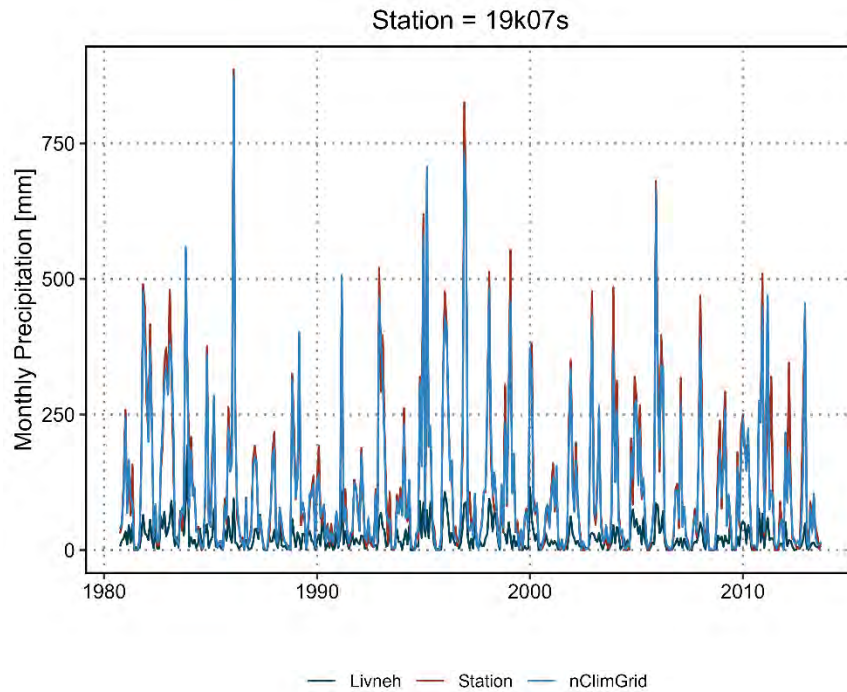


Figure E-37.—Comparison of monthly total precipitation (mm) for calendar years 1980–2015 between the Livneh dataset, station data, and nClimGrid daily dataset at the Mt Rose SNOTEL site.

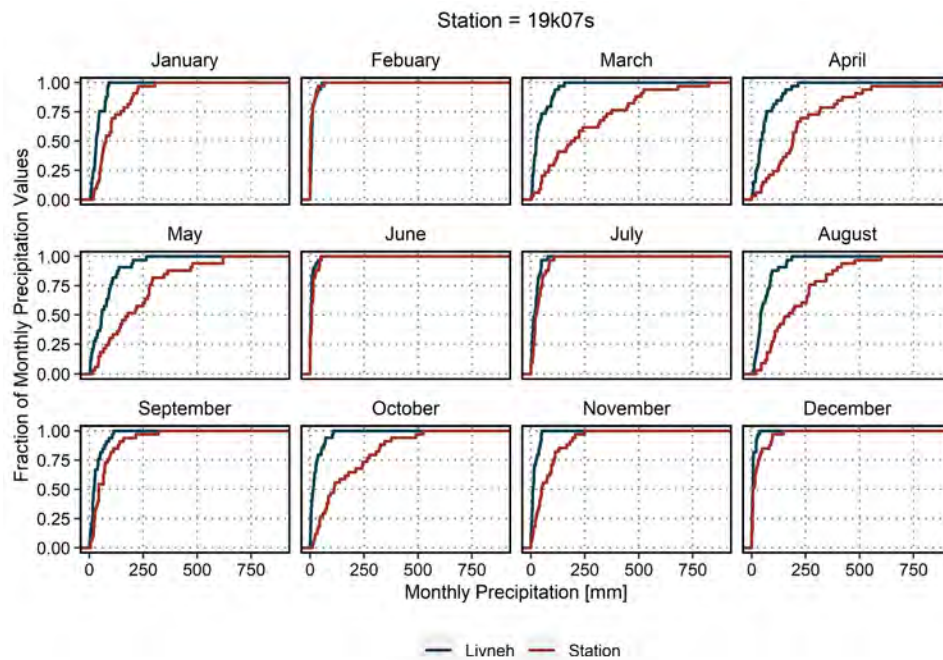


Figure E-38.—Comparison of CDFs of monthly total precipitation (mm) for calendar years 1980–2015 between the Livneh dataset and station data at the Mt Rose SNOTEL site (ID 19k07s).

Figure E-1 illustrates monthly total precipitation at the Mt. Rose SNOTEL site. Monthly total precipitation observations at the Mt. Rose SNOTEL site compare closely with precipitation at the nClimGrid grid cell that encompasses this site. Monthly total precipitation at the Livneh dataset grid cell that encompasses the Mt. Rose SNOTEL site is noticeably lower than the other two datasets. This is notable because the Livneh dataset informs the LOCAv2 statistical downscaling approach applied to CMIP5 climate projections, so using the climate projections with no bias corrections would result in biased hydrologic model simulations.

Figure E-2 illustrates differences in the CDFs of monthly total precipitation across the years 1980 through 2015. This figure illustrates the underestimation of precipitation by the Livneh dataset at the Mt. Rose SNOTEL site. There may be a variety of reasons for the difference. Extensive analysis of differences was not performed; however, one cause of the difference may be due to the interpolation of station data to develop gridded precipitation, as well as the large elevation gradient around the SNOTEL site that strongly influences local precipitation. Notable biases illustrated in this figure support the need for bias correction and support the approach developed and applied for daily precipitation and temperature, further described in section 3.3.1 of the main report.

In another example, figures E-3 and E-4 illustrate monthly total precipitation and CDFs of monthly precipitation (respectively) at the Rubicon#2 SNOTEL site, based on the same datasets and periods as figures E-1 and E-2. Comparisons are similar in terms of the general underestimation of precipitation by the Livneh dataset at the grid cell that encompasses the SNOTEL site. Bias correction of the CMIP5 LOCA projections using observed precipitation and temperature at all relevant climate stations used by PRMS reduces biases that are evident in the Livneh dataset.

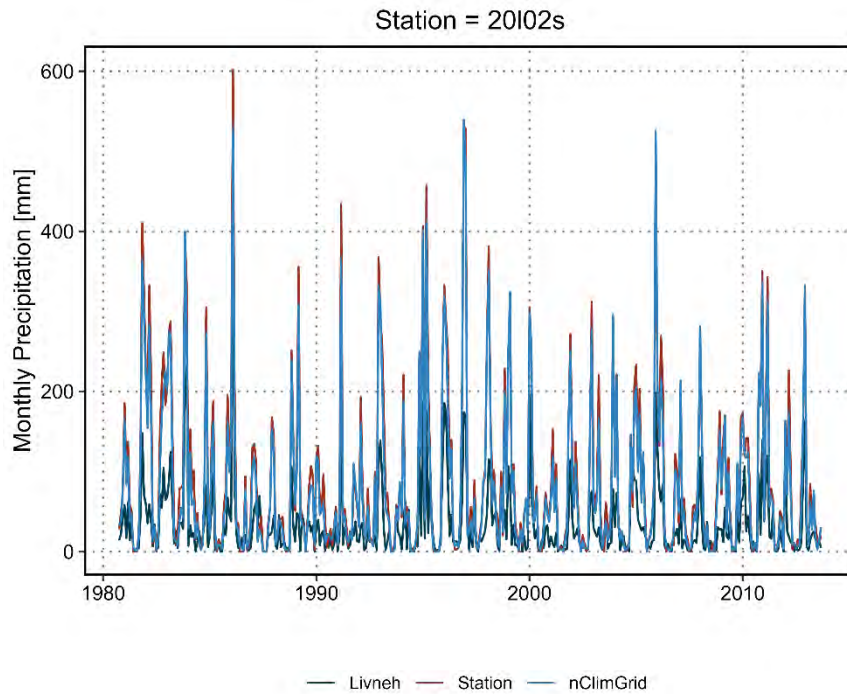


Figure E-39.—Comparison of monthly total precipitation (mm) for calendar years 1980–2015 between the Livneh dataset, station data, and nClimGrid daily dataset at the Rubicon #2 SNOTEL site (ID 20102s).

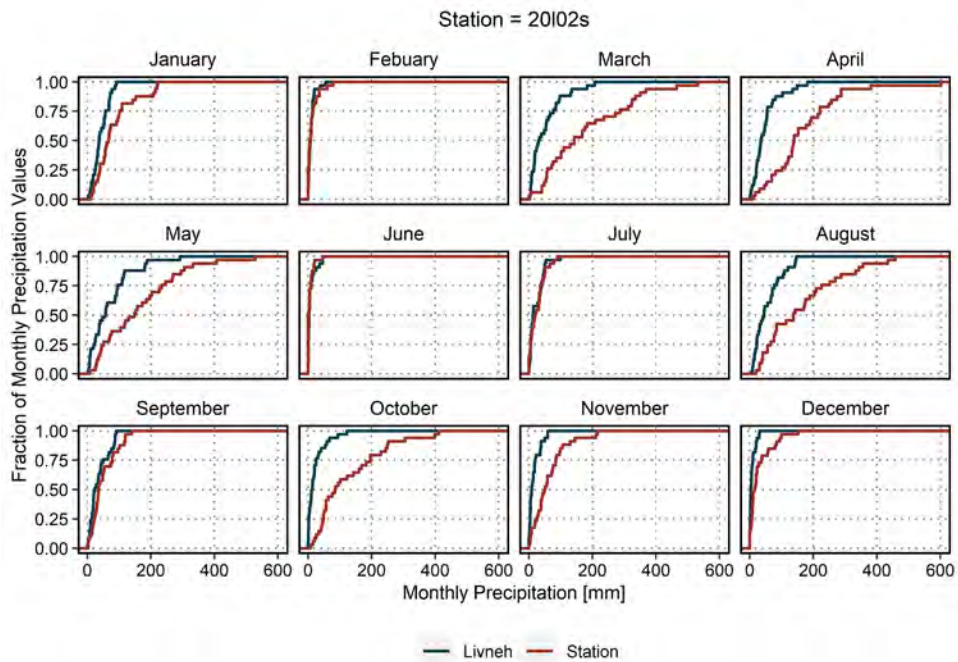


Figure E-40.MComparison of CDFs of monthly total precipitation (mm) for calendar years 1980–2015 between the Livneh dataset and station data (Rubicon #2 SNOTEL site).

Comparisons Related to Lake Tahoe Evaporation

Evaporation from Lake Tahoe constitutes a large component of the lake’s water budget due to its large surface area. This section summarizes available estimates of evaporation rates at Lake Tahoe based on previous modeling studies as well as the Pilot Study. It also summarizes readily available evaporation model inputs to document differences in these studies.

A comparison of evaporation rates relies on studies by PWRE (2020; which relies on work by Huntington and McEvoy 2011), Holman et al. (2024), and this Pilot Study (Reclamation 2025). Table E-1 shows that mean annual evaporation rates from the Pilot Study are lower than those from PWRE (2020) over the same or similar periods. Simulated evaporation rates from PWRE (2020) and the Pilot Study both rely on the monthly CRLE model. The Pilot Study’s mean annual evaporation estimates are also lower than estimates by Holman et al. (2024) from the same model (CRLE), as well as DLEM for similar periods of record.

Table E-17.—Estimates of average annual evaporation rates by previous studies, including the period of record and study reference. Information developed by the Pilot Study is highlighted in light gray.

Description	Estimate Period	Estimated Evaporation Rate (inches)	Reference
Annual Evaporation Rate, CRLE	2000–2009	46.0	PWRE (2020)*
Annual Evaporation Rate, CRLE	2000–2009	35.9	Pilot Study, Reclamation (2025)
Annual Evaporation Rate, CRLE	September 1980–December 1999	38.9	Holman et al. (2024)
Annual Evaporation Rate, DLEM	September 1980–December 1999	41.2	Holman et al. (2024)
Annual Evaporation Rate, CRLE	1981–1999	33.3	Pilot Study, Reclamation (2025)

* Precision Water Resources Engineering [PWRE] (2020) supports the Truckee Meadows Water Authority study and relies on CRLE model simulations by Huntington and McEvoy (2011).

Evaporation rates and the estimated Lake Tahoe surface area together determine the estimated volume of water lost to evaporation. Due to its large size, differences in either evaporation rate or surface area can lead to substantial differences in estimated evaporation volume. The study by PWRE (2020) estimates the surface area as 120,583 acres, which is the average over the period October 2000 through May 2015. The Pilot Study estimates the surface area as 143,000 acres, which is based on the area of the Lake Tahoe hydrologic response unit in the PRMS model. **As a result, the study by PWRE estimates average annual Lake Tahoe evaporation volume to be 462,000 AF (based on calendar years 2000-2009), while the Pilot Study estimates the**

average annual Lake Tahoe evaporation volume to be 429,000 AF (using data for the same calendar years 2000–2009), which is a 33,000 AF difference. In summary, the Pilot Study estimates lower evaporation rates overall and assumes a higher Lake Tahoe surface area than the PWRE (2020) study.

Inputs to the CRLE model were also compared between the PWRE (2020) report and the Pilot Study to evaluate whether differences in evaporation rate may be due to model inputs.

Table E-18.—Summary of CRLE model inputs for Lake Tahoe based on PWRE (2020) study and the Pilot Study

Description of CLRE Model Inputs for Lake Tahoe	PWRE (2020) Study	Pilot Study
Historical monthly precipitation	Station measurements (refer to table 2 in Huntington and McEvoy 2011)	Output from PRMS as the weighted average precipitation over Lake Tahoe
Historical monthly Tmin and Tmax	Station measurements (refer to table 2 in Huntington and McEvoy 2011)	Output from PRMS as the weighted average precipitation over Lake Tahoe
Historical average depth	50 meters	60 meters
Historical total dissolved solids	60 mg/L	60 mg/L
Historical solar radiation	Station measurements (refer to table 2 in Huntington and McEvoy 2011)	Area weighted within PRMS
Historical dewpoint temperature, Tdew (°C)	Station measurements (refer to table 2 in Huntington and McEvoy 2011) Note: k0 calculated as Tmin-Tdew	Calculated as $T_{dew} = T_{min} - k_0$, where: Tmin source is PRMS k0 source is PRISM dataset

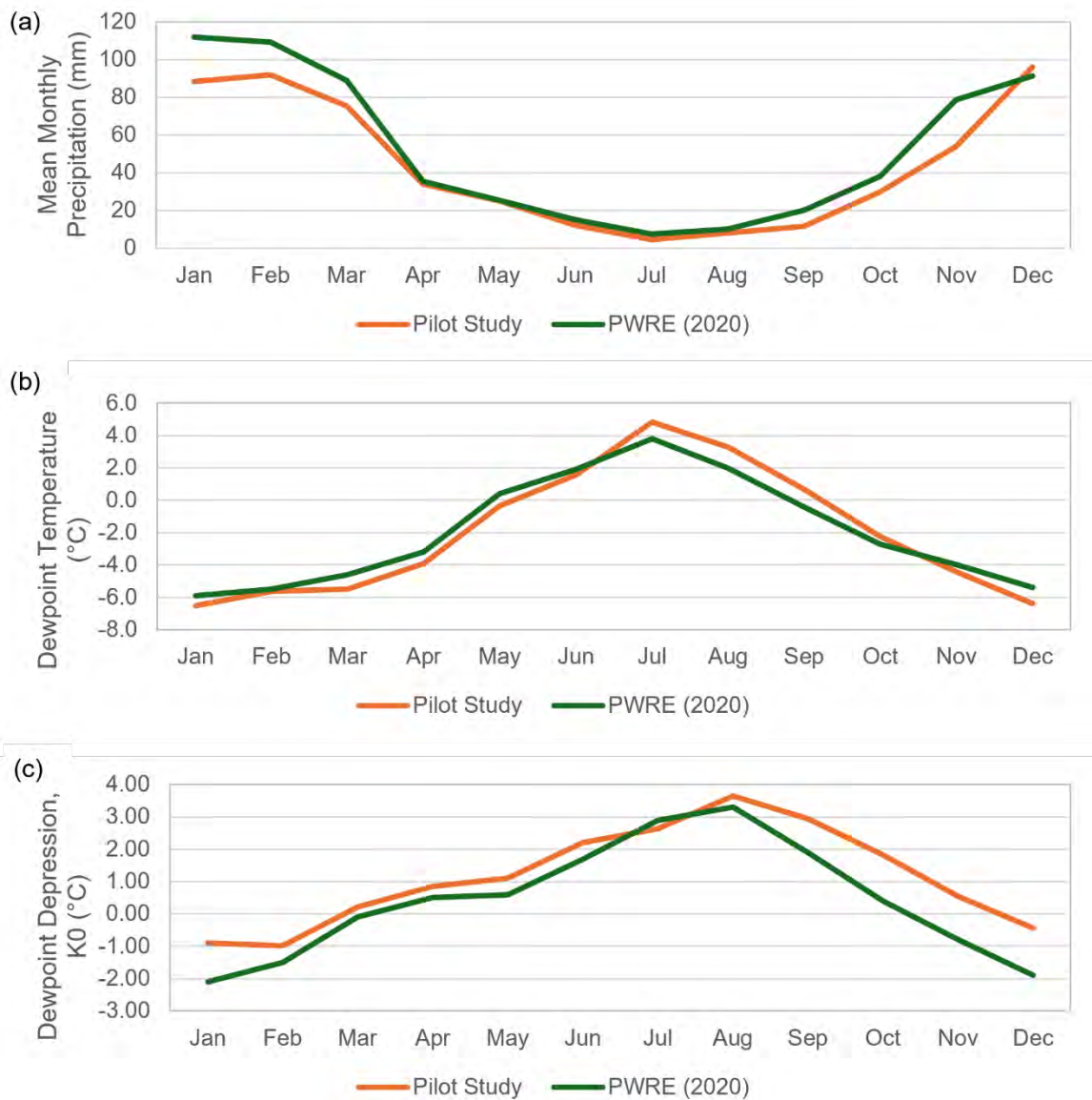


Figure E-41.—Comparison of CRLE model inputs, including (a) mean monthly precipitation (mm), (b) dewpoint temperature (°C), and (c) dewpoint depression (°C).

Figure E-5 illustrates means of monthly total precipitation (panel a, units of mm), mean dewpoint temperature (panel b, units of °C), and mean dewpoint depression (panel c, units of °C). Notably, the historical periods over which monthly means were calculated differ between studies, with means of 1971–2000 for the PWRE (2020) study and means of 1986–2015 for the Pilot Study. Because periods are different between the two studies, comparisons are useful only to get a qualitative sense of their differences and thereby influence estimated evaporation rates. It was beyond the scope of this effort to collect data from the sources and develop a more rigorous comparison.

Monthly total precipitation in the PWRE (2020) report is based on the spatial average of 400m resolution PRISM data over Lake Tahoe (as that study defines its spatial extent). Monthly precipitation in the Pilot Study is based on the weighted average precipitation for the Lake Tahoe Hydrologic Response Unit (HRU) represented in the PRMS model. PWRE (2020) monthly precipitation averages are slightly higher than those from the Pilot Study, except in December. Mean monthly dewpoint temperature in the PWRE (2020) report is based on Tahoe City Cooperative Observer Network (COOP) station observations, while in the Pilot Study it is computed as the weighted average of daily minimum temperature for the Lake Tahoe HRU represented in the PRMS model minus weighted average dewpoint depression from the PRISM dataset for the same spatial domain. Panel b shows that these mean monthly values are similar to those of the Pilot Study, with higher values from July through October. Mean monthly dewpoint depression in the PWRE (2020) report is based on station data from Stampede RAWS for 2000–2003 and Lake Tahoe UC Davis Coast Guard pier for 2004–2009. Mean monthly dewpoint depression in the Pilot Study is based on the weighted average dewpoint depression from the PRISM dataset for the Lake Tahoe HRU. Mean monthly values are similar, but the Pilot Study reports a higher mean monthly dewpoint depression in all months except July.

Solar radiation is another variable that is input to the CRLE model. A comparison of mean monthly solar radiation was not performed because the PWRE (2020) report did not tabulate this information, and it was out of scope of this effort to re-collect the source data. The PWRE (2020) reported solar radiation estimates are based on station data from Stampede RAWS for 2000–2003 and Lake Tahoe UC Davis Coast Guard pier for 2004–2009. Solar radiation in the Pilot Study is based on the weighted average of solar radiation for the Lake Tahoe HRU represented in the PRMS model.

Modeled Lake Tahoe Inflow Comparisons

Uncertainty in a modeling study may also be attributed to biases in process representation by the model or models used or applied. In the Pilot Study, several models were used to create a modeling workflow comprised of climate models, a surface hydrology model, and a river system model. Investigation of the methodological choices that result in estimates of Lake Tahoe inflow is the primary focus of this appendix. Previous sections compare precipitation datasets that are relevant to the Pilot Study and inputs and models used to estimate Lake Tahoe evaporation. Here, the hydrology model used to simulate inflow to Lake Tahoe was examined. In the Pilot Study, streamflow was generated by the PRMS surface hydrology model. The PRMS model configuration used in the Pilot Study is the same calibrated model that was developed by the 2015 Truckee Basin Study (Reclamation 2015). For this appendix, the study team used simulations of the Lake Tahoe Basin (i.e., watersheds contributing streamflow to Lake Tahoe) using the Monthly Water Balance Model (McCabe and Markstrom 2007) as an independent verification of PRMS historical simulated streamflow at a monthly timestep.

The Monthly Water Balance model used area-averaged monthly total precipitation, monthly average minimum temperature, and monthly average maximum temperature. Default parameters were used and are summarized by Gangopadhyay et al. (2015) and by table E-1.

Table E-19.—Summary of Monthly Water Balance Model parameters for the Lake Tahoe Basin

Parameter Name	Parameter Description	Default Value
R_{direct}	The fraction of monthly P that becomes direct runoff	0.05
T_{rain}	Temperature threshold that determines the proportions of monthly P that is rain	7.0 °C
T_{snow}	Temperature threshold that determines the proportions of monthly P that is snow	-4.0 °C
a	Snowmelt factor	0.47
r_{factor}	Runoff fraction that specifies how much surplus in a month becomes runoff	0.5

Simulated water year annual total inflows to Lake Tahoe for the period 1980–2015 are illustrated in figure E-6. This figure shows that annual simulated inflow to Lake Tahoe is similar, comparing PRMS estimates and Monthly Water Balance Model estimates. This effort provided the needed verification that, while PRMS and the Monthly Water Balance Model overestimate annual inflow compared to the TROA Planning Model dataset, both models do so in a similar way. This comparison shows a Spearman correlation of 0.96 between PRMS estimated annual inflow and annual inflow based on the TROA Planning Model dataset. This comparison provided further justification for bias correction of Lake Tahoe inflow using an annual CDF quantile mapping approach (summarized in appendix D).

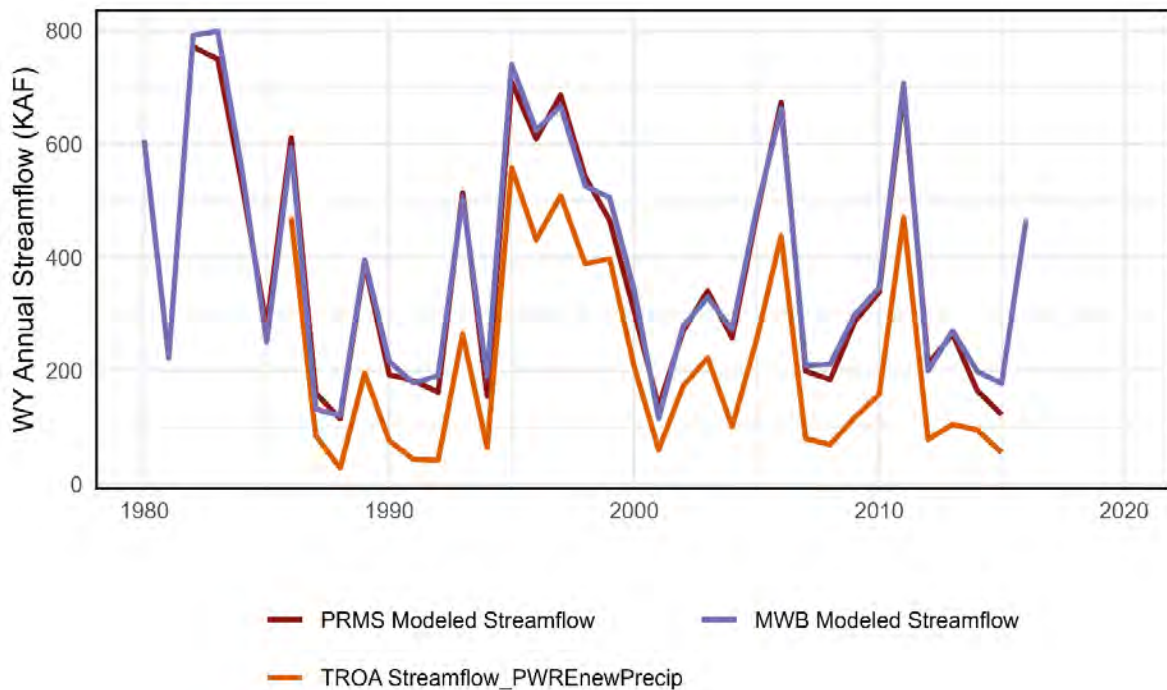


Figure E-42.—Comparison of water year annual inflow to Lake Tahoe (units of thousand acre-feet, KAF) based on PRMS (brown), the Monthly Water Balance Model (purple), and the TROA Planning Model Dataset (orange).

References

- Gangopadhyay, Subhrendu, Gregory J. McCabe, and Connie A. Woodhouse. 2015. Beyond annual streamflow reconstructions for the Upper Colorado River Basin: A paleo-water-balance approach. *Water Resources Research* 51(12): 9763–9774.
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