Appendix F, Modeling

Attachment 1-1 Climate Change

1 Objective

The project team has developed model simulations to support analysis of the Central Valley Project (CVP) and State Water Project (SWP) long-term operations as part of reviewing proposed operations under the 2021 Reinitiation of Consultation on the Coordinated Long-Term Operation (2021 LTO) of the CVP and SWP. This technical memorandum describes the overall analytical framework and contains descriptions of the key analytical tools and approaches used.

2 Climate Change

In California, hydrology, regulations, and demands in the Delta and other regions in the State affect the operation of the Central Valley Project (CVP) and State Water Project (SWP) reservoirs and export facilities. While greater usage and restrictive compliance demands pose challenges, climate change represents the most significant and least well-understood threat to Reclamation's operations in California. Climate analyses can provide valuable insight into the projected impacts and future conditions that may result from climate change. The impacts of climate change on water management in California were analyzed as part of the 2021 LTO of the CVP and SWP.

Climate change impact representing 2022±15 climate conditions were analyzed by updating CalSim II and CalSim 3 meteorologic and hydrologic boundary conditions for Long Term Operations (LTO) of Central Valley Project (CVP) and State Water Project (SWP). The 2022±15 future climate condition was developed with 40 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate projections, selected for LTO. Future climate change analysis was based on the 2022 median climate change scenario. A set of different scenarios, to review range of uncertainty, were developed representing 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median conditions.

The integrated Daily historical Livneh data (Livneh et al., 2013 and updated thereafter) and Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Daly et al., 1994), were processed and then perturbed using the differences observed in the ensemble of the 40 selected global climate projections. Historical and perturbed meteorological data were used for simulating projected surface runoff, baseflow, surface water evaporation, and potential evapotranspiration variables for future period using the Variable Infiltration Capacity (VIC) model. The differences between simulated historical and projected variables were applied to the historical CalSim 3 boundary conditions to represent 2022±15 conditions.

2.1 Introduction

The details of the methodology used in developing hydroclimate boundary conditions for the CalSim 3 models to represent 2022±15 conditions are outlined in this document. Figure 1 illustrates the overall dataset development and modeling sequence used for the analysis. Table 1 shows the various datasets used for perturbing different variables of CalSim 3 model to represent future climate conditions.

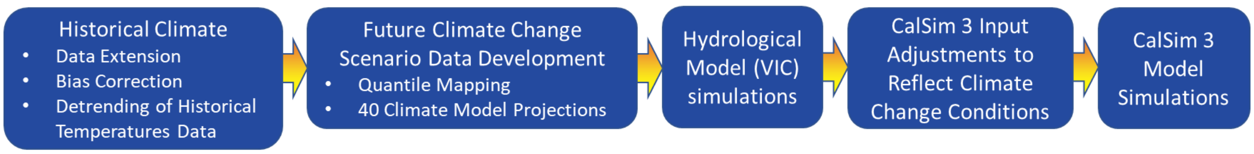

Figure 1. Dataset Development and Modeling Sequence

Table 1. Summary of the principal data sources used in the climate change analysis.

Data	**Use in Climate Change Analysis**	**Spatial and Temporal Resolution**	**Source**
Daily Gridded Historical Climate Data (Livneh et al, 2013 and updated thereafter)	Used in VIC model simulations and developing climate change scenarios	Daily data at 1/16-degree (~6 km) spatial resolution over the period 1915-2015	Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu)
Daily Historical Gridded Climate Data (PRISM)	Used in extending Livneh et al. daily gridded historical climate data	Daily data at ~800-m spatial resolution over the period 2016-2020 and ~4-km spatial resolution for 2021	PRISM Climate Group at Oregon State University (http://www.prism.oregonstate.edu/)
Monthly Historical Gridded Climate Data (PRISM)	Used in adjusting the extended Livneh et al. daily gridded historical climate data	Monthly data at ~800-m spatial resolution over the period 1895-2020 and ~4-km spatial resolution for 2021	PRISM Climate Group at Oregon State University (http://www.prism.oregonstate.edu/)
CMIP5 Downscaled Climate Projections (LOCA method)	Used in developing climate change scenarios	Daily data at 1/16-degree (~6 km) spatial resolution over the period 1950-2099	Scripps Institution of Oceanography

2.2 Climate Change Scenario Development

2.2.1 Historical Observed Meteorology Data and processing

Livneh et al. (2013, updated thereafter) daily historical meteorology data at 1/16th degree (~6 km or ~3.75 miles) spatial resolution over the period 1915 through 2015 was extended using the PRISM daily historical meteorology data from 2016 to 2021. Livneh et al. (2013, updated thereafter) was gridded from observations of precipitation and minimum and maximum daily temperature at National Climatic Data Center (NCDC) Cooperative Observer (COOP) stations across the conterminous United States using the synergraphic mapping system algorithm. Wind data were linearly interpolated from a larger NCEP–NCAR reanalysis grid (Kalnay et al. 1996).

This extended daily historical precipitation, minimum and maximum temperatures data were adjusted based on PRISM monthly data (Daly et al., 1994) to correct biases found in the period of interest. The bias corrected minimum (T_{min}), and maximum (T_{max}) temperature were detrended using the Linear Trend Removing Technique to represent the current climate condition (Zhang et al., 2011). The temperature detrending was performed by removing the month-specific trends and adding the daily residuals of 1915-2021 to the monthly climatology for 1991-2020. The approach was followed for detrending T_{max} and daily temperature range (DTR), while detrended T_{min} was estimated as the difference between detrended T_{max} and DTR. The anchor period used for the temperature detrending was over the period 1991-2020, consistent with the National Oceanic and Atmospheric Administration (NOAA) climatological normal period.

The extended daily historical meteorological data was used for historical VIC simulation. Bias corrected daily precipitation and detrended daily temperature were used for the development of the future climate change scenarios dataset using Global Climate Models (GCMs).

2.2.2 Global Climate Model Selections

The 2022±15 median climate change scenario and various sensitivity scenarios were developed using 40 Coupled Model Intercomparison Project 5 (CMIP5) global climate model (GCM) projections. These projections were downscaled using the localized constructed analog (LOCA) method at 1/16th degree spatial resolution (Pierce et al., 2014). The LOCA method is a statistical scheme that uses future climate projections combined with historical analog events to produce daily downscaled precipitation, and maximum and minimum temperature time series data. More details on the LOCA downscaling can be found in Pierce et al. (2014).

The 40 CMIP5 global climate model projections were selected by LTO as the most appropriate projections for Central Valley Project (CVP) and State Water Project (SWP) long-term operations. The 40 climate projections were generated with 20 global climate models and two emission scenarios, one optimistic (Representative Concentration Pathway [RCP] 4.5) and one pessimistic (RCP 8.5) (Table 2).

The selection of the climate models for likely representation of future climate conditions within California was made by evaluating the accuracy of the GCMs over the historical period (1950-2005) in comparison to observationally informed datasets (PRISM). Downscaled GCM performance was evaluated using metrics of temporal skill, spatial skill, and interannual variability over the historical period produced using an updated climate change understanding.

Differences in temporal and spatial skill were insufficient to identify GCMs that did not accurately represent climate conditions. Instead, the representation of interannual variability representation was used to eliminate GCMs that least accurately replicated California during the historical period. Out of the initial set of 32 GCMs from CMIP5, 20 GCMs were selected for the climate change analysis based on California-specific water management metrics.

Table 2. Recommended Global Climate Models

Model Number	**Model Name**	**Model Institution**
1	ACCESS1-0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
2	ACCESS1-3	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
3	bcc-csm1-1	Beijing Climate Center, China Meteorological Administration
4	CESM1-BGC	National Science Foundation, Department of Energy, National Center for Atmospheric Research
5	CESM1-CAM5	National Center for Atmospheric Research
6	CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici
7	CNRM-CM5	Centre National de Recherches Météorologiques, Centre Européen de Recherche et Formation Avancées en Calcul Scientifique
8	CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence
9	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory
10	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
11	GISS-E2-H	NASA Goddard Institute for Space Studies
12	GISS-E2-R	NASA Goddard Institute for Space Studies
13	HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration
14	HadGEM2-ES	Met Office Hadley Centre; additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais
15	INM-CM4	Institute for Numerical Mathematics
16	IPSL-CM5A-MR	Institute Pierre-Simon Laplace
17	MIROC5	Atmosphere and Ocean Research Institute at the University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
18	MPI-ESM-LR	Max Planck Institute for Meteorology
19	MPI-ESM-MR	Max Planck Institute for Meteorology
20	NorESM1-M	Norwegian Climate Center

Notes: Models are listed alphabetically.

2.2.3 Future Climate Change Scenario

Future climate change scenario (2022±15 median climate condition) was developed over the bias corrected daily precipitation and detrended daily temperature using the quantile mapping approach based on selected 40 global climate model projections. Adjustments to temperature and precipitation were calculated with cumulative distribution functions, mapped with the 40 downscaled CMIP5 GCM projections (Taylor et al., 2012). The quantile mapping approach involves the following steps:

- A 30-year slice of climate model data (precipitation, and maximum and minimum temperatures) was extracted from each of the 40 downscaled climate model simulations centered on the model-simulated reference period (1995: 1981-2010) and future period (2022: 2008-2037).
- For each calendar month (e.g., January) of the model simulated reference period, the CDF for each climate model projection of temperature and precipitation at each grid cell was determined separately. 50^{th} percentile value for each quantile of the 40 CDFs was computed to form a model simulated reference period CDF.
- For each calendar month of the future period, the CDF for each climate model projection of temperature and precipitation at each grid cell was determined separately. 50^{th} percentile value for each quantile of the 40 CDFs was computed to form a model simulated future period CDF.
- The change was computed as the ratio (future period divided by reference period) for precipitation and 'deltas' (future period minus reference period) for temperature at each quantile from the reference and future period CDFs.
- These ratios and deltas were applied to historical precipitation and detrended temperature data to develop a monthly time series of temperature and precipitation at $1/16^{th}$ degree over 1915-2021 that incorporates the future climate shift.
- Monthly time series was converted to a daily time series by scaling monthly values to daily sequence found in the observed record.

Figure 2 shows the projected change in long-term average temperature for the major watersheds in the Sacramento and San Joaquin River Basins under 2022±15 median climate change scenario. The temperature is projected to increase by 1.6°C across major watersheds with a minimum increase of 1.4°C under 2022±15 median condition with respect to the historical reference period (1995). The highest temperature increases are projected for Feather River (1.7°C) watershed in the Sacramento River Basin and Merced River (1.7°C) watershed in the San Joaquin River Basin.

Projected change in long-term average precipitation for major watersheds in the Sacramento and San Joaquin River Basins are presented in Figure 3. Overall, all major watersheds are projected to be wetter under 2022±15 median condition, with average increases from 0.9% to 2%. Sacramento River Basin is projected to experience a higher increase in long-term average precipitation than the San Joaquin River Basin.

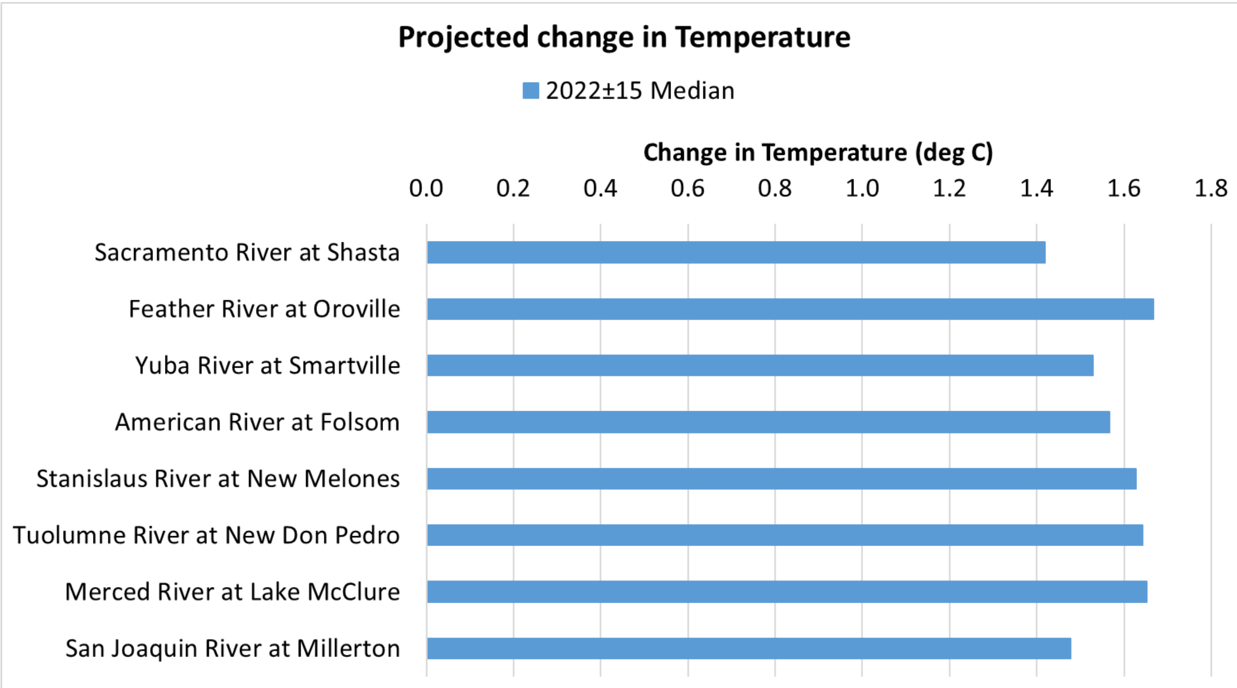

Figure 2. Projected Changes in Average Temperature for Major Watersheds in the Sacramento and San Joaquin River Basins under 2022±15 Median Climate Change Scenario.

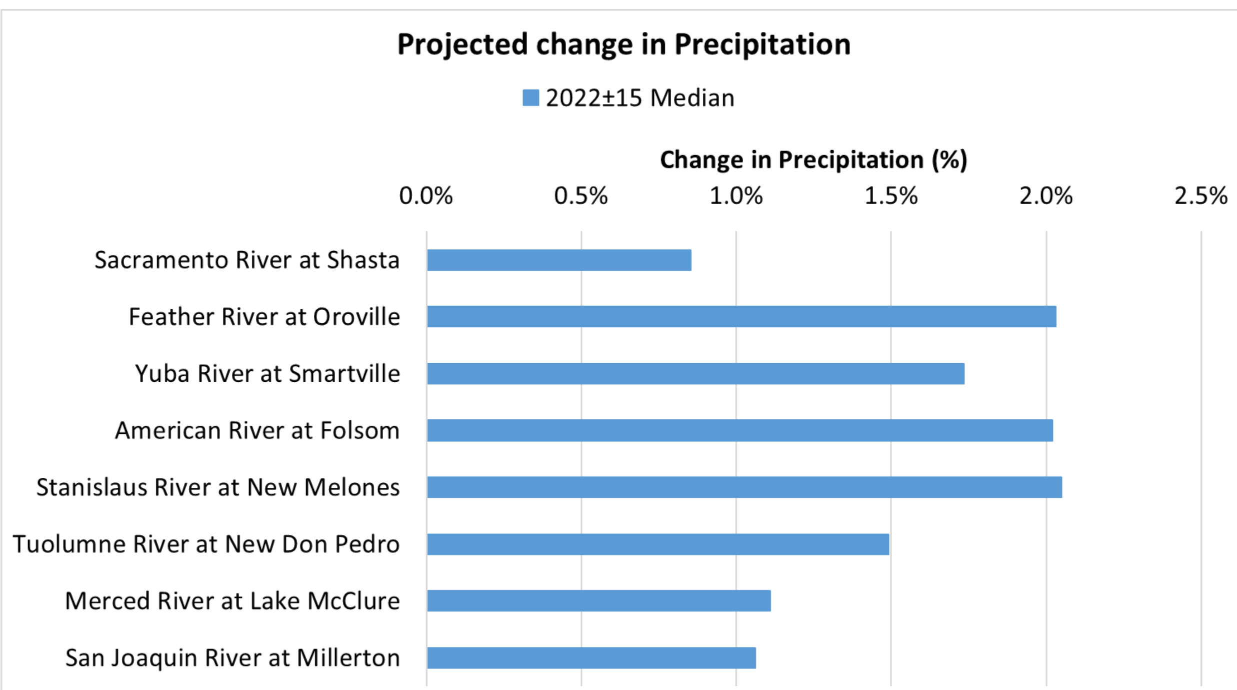

Figure 3. Projected Changes in Precipitation for Major Watersheds in the Sacramento and San Joaquin River Basins under 2022±15 Median Climate Change Scenario.

2.3 VIC model simulations

Variable Infiltration Capacity (VIC, Liang et al., 1996, Nijssen et al., 1997) model was used for simulating the daily historical and projected surface runoff, baseflow, surface water evaporation and potential evapotranspiration at 1/16th degree by inputting historical and projected meteorological data under different climate change scenarios. The VIC model simulates land-surface-atmosphere exchanges of moisture and energy at each model grid cell. The model incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes.

The comparison of VIC model simulated fluxes between historical and future conditions were used to perturb CalSim 3 boundary conditions. Surface runoff and baseflow were used to produce total runoff at all locations that correspond to CalSim 3 rim inflows and unimpaired flow. Potential evapotranspiration was used to estimate crop evapotranspiration throughout the Sacramento and San Joaquin Valleys. Surface water evaporation was used to estimate evaporation rates at reservoirs within the CalSim 3 model domain.

2.4 CalSim 3 Inputs Development

CalSim 3 projected hydroclimate input data under different climate change scenario was developed using the following methods:

- For all watersheds, simulated changes in streamflows (simulated future streamflows divided by historical simulated streamflows) were applied to the CalSim 3 inflows. These fractional changes were first applied for every month of the 106-water year period (1915-2021) consistent with the VIC model simulated patterns. A second order correction was then applied to confirm that the annual shifts in runoff at each location were consistent with the shifts observed in the VIC model.
- Total flows of major watersheds were perturbed with the two-step process described above. Then, the perturbed runoff of each contributing watershed was adjusted to match the perturbed total flow in the watershed.
- For watersheds where streamflows are heavily impaired, a process was implemented by calculating historical impairment based on observed data and adding that impairment back onto the VIC model simulated flows at a location upstream of the impairment.
- Similarly, fractional changes (described in the first bullet) were also used to simulate changes in precipitation, temperature, surface water evaporation and evapotranspiration as needed for calculation of certain parameters used in CalSim 3.

2.5 Use of Fractional Changes for HydroClimate Data

Fractional changes (simulated future data divided by historical simulated data) were applied to the CalSim 3 inflow, precipitation, surface water evaporation, and evapotranspiration boundary conditions. Absolute changes (difference in simulated future data and historical simulated data) were applied to CalSim 3 temperature boundary conditions. For the CalSim 3 boundary conditions, climate variables and perturbation methods used are further detailed below.

2.5.1 Rim Inflows

Rim inflows, or inflows from the "rim" of the California watershed, routing through a system of reservoirs, channels, and diversions is simulated by CalSim3 model. Perturbation of CalSim 3 inflow boundary conditions were based on VIC simulated watershed area-weighted total runoff (surface runoff plus baseflow). The following steps were used to perturb CalSim 3 rim inflows and major watershed flows:

Monthly change factors were calculated for every month in the simulation period from WY 1922 to 2021 using VIC historical and 2022±15 median condition simulated total runoff.

- Monthly CalSim 3 historical rim inflows were perturbed using the monthly change factors from the previous step.
- Annual perturbation, based on water year, was applied to the monthly perturbed CalSim 3 flows. These water year change factors were calculated as the ratio between the water year change factors of the VIC simulated (2022±15 median and historical) total runoff and the water year change factors of the monthly perturbed historical CalSim 3 flow and observed historical CalSim 3 flow.
- A correction factor was applied to major watershed flow locations by calculating the difference between perturbed CalSim 3 flow at the major flow location and the sum of perturbed CalSim 3 flow from all contributing watersheds at that major flow location. Major watershed flow locations and the number of contributing watersheds to each location are tabulated in 3.
- The calculated difference (step above) was applied to the perturbed CalSim 3 flow at the contributing watersheds. At each time step, the difference is proportionally distributed to perturbed CalSim 3 flow. Proportioning of error distribution is based on the ratio of the perturbed CalSim 3 flow magnitude from an individual watershed to the total CalSim 3 flow magnitude from all contributing watersheds.

Table 3. Major Watershed Flow Locations in CalSim 3

Basin Name	Flow Location	No. Contributing Watersheds
Feather River	Total Inflow to Lake Oroville	21
Yuba River	Yuba River at Smartville	18
Bear River	Bear River at Confluence with Feather River	5
American River	Total Inflow to Folsom Lake	46
Mokelumne River	Total Inflow to Pardee Reservoir	9
Stanislaus River	Total Inflow to New Melones Lake	21
Tuolumne River	Total Inflow to New Don Pedro Reservoir	4

Eight River Index (8RI) is the sum of the rivers included in the Sacramento Valley (SAC-4) and San Joaquin Valley (SJR-4) 4 Rivers Indices. The Sacramento Valley Four Rivers Index (SAC-4) is the sum of four streamflows including the Sacramento River above Bend Bridge, Feather River inflow at Lake Oroville, Yuba River at Smartville, and American River inflow to Folsom Lake. The San Joaquin Valley Four Rivers Index (SJR-4) is the sum of four streamflows including the Stanislaus River inflow to New Melones Lake, Tuolumne River inflow to New Don Pedro River, Merced River inflow to Lake McClure, and San Joaquin River inflow to Millerton Lake.

Projected change in the Eight River Index (8RI), Sacramento Valley Four Rivers Index (SAC-4), San Joaquin Valley Four Rivers Index (SJR-4), and runoff at eight major rivers under 2022±15 median climate conditions is provided in Figure 4. 8RI runoff change is dominated by the change in the Sacramento Valley runoff and projected to increase. The runoff in the Sacramento Valley is projected to increase by 0.3%, while San Joaquin Valley runoff is projected to reduce by 0.6%. Runoff increases in all major basins except for the San Joaquin River and Merced River basins, where runoff decreases by more than 1%.

Long-term average monthly flows of SAC-4 and SJR-4 are presented in Figure 5. As compared to historical runoff, increased precipitation under 2022±15 median climate conditions lead to a higher peak in SAC-4 peak runoff. 2022±15 median climate SJR-4 peak runoff volume and timing remain similar to historical runoff. In both basins, runoff increases in winter and decreases in spring and summer. Increased winter temperatures lead to a higher portion of precipitation that directly results in runoff, as opposed to snowpack. Similarly, with decreased snowpack, runoff during the summer, when the majority of runoff is snowmelt under historical conditions, decreases.

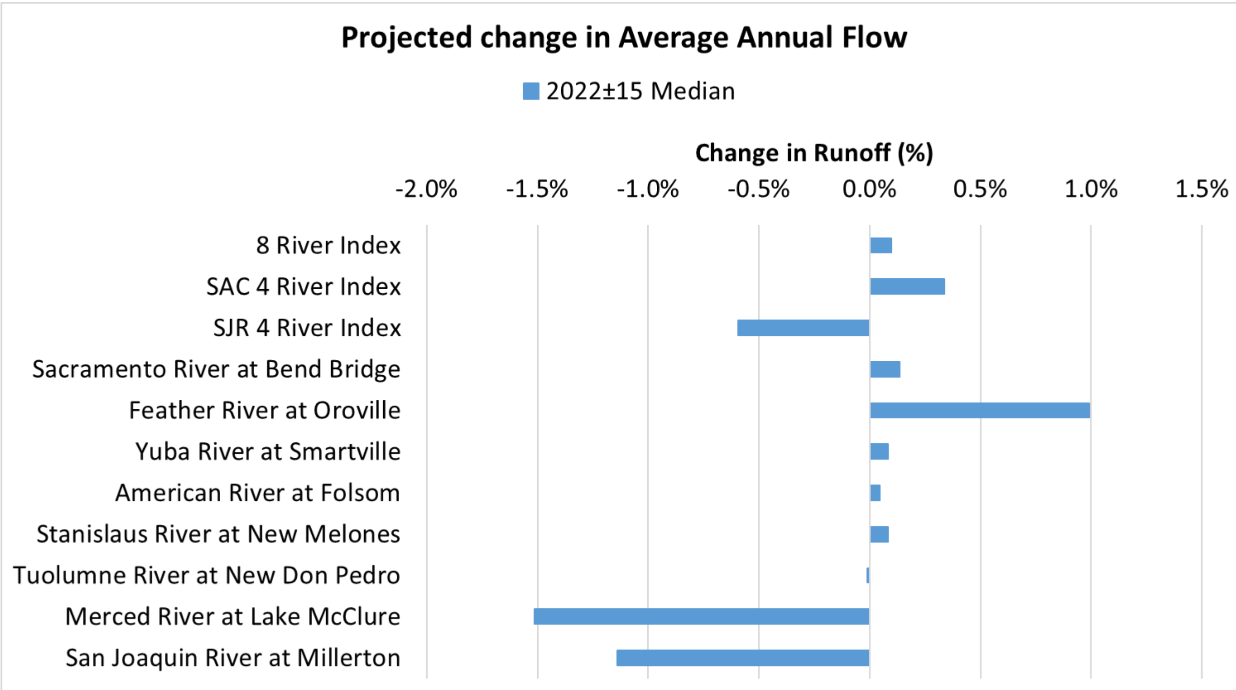

Figure 4. Projected Changes in Runoff for Major Watersheds in the Sacramento and San Joaquin River Basins for 2022±15 Median Climate Change Scenario

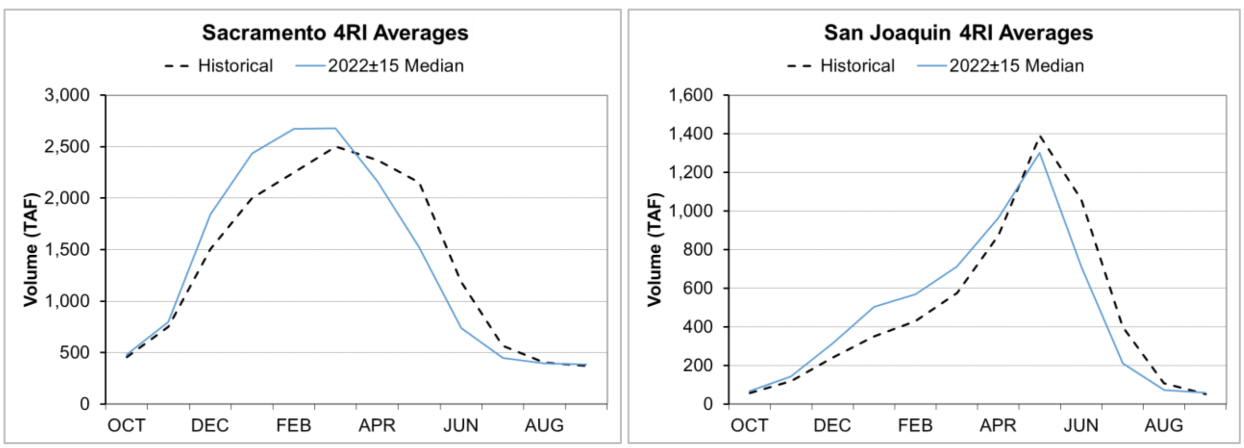

Figure 5. Projected Changes in Monthly Pattern of Runoff for the Sacramento Basin (left) and San Joaquin Basin (right) for 2022±15 Median Climate Change Scenario.

2.5.2 Valley Floor Flows

CalSimHydro is a surface water hydrologic model that estimates CalSim 3 boundary conditions in the Sacramento and San Joaquin Valleys. The CalSimHydro model estimates applied crop water, surface runoff, return flow and deep percolation data for use in CalSim 3. The input variables to the CalSimHydro model include daily precipitation, crop evapotranspiration (ET), reference evapotranspiration, pan evaporation, land use area, and urban demand. More details regarding the CalSimHydro model are available at CalSimHydro Reference Manual (California

Department of Water Resources 2019). The following steps were used to perturb CalSimHydro input variables:

- Monthly change factors were calculated for every month in the simulation period from WY 1922 to 2021 using VIC historical and 2022±15 median condition simulated data.
- Monthly historical data were perturbed using the monthly change factors from the previous step.
- Annual perturbation, based on water year, was applied to the monthly perturbed data. These water year change factors were calculated as the ratio between the water year change factors of the VIC simulated (2022±15 median and historical) data and the water year change factors of the monthly perturbed historical data and observed historical data.

Figure 6 shows the projected change to applied crop water in the Sacramento and San Joaquin Valleys, as estimated with the CalSimHydro model under 2022±15 median condition. Applied water increases in both valleys due to increased evapotranspiration, a result of increased temperature (Figure 2). As estimated with CalSimHydro, changes to pattern and magnitude of precipitation (Figure 3) result in small increases to surface runoff, return flow, and deep percolation.

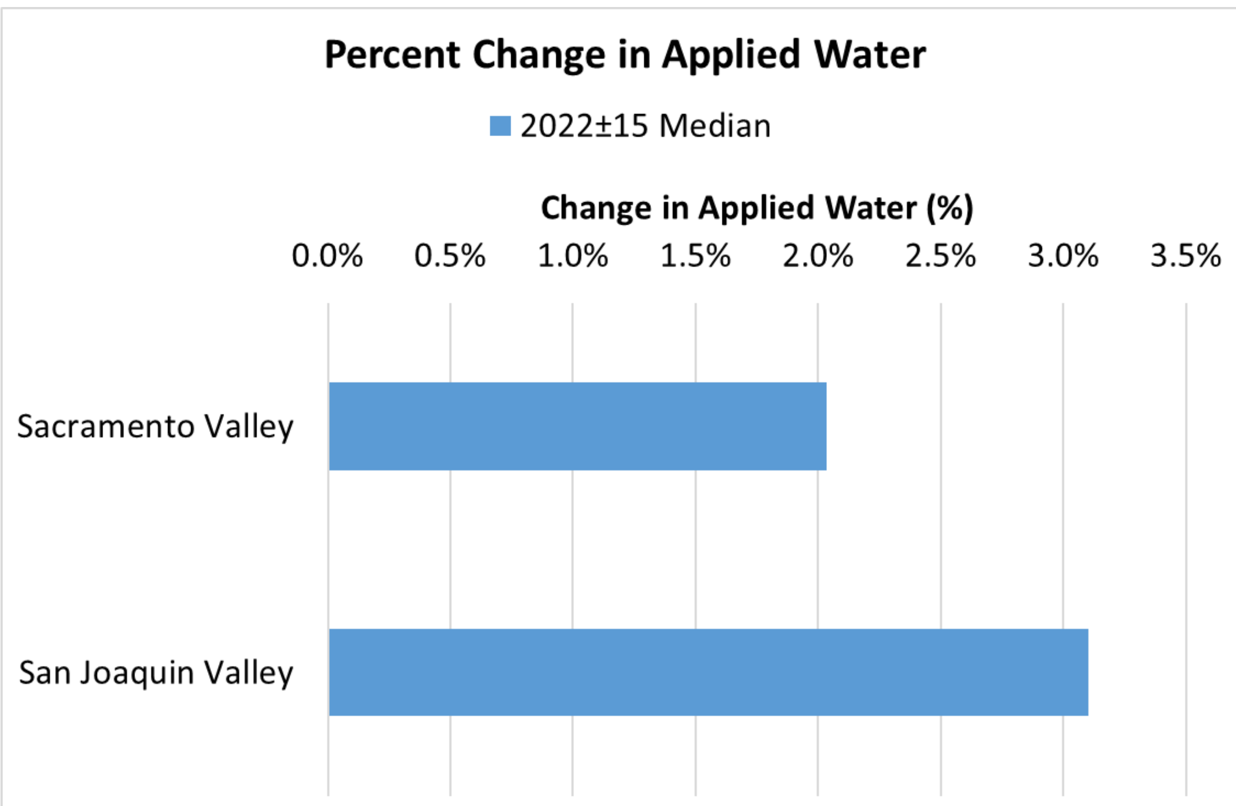

Figure 6. Projected Changes in Applied Water for Sacramento and San Joaquin for 2022±15 Median Climate Change Scenarios.

2.5.3 Delta Channel Depletion

The Delta Channel Depletion (DCD) model was used to estimate CalSim 3 irrigation, drainage, and seepage in the Sacramento – San Joaquin River. The DCD model depends on the Delta Evapotranspiration of Applied Water (DETAW) model to estimate Delta crop evapotranspiration. Inputs to the DCD model include daily timeseries of precipitation and temperature at several locations throughout the Delta. More details regarding the DCD model are available at Methodology for Flow and Salinity Estimates in the Sacramento – San Joaquin Delta and Suisun Marsh, Chapter 2: Calibrating and Validating Delta Channel Depletion Estimates (California Department of Water Resources 2018).

Perturbation of the precipitation data was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.2 *Valley Floor Flows*. Daily maximum and minimum temperature boundary conditions are referenced to estimate Delta evapotranspiration. The following steps were used to perturb temperature data:

- Monthly absolute differences, or deltas, were calculated for every month in the simulation period from WY 1922 to 2021 using historical and 2022±15 median condition temperature data.
- Daily historical minimum and maximum temperature data were perturbed using the monthly absolute differences from the previous step.

Figure 7 shows the projected change to Sacramento – San Joaquin River Delta irrigation, drainage, and seepage under 2022±15 median condition as estimated with the DCD model. Irrigation and seepage increase due to increased evapotranspiration, a result of increased temperature (Figure 2). As estimated with DCD, changes to pattern and magnitude of precipitation (Figure 3) and increased irrigation result in a small increase to Delta Island drainage.

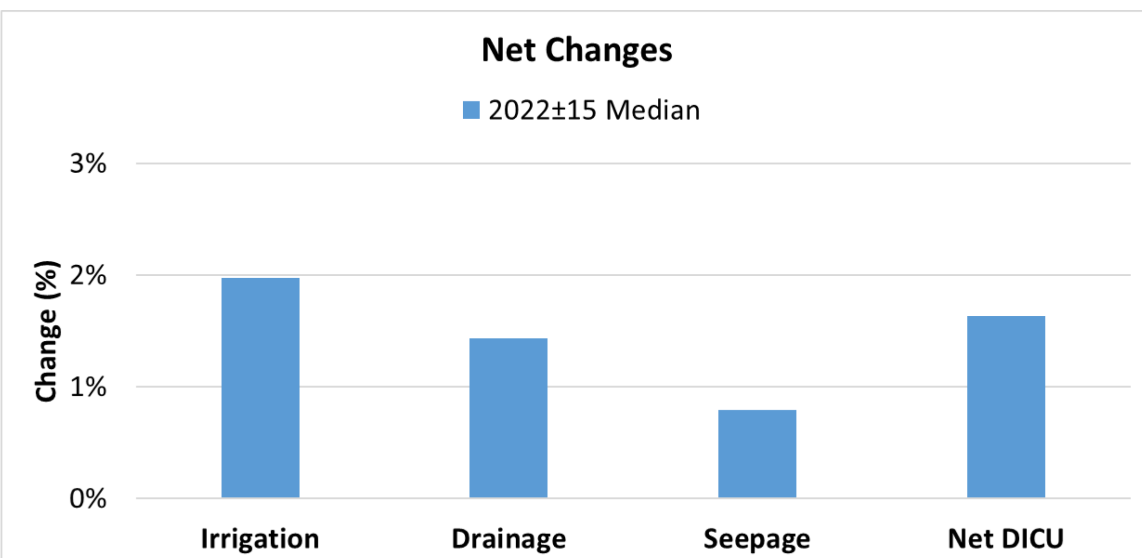

Figure 7. Projected Changes in Delta Island Consumptive Use for 2022±15 Median Climate Change Scenario.

2.5.4 Reservoir Evaporation

Evaporation rate boundary conditions are applied to all reservoirs in the CalSim 3 spatial domain. Gross evaporation rates were applied at most reservoirs. Net evaporation rates (evaporation rate minus precipitation) boundary conditions were applied at terminal reservoirs, or reservoirs without natural inflow.

Gross evaporation and precipitation data were perturbed separately to develop net evaporation at 2022±15 median conditions. Perturbation of the surface water evaporation and precipitation data was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.2 *Valley Floor Flows*.

Figure 8 shows the projected change in evaporation rate at major reservoirs under 2022±15 median conditions. The evaporation rates of the reservoirs are projected to increase due to increase in temperature and diurnal temperature range.

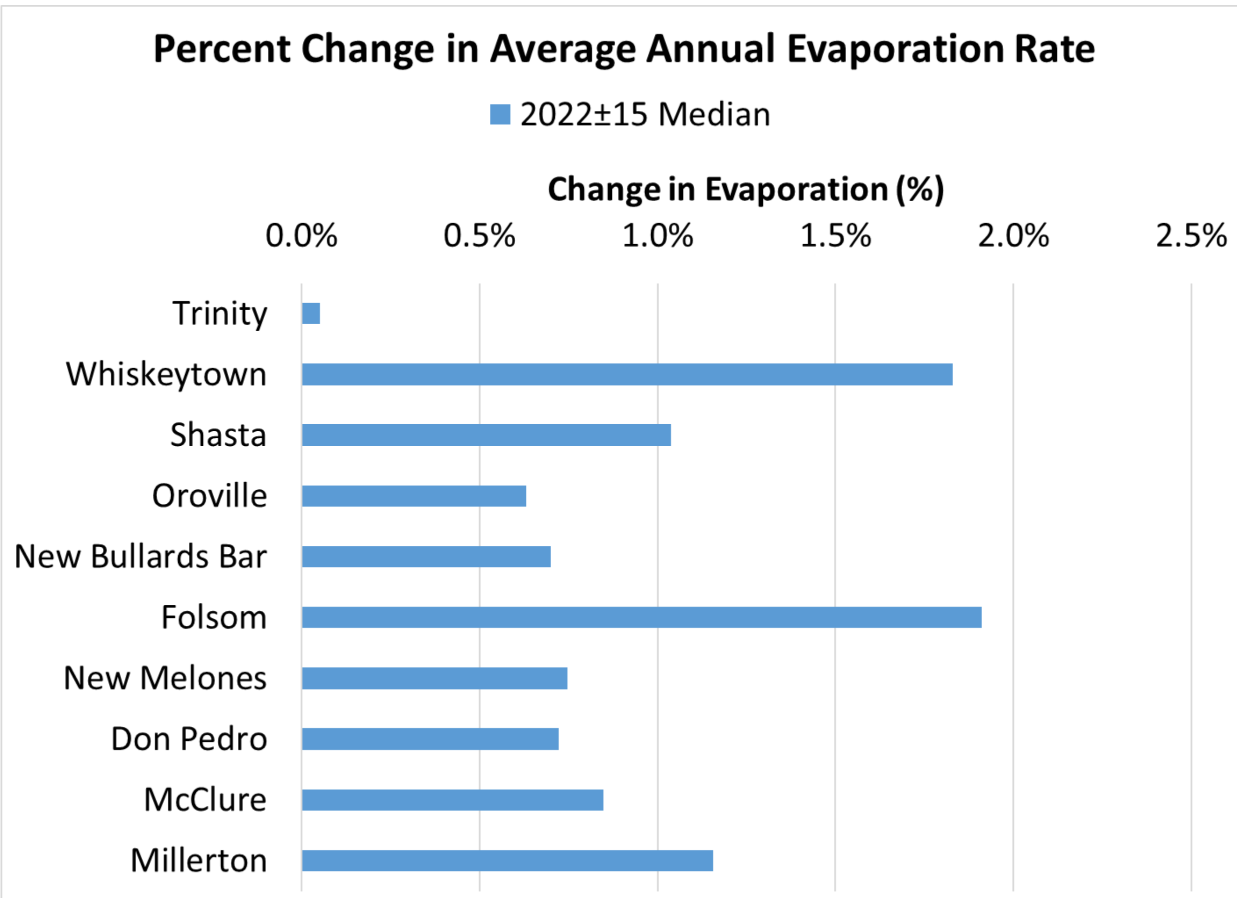

Figure 8. Projected Changes in Evaporation Rate at Major Reservoirs for 2022±15 Median Climate Change Scenario.

2.5.5 Inputs for Lookup Tables

CalSim 3 operations decisions are based upon several water year types, and meteorologic and hydrologic indices. CalSim 3 calculates these indices based on unimpaired runoff at 10 distinct locations Table 4. Additionally, CalSim 3 requires precipitation data to forecast runoff in several river basins, including the eight major river basins, and reservoir operations. In practice, statistical forecast functions are developed based on observed precipitation and runoff. To mimic the same procedure for forecasts in future climate conditions, CalSim 3 implements forecast functions based on precipitation and runoff.

Table 4. Unimpaired Flow Inputs to CalSim 3

CDEC Station Name	Station Description
AMF	American River at Folsom
MRC	Merced River at Exchequer Reservoir
ORO	Feather River at Oroville
SIS	Sacramento River inflow to Shasta
SJF	San Joaquin River at Millerton
SBB	Sacramento River above Bend Bridge
SNS	Stanislaus River at New Melones
TNL	Trinity River at Lewiston
TLG	Tuolumne River at New Don Pedro
YRS	Yuba River near Smartville

Perturbation of the precipitation and unimpaired runoff data was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.2 *Valley Floor Flows*. For perturbation of the precipitation data, the following steps were taken:

- Basin-wide average precipitation or point precipitation at a given station were estimated for historical and 2022±15 median conditions.
- Sensitivity factors, based on simulated historical and 2022±15 median conditions, for precipitation were calculated and applied to historical data.

Point and basin average precipitation are projected to change similarly as for the major watersheds in the Sacramento and San Joaquin River basins under 2022±15 median climate change scenario as shown in Figure 3. Also, the projected change in unimpaired flows is similar to the rim inflows changes for major watersheds (Figure 4).

2.5.6 Groundwater

CalSim 3 requires two types of groundwater boundary conditions along the edges of its spatial domain: (1) deep percolation and (2) lateral flows. Deep percolation and later flow boundary conditions are developed by the CalSimHydroEE and SmallWatersheds models, respectively. Both models estimate groundwater flow with assumptions consistent to the CalSimHydro model. These models are described in Chapter 15 of the CalSim 3.0 Draft Report (California Department of Water Resources 2017).

CalSimHydroEE and SmallWatersheds models uses precipitation and evapotranspiration data for estimating rainfall-runoff, evapotranspiration, and percolation. Perturbation of the precipitation and evapotranspiration data was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.2 *Valley Floor Flows*.

Figure 9 shows the projected change in average annual deep percolation, precipitation, surface runoff, baseflow, and ET under 2022±15 median climate conditions. Perturbed deep percolation and lateral flow input boundary conditions slightly decreases under 2022±15 median climate change scenario. However, relative to all of the other CalSim 3 boundary conditions, these changes are negligible.

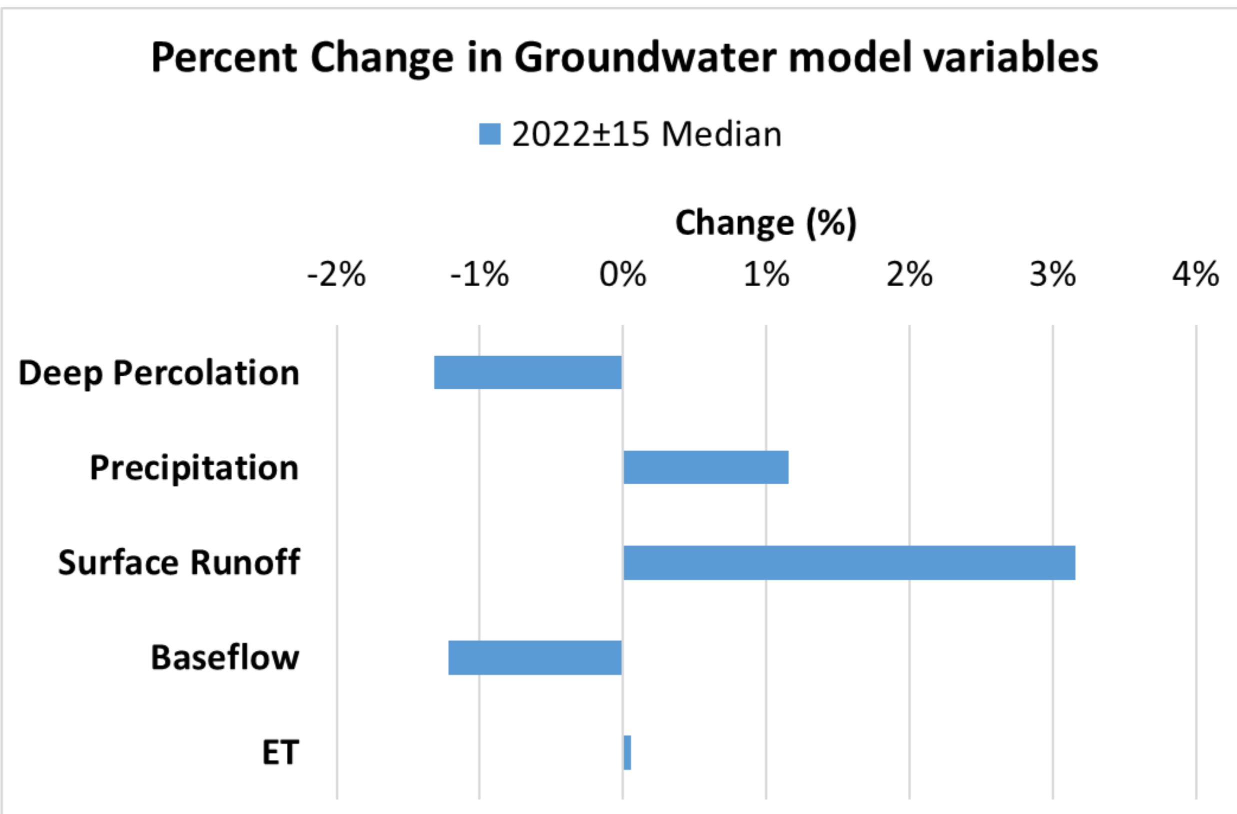

Figure 9. Projected Changes in Average Annual Deep Percolation, Precipitation, Surface Runoff, Baseflow, and ET under 2022±15 Median Climate Change Scenario.

2.6 Use of Projected Runoff from the VIC Model for Impaired Streamflows

Impaired rim inflows in the upper San Joaquin of CalSim 3 were unimpaired before perturbation process. The rim inflows were “re-impaired” after perturbing the unimpaired inflows to represent future climate conditions. As information on specific local project operations (impairment) at these locations was not available, impairment was calculated as the difference between the unimpaired historical flow and the CalSim 3 inflow time series. This method assumes the local project operations will be the same in future climate conditions and does not account for any adaptation in local project operations. This method was applied to 2022±15 median climate condition.

2.7 Climate Change Scenarios for Sensitivity

In addition to 2022±15 median condition, the datasets were also developed for three sensitivity scenarios: 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median climate conditions. The climate change scenarios differ based on centered-future period and quantile value across all climate model projections used for the development of precipitation and temperature future climate data (Table 5).

Table 5. Details of the Climate Change Scenarios

Climate Change Scenario	Centered-Future Period	Quantile of Temperature	Quantile of Precipitation
2022±15 Median	2022 (2008-2037)	50th percentile	50th percentile
2022±15 Hot-Dry	2022 (2008-2037)	75th percentile	25th percentile
2022±15 Warm-Wet	2022 (2008-2037)	25th percentile	75th percentile
2040±15 Median	2040 (2026-2055)	50th percentile	50th percentile

Similar to 2022±15 median climate change condition, historical detrended temperature and bias corrected precipitation were adjusted based on quantile mapping approach to represent three sensitivity scenarios. The quantile mapping approach for developing the sensitivity scenarios was implemented with future periods and quantile values for temperature and precipitation as outlined in Table 5.

Figure 10 shows the projected change in long-term average temperature for the major watersheds in the Sacramento and San Joaquin River Basins under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median climate conditions. The average temperature across major watersheds is projected to increase by 2.1°C, 1.1°C, and 2.3°C under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median conditions, respectively.

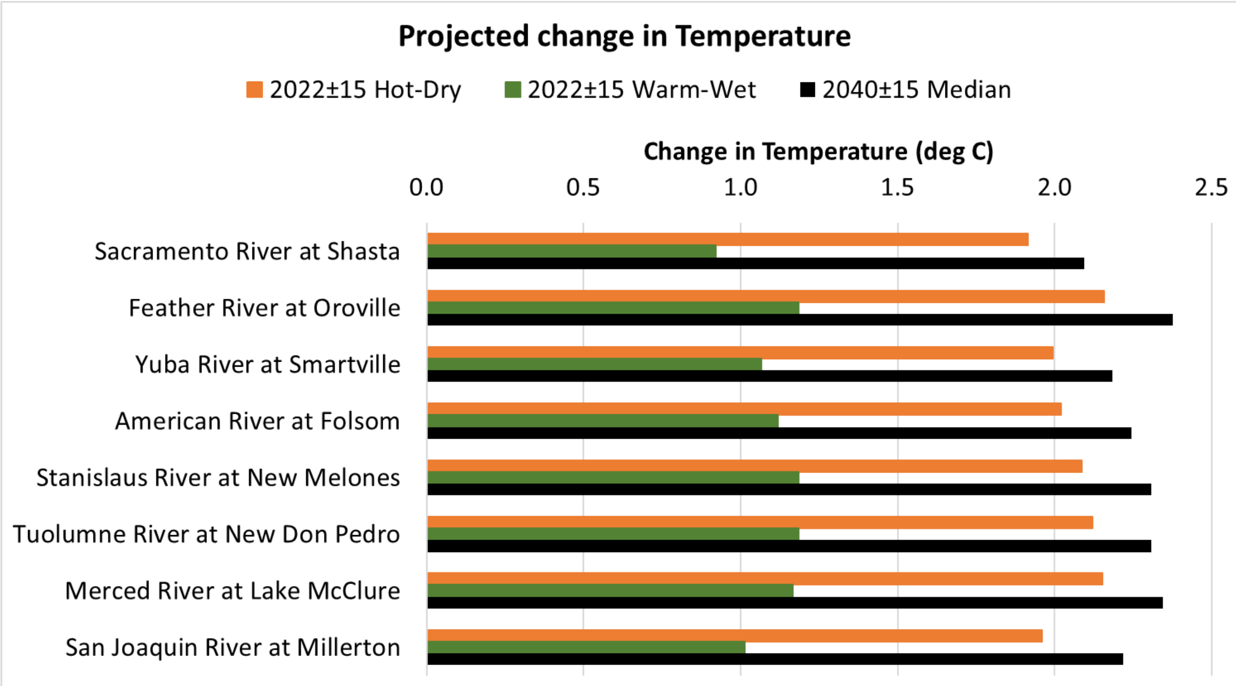

Figure 10. Projected Changes in Average Temperature for Major Watersheds in the Sacramento and San Joaquin River Basins under 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

Projected change in long-term average precipitation for major watersheds in the Sacramento and San Joaquin River Basins under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median climate conditions are presented in Figure 11. Overall, all major watersheds are projected to be drier under 2022±15 hot-dry climate condition and wetter under 2022±15 warm-wet, and 2040±15 median climate conditions. On an average, long-term average precipitation is projected to change by -13.2%, +17.8%, and +1.6% under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median conditions, respectively.

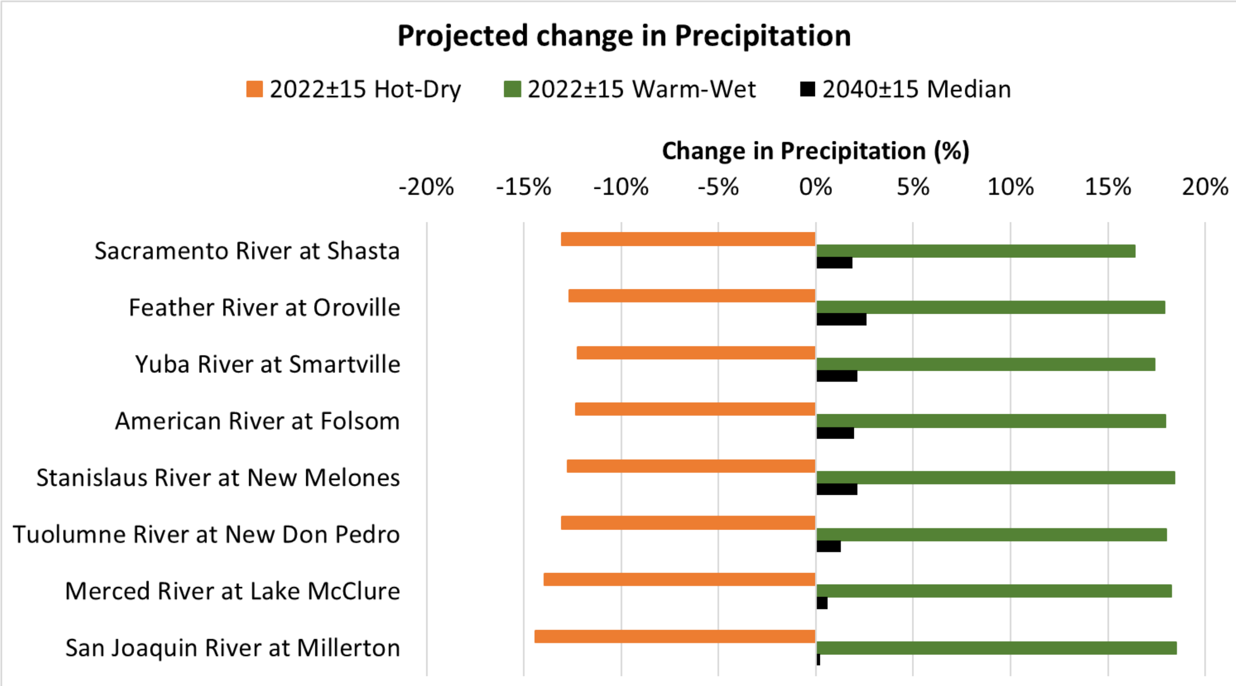

Figure 11. Projected Changes in Precipitation for Major Watersheds in the Sacramento and San Joaquin River Basins under 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

2.8 Use of Fractional Changes for Sensitivity Analysis

CalSim 3 boundary conditions for sensitivity scenarios were developed using the similar climate variables and perturbation methods as 2022±15 median climate change scenario. Fractional changes were applied to the CalSim 3 inflow, precipitation, surface water evaporation, and evapotranspiration boundary conditions. Absolute were applied to CalSim 3 temperature boundary conditions.

2.8.1 Rim Inflows

Perturbation of CalSim 3 inflow boundary conditions was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.1 *Rim Inflows*. CalSim 3 rim inflows and major watershed flows were perturb separately for the three sensitivity climate change scenarios similar to 2022±15 median climate change scenario.

Projected change in the Eight River Index (8RI), Sacramento Valley Four Rivers Index (SAC-4), San Joaquin Valley Four Rivers Index (SJR-4), and runoff at eight major rivers under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median climate conditions is provided in Figure 12. As compared to 0.1% increase for 2022±15 median climate conditions, the average annual 8RI varies between -23% and 26% under sensitivity climate change scenarios. Runoff decreases in all major basins for 2022±15 hot-dry climate conditions, while the increase is projected under 2022±15 warm-wet climate conditions.

Long-term average monthly flows of SAC-4 and SJR-4 under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median climate conditions are presented in Figure 13. Similar to 2022±15 median climate conditions, runoff increases in winter and decreases in spring and summer in both basins under the sensitivity climate scenarios. As compared to historical runoff, change in precipitation lead to a reduced peak for 2022±15 hot-dry and higher peak for SAC-4 and SJR-4 under 2022±15 warm-wet, and 2040±15 median climate conditions.

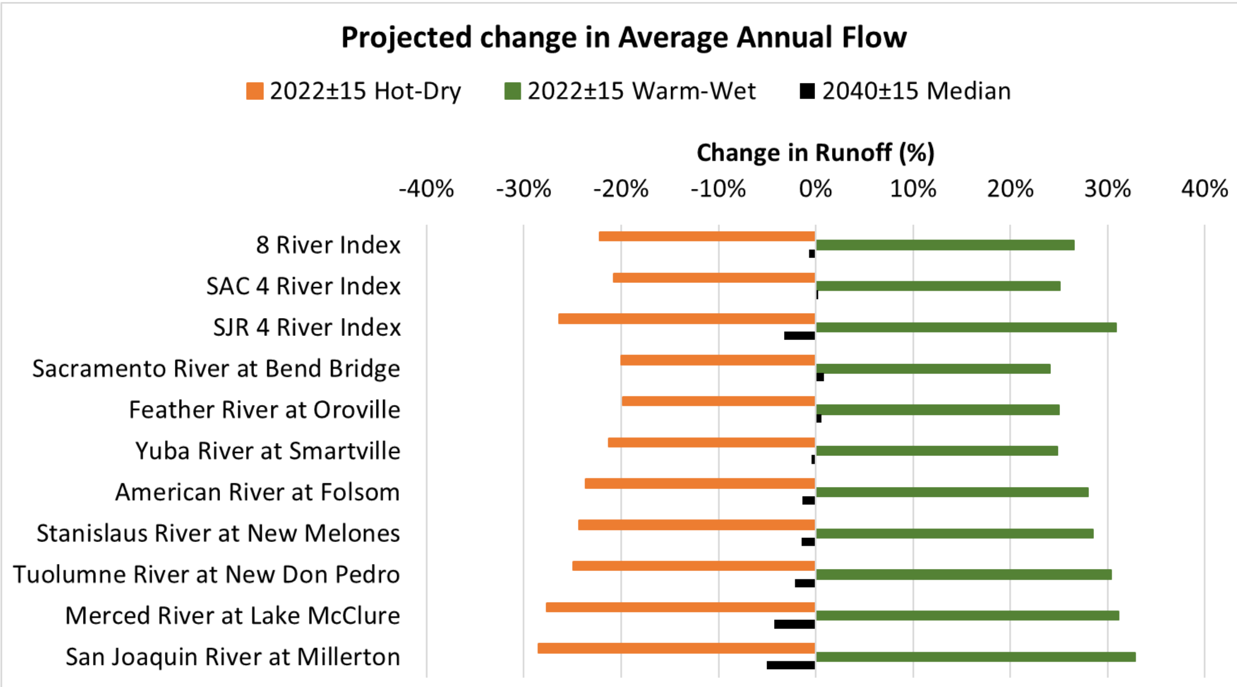

Figure 12. Projected Changes in Runoff for Major Watersheds in the Sacramento and San Joaquin River Basins for 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

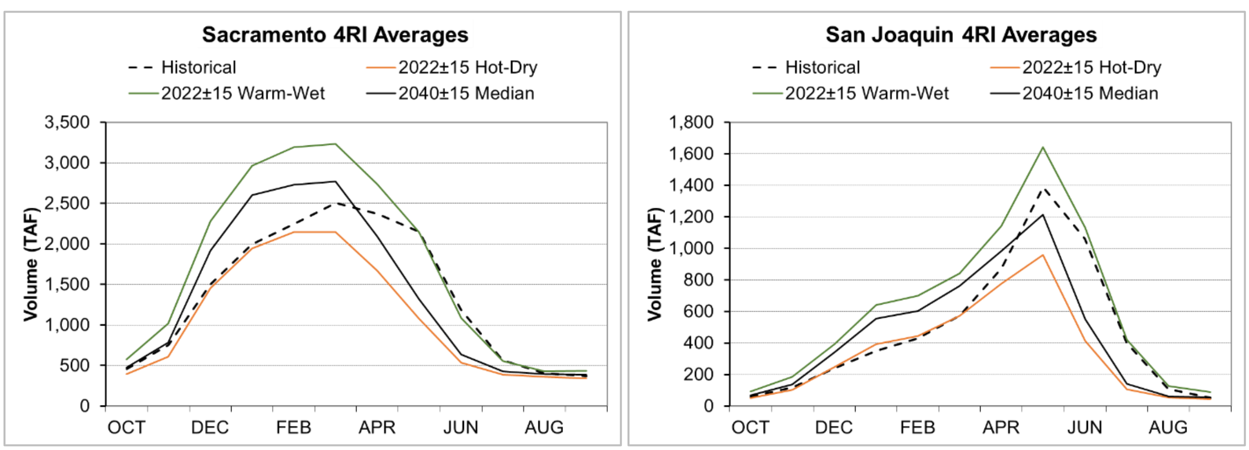

Figure 13. Projected Changes in Monthly Pattern of Runoff for the Sacramento Basin for 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

2.8.2 Valley Floor Flows

Perturbation of CalSim 3 boundary conditions was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.2 *Valley Floor Flows*. CalSimHydro input variables were perturb separately for the three sensitivity climate change scenarios similar to 2022±15 median climate change scenario.

Figure 14 shows the projected change to applied crop water in the Sacramento and San Joaquin Valleys, as estimated with the CalSimHydro model under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median climate conditions. Under the sensitivity climate scenarios, the applied water varies from -1.3% to +5.4% in Sacramento Valley and from -2.6% to +8.8% in and San Joaquin Valley. As estimated with CalSimHydro, changes to pattern and magnitude of precipitation (Figure 11) result in small increases to surface runoff, return flow, and deep percolation.

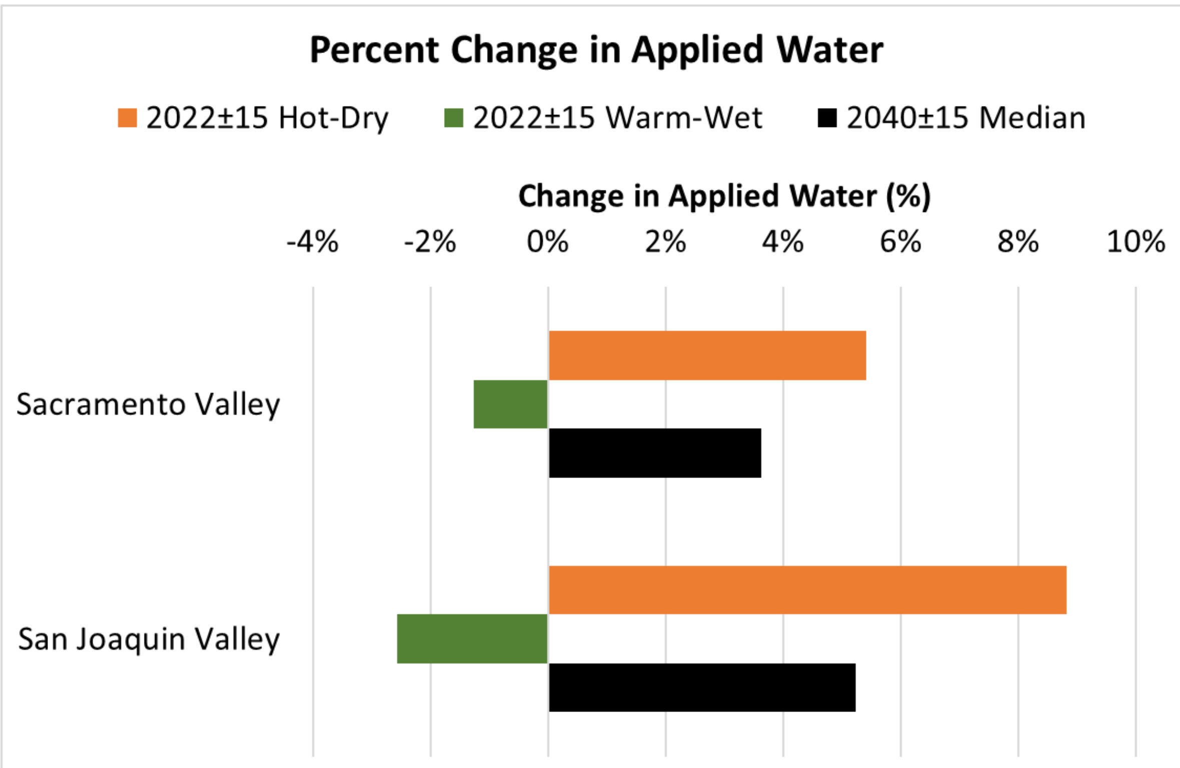

Figure 14. Projected Changes in Applied Water for Sacramento and San Joaquin for 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

2.8.3 Delta Channel Depletion

Perturbation of CalSim 3 delta evaporation boundary conditions was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.3 *Delta Channel Depletion*. Precipitation and daily maximum and minimum temperature were perturbed separately for the three sensitivity climate change scenarios similar to 2022±15 median climate change scenario.

Figure 15 shows the projected change to Sacramento – San Joaquin River Delta irrigation, drainage, and seepage under 2022±15 hot-dry, 2022 ±15 warm-wet, and 2040±15 median climate conditions as estimated with the DCD model. Irrigation and seepage increase due to increased evapotranspiration, a result of increased temperature for 2022±15 hot-dry, and 2040±15 median climate conditions (Figure 10). As estimated with DCD, changes to pattern and magnitude of precipitation (Figure 11) and irrigation result in a small change to Delta Island drainage. The change in the Net Delta Island Consumptive Use (DICU) ranges from -7.5% to 9.8% under three sensitivity climate change scenarios.

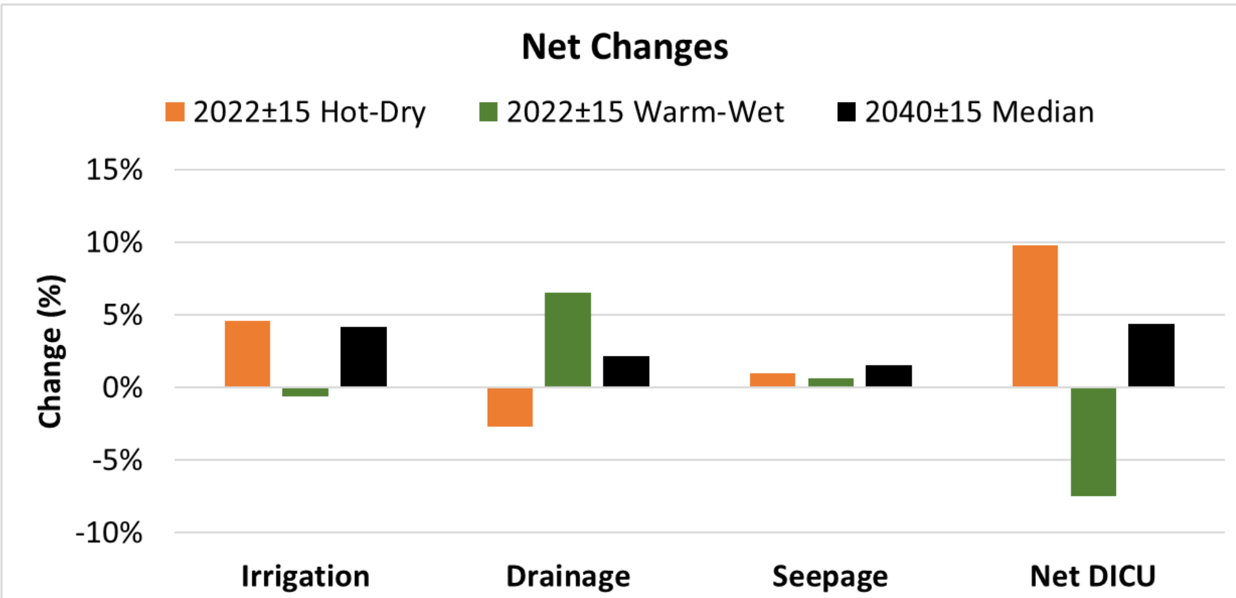

Figure 15. Projected Changes in Delta Island Consumptive Use for 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

2.8.4 Reservoir Evaporation

Perturbation of surface water evaporation and precipitation boundary conditions was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.3 *Delta Channel Depletion*. Gross evaporation and precipitation were perturbed separately for the three sensitivity climate change scenarios similar to 2022±15 median climate change scenario.

Figure 16 shows the projected change in evaporation rate at major reservoirs under 2022±15 hot-dry, 2022 ±15 warm-wet, and 2040±15 median climate conditions. The evaporation rates for all the major reservoirs are expected to increase due to rise in temperature under 2022±15 hot-dry and 2040±15 median climate conditions. For 2022±15 warm-wet climate change scenario, the evaporation rate is projected to reduce for most of the reservoirs due to relatively less rise in temperature and increase in precipitation as compared to other climate change scenarios. The evaporation rates of the reservoirs are affected by diurnal temperature range.

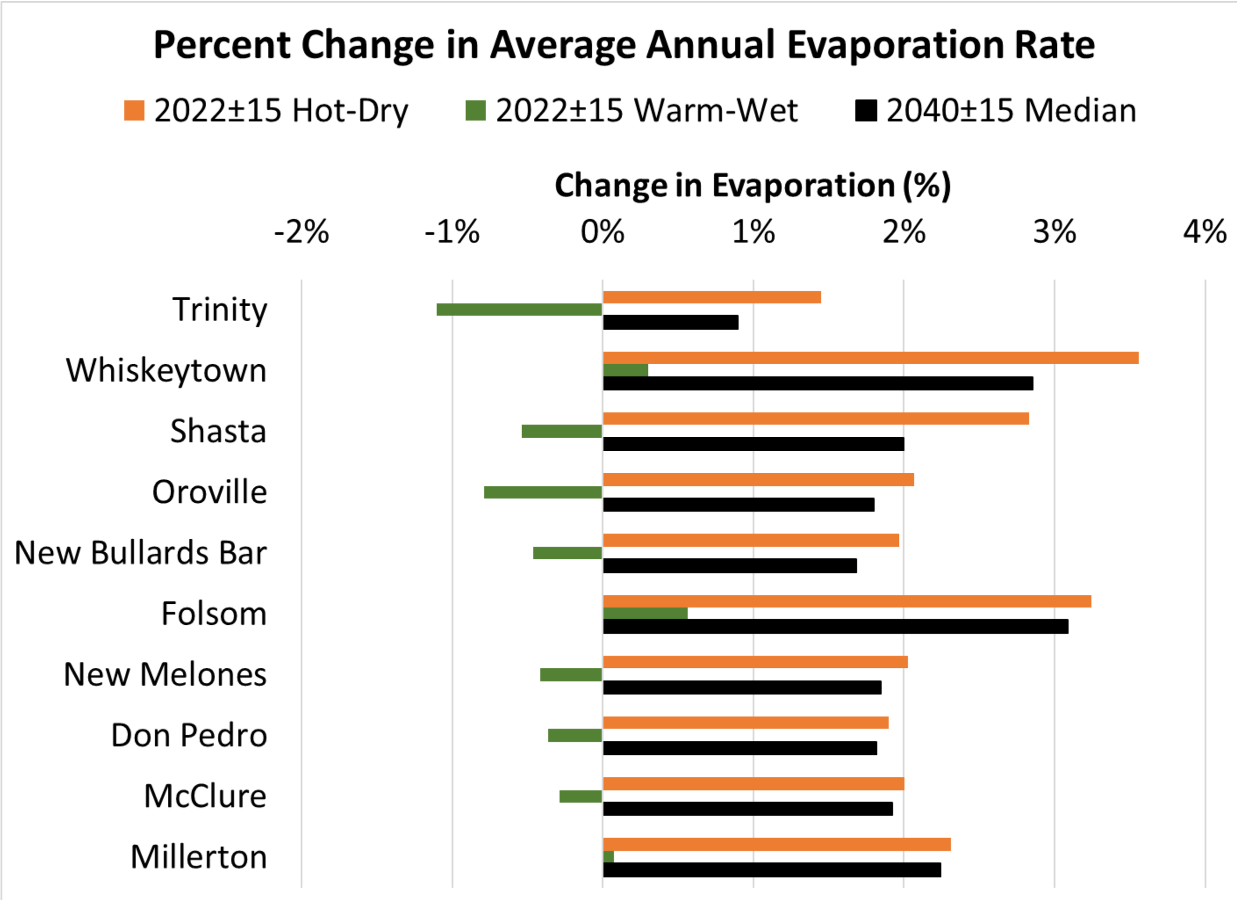

Figure 16. Projected Changes in Evaporation Rate at Major Reservoirs for 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

2.8.5 Inputs for Lookup Tables

Perturbation of the precipitation and unimpaired runoff data was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.5 *Inputs for Lookup Tables*. Dats was perturbed separately for the three sensitivity climate change scenarios similar to 2022±15 median climate change scenario.

Point and basin average precipitation are projected to change similarly as for the major watersheds in the Sacramento and San Joaquin River basins under 2022±15 hot-dry, 2022±15 warm-wet, and 2040±15 median Climate Change Scenarios as shown in Figure 11. Also, the projected change in unimpaired flows will be similar to the rim inflows changes for major watersheds under the sensitivity climate change scenarios (Figure 12).

2.8.6 Groundwater

Deep percolation and later flow boundary conditions are developed by the CalSimHydroEE and SmallWatersheds models, respectively, using precipitation and evapotranspiration data. Perturbation of the precipitation and evapotranspiration data was performed using the monthly and water year climate change rate-based approach as described in Section 2.5.6 *Groundwater*.

Figure 17 shows the projected change in average annual deep percolation, precipitation, surface runoff, baseflow, and ET under 2022±15 hot-dry, 2022 ±15 warm-wet, and 2040±15 median climate conditions. Perturbed deep percolation and lateral flow input boundary conditions change under sensitivity scenarios were dominated by precipitation change. Deep percolation is projected to change between -32% and +46% under three sensitivity climate change scenarios.

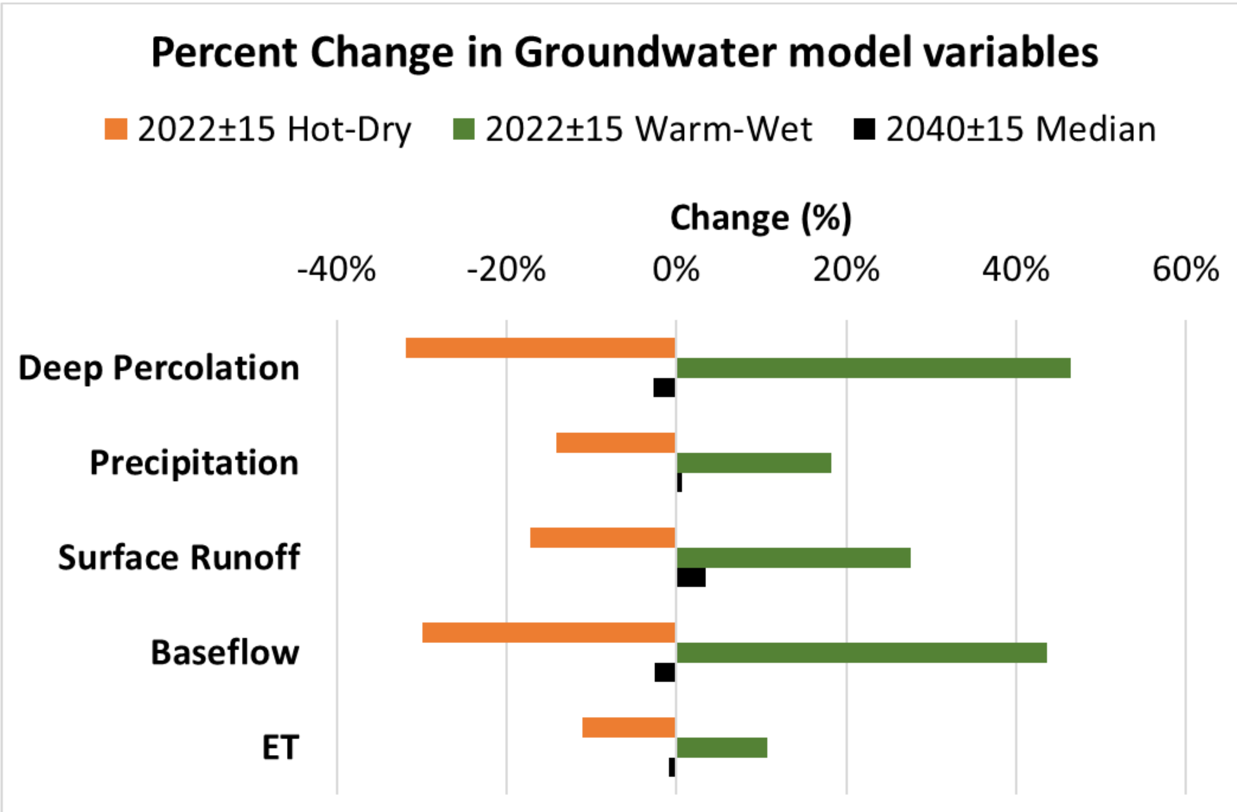

Figure 17. Projected Changes in Average Annual Deep Percolation, Precipitation, Surface Runoff, Baseflow, and ET under 2022±15 Hot-Dry, 2022±15 Warm-Wet, and 2040±15 Median Climate Change Scenarios.

2.9 Use of Projected Runoff from the VIC Model for Impaired Streamflows

Impaired rim inflows in the upper San Joaquin of CalSim 3 were unimpaired before perturbation process. The rim inflows were “re-impaired” after perturbing the unimpaired inflows to represent future climate conditions. As information on specific local project operations (impairment) at these locations was not available, impairment was calculated as the difference between the unimpaired historical flow and the CalSim 3 inflow time series. This method assumes the local project operations will be the same in future climate conditions and does not account for any adaptation in local project operations. This method was applied to 2022±15 hot-dry, 2022 ±15 warm-wet, and 2040±15 median climate conditions.

2.10 Limitations and Appropriate Use of Results

Daily gridded windspeed data was used in simulating the VIC hydrologic model. Observational data for wind are generally sparce but several reanalysis datasets exist for historical data. In this study, climatological averages of daily reanalysis data over the period 1948–2015 is used as a repeating annual signal in both baseline and all future climate scenarios because of a lack of available data prior to 1948, after 2015, and for future climate scenarios. Windspeed can have impacts on evapotranspiration, snow ablation, soil moisture, and other important hydroclimate variables. However, previous analysis (https://loca.ucsd.edu/loca-vic-runs/) has shown that VIC has a modest sensitivity to windspeed.

Temperature detrending was performed to represent recent climate conditions but the precipitation was not detrended as the trends are statistically insignificant. During the bias correction process, negative daily temperature range (DTR) was observed in the time series, which further amplified during the temperature detrending process. However, the frequency if occurrence of negative DTR was less than 0.2% annually. Spatial variation of the hydrological parameter at grid level and watershed averaged hydrology at seasonal and monthly scale are negligible (<0.5%) affected by negative DTR. Projected changes in temperatures remain unaffected by negative DTR under future climate change conditions.

Future climate change scenarios are developed based on historical meteorology (Livneh et al and PRISM datasets), historical hydrology, and projected changes simulated by global climate models (GCMs). The refinements in historical meteorological, historical hydrological datasets, and GCM projections may affect the future climate scenarios. There is considerable uncertainty in GCM projections embedded in characterizing extremely complicated systems using climate modeling. Development of a climate change scenario requires the application of various tools and approaches, such as emission scenarios (RCPs and Shared Socioeconomic Pathways (SSPs)), GCMs (CMIP5 and CMIP6), downscaling approach, climate change scenarios development approach (scenario-based approaches and decision-scaling approaches) and climate impact models. Each tool and approach come with varying degrees of uncertainty, which accumulates as they are implemented together in the full development of a climate change scenario.

Numerical models developed and applied for the LTO are generalized and simplified representations of a complex water resources system. The models are not predictive models of project operations and results cannot be considered as absolute with a quantifiable confidence interval. The model results are only useful in a comparative analysis and can only serve as an indicator of conditions.

Due to the assumptions involved in the input data sets and model logic, care must be taken to select the most appropriate timestep for the reporting of model results. Sub-monthly (e.g., weekly, or daily) reporting of raw model results is not consistent with how the models were developed, and results should be presented on a monthly or more aggregated basis.

Absolute differences computed at a point in time between model results from an alternative and a baseline to evaluate impacts is an inappropriate use of model results (e.g., computing differences between the results from a baseline and an alternative for a particular month and year within the period of record of simulation). Likewise computing absolute differences between an alternative or a baseline and a specific threshold value or standard is an inappropriate use of model results. Statistics computed based on the absolute differences at a point in time (e.g., average of monthly differences) are an inappropriate use of model results. Computing the absolute differences in this way disregards the changes in antecedent conditions between individual scenarios and distorts the evaluation of impacts of a specific action.

Reporting seasonal patterns from long-term averages and water year-type averages is appropriate. Statistics computed based on long-term and water year-type averages are an appropriate use of model results. Computing differences between long-term or water year-type averages of model results from two scenarios are appropriate.

All models include simplifications and generalizations compared to the "real-world" scenarios that they represent. Therefore, all models will have limitations to how accurately they can represent the real world. It is necessary to understand these limitations to correctly interpret results. Some of these limitations are discussed in general terms above, but because limitations are often model-specific, each section of the Modeling Technical Appendix includes subsections that further describe model limitations specific to the model being discussed and appropriate presentation and use of model results.

3 References

California Department of Water Resources. 2017. *CalSim 3.0 Draft Report.* Sacramento, CA. https://data.cnra.ca.gov/dataset/271c4a1d-fa8e-464e-bd51-c64a459f5739/resource/1d61d890-3782-4ca2-aa68-874f2ecbe8e3/download/mainreport.pdf.

California Department of Water Resources. 2018. *Methodology for Flow and Salinity Estimates in the Sacramento – San Joaquin Delta and Suisun Marsh.* Sacramento CA. https://data.cnra.ca.gov/dataset/a4abe322-75b0-45ba-a85c-97aa9bb60520/resource/24890484-11a6-4ada-a61a-3d1f7fdd948e/download/final6baydelta39thprogress-report071918.pdf.

California Department of Water Resources. 2019. *CalSimHydro Reference Manual.* Sacramento CA. https://data.cnra.ca.gov/dataset/271c4a1d-fa8e-464e-bd51-c64a459f5739/resource/1d61d890-3782-4ca2-aa68-874f2ecbe8e3/download/mainreport.pdf.

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology and Climatology* 33:140–158.

Kalnay, E., and Coauthors. 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bull. *American Meteorological Society* 77:437–471

Liang, X., D. P. Lettenmaier. E. F. Wood, and S. J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research* 99:14415–14428. https://doi.org/10.1029/94JD00483.

Liang, X., E. F. Wood, and D. P. Lettenmaier. 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. *Global and Planetary Change* 13:195–206.

Livneh, B., E. A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K. M. Andreadis, E. P. Maurer, and D. P. Lettenmaier. 2013. A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions. *Journal of Climate* 26:9384–9392. https://doi.org/10.1175/JCLI-D-12-00508.1.

Nijssen, B., D. P. Lettenmaier, X. Liang, S. W. Wetzel, and E. F. Wood. 1997. Streamflow simulation for continental-scale river basins. *Water Resources Research* 33:711–724.

Pierce, D. W., D. R. Cayan, and B. L. Thrasher. 2014. Statistical downscaling using localized constructed analogs (LOCA). *Journal of Hydrometeorology* 15:2558–2585.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. An Overview of CMIP5 and the Experiment Design. Bull. *American Meteorological Society* 93:485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Zhang, Q., Y. Zhou, V. P. Singh, and Y. D. Chen. 2011. Comparison of detrending methods for fluctuation analysis in hydrology. *Journal of Hydrology* 400(1–2):121–132.