Appendix F, Modeling

Section F.2-1 Climate Change Sensitivity Analysis, No Action Alternative

F.2-1.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to the No Action Alternative (NAA) under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used for quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-1.1.1 Climate Change Comparison

F.2-1.1.1.1 CalSim 3

Figure F.2-1-1 through **Error! Reference source not found.** shows CalSim 3 simulation results for the NAA. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, any assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for the NAA were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough

- Sacramento River at Verona
- Sacramento River at Freeport
- Flow though Yolo Bypass
- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-1-1) and end of September (Figure F.2-1-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 15% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows, long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, the main months of reservoir management season, the differences are less notable. Summer months are commonly when river flows are due primarily to releases from storage instead of runoff events. Flows under 2040 Median climate are mostly similar to flows under 2022 Median climate.

Clear Creek below Whiskeytown (Figure F.2-1-7) flow changes are similar to the changes observed in the Sacramento River watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in fall and winter months. For Spring Creek inflow to Keswick Reservoir (Figure F.2-1-8), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-1-10) Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-1-11), changes to flow are similar to the changes in the Sacramento watershed. In all months, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May and June due to lower Folsom inflows in spring months. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. Compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in January of 2040 Median conditions due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-1-12), changes are similar to the changes in the Sacramento watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows.

For long-term monthly average San Joaquin River flows, changes to flow are similar to the changes in the Sacramento watershed. San Joaquin River at Gravelly Ford (Figure F.2-1-13) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced.

For long-term monthly average flows in the Delta (Figure F.2-1-16 through Figure F.2-1-21), changes are generally similar to the changes in the Sacramento watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows. Flows across all climate conditions are mostly similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure F.2-1-20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

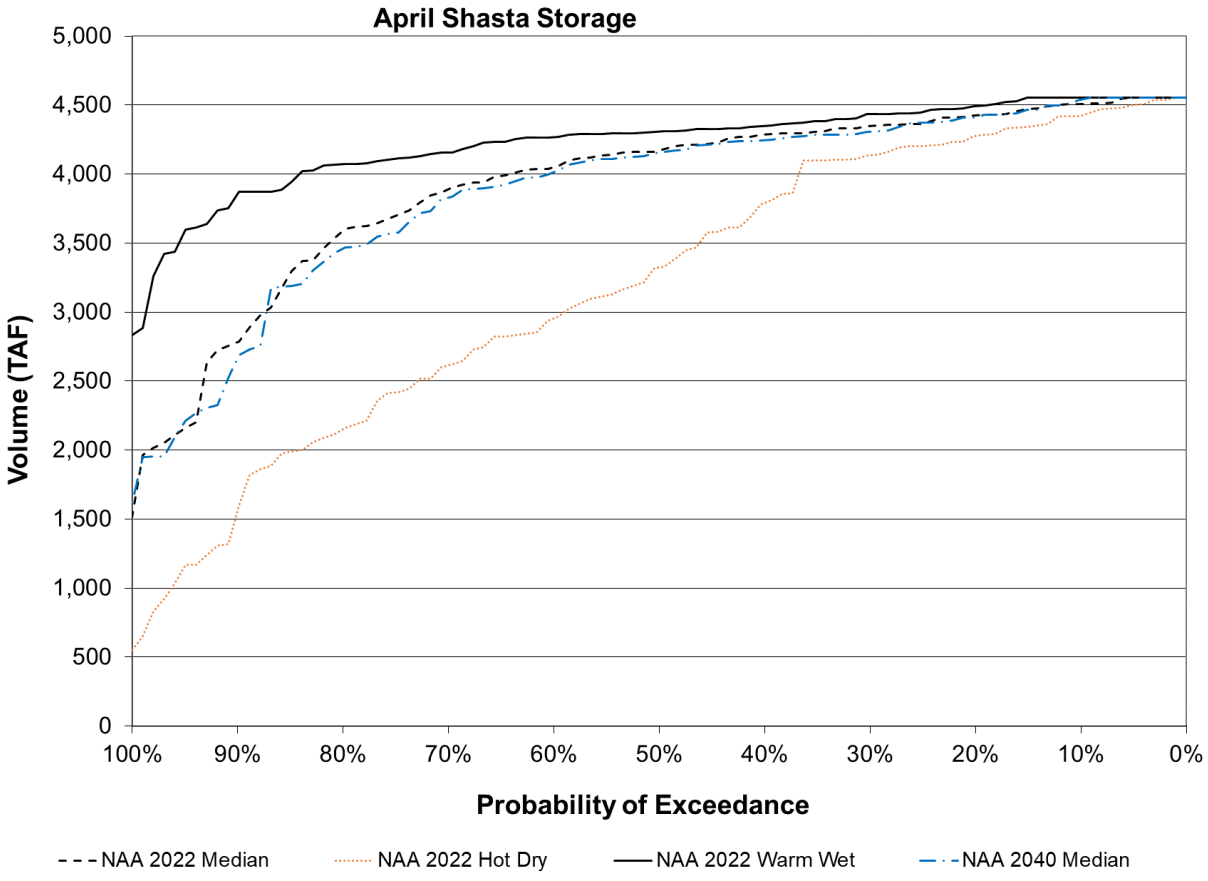

Figure F.2-1-1. End of April Shasta Storage

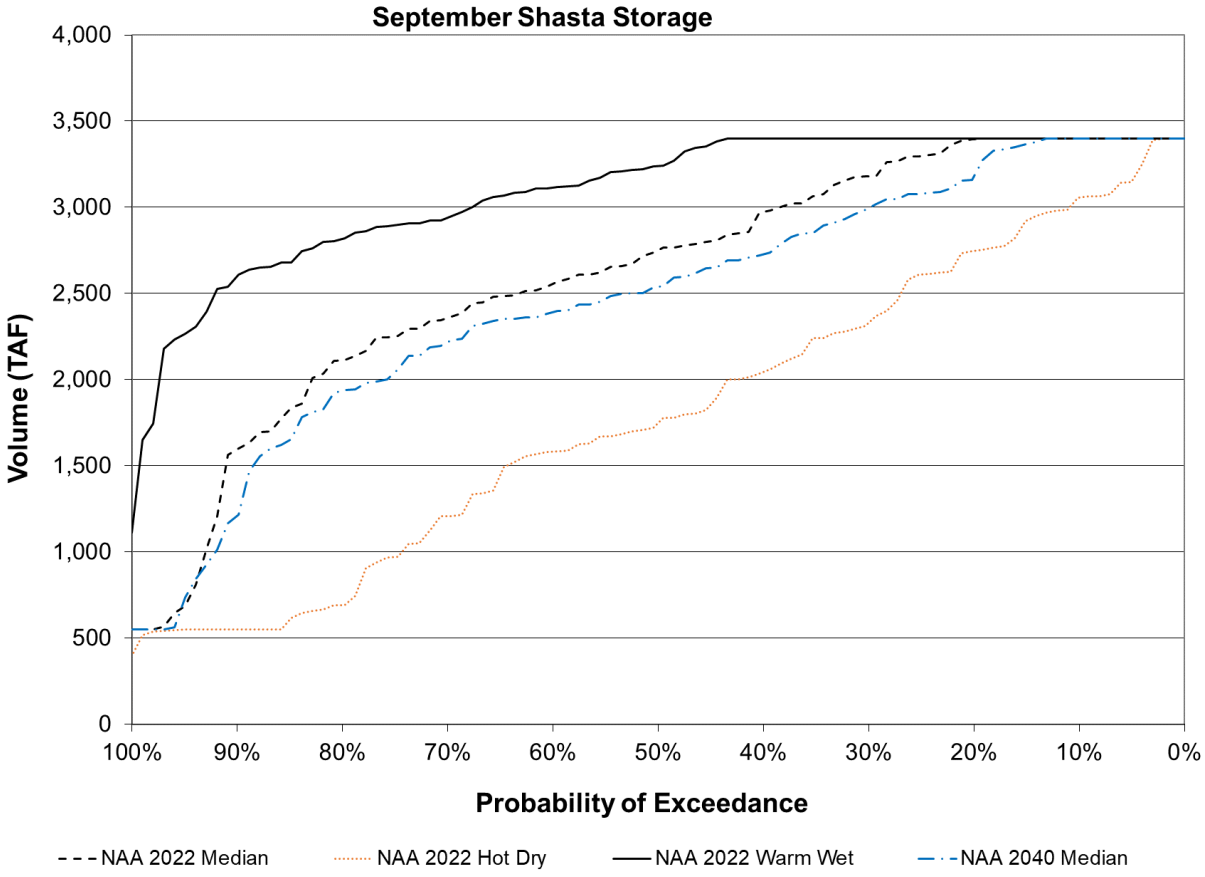

Figure F.2-1-2. End of September Shasta Storage

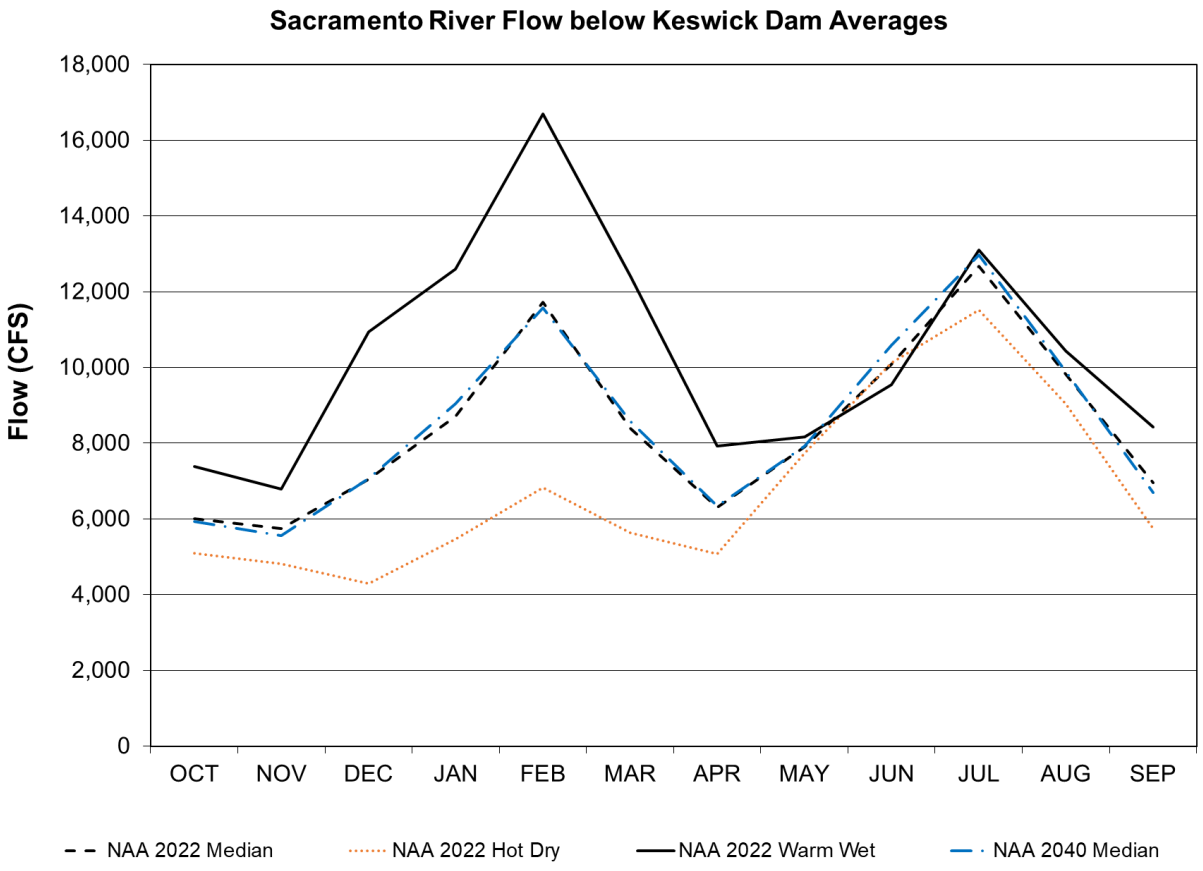

Figure F.2-1-3. Long-term Average Sacramento River flow below Keswick Dam

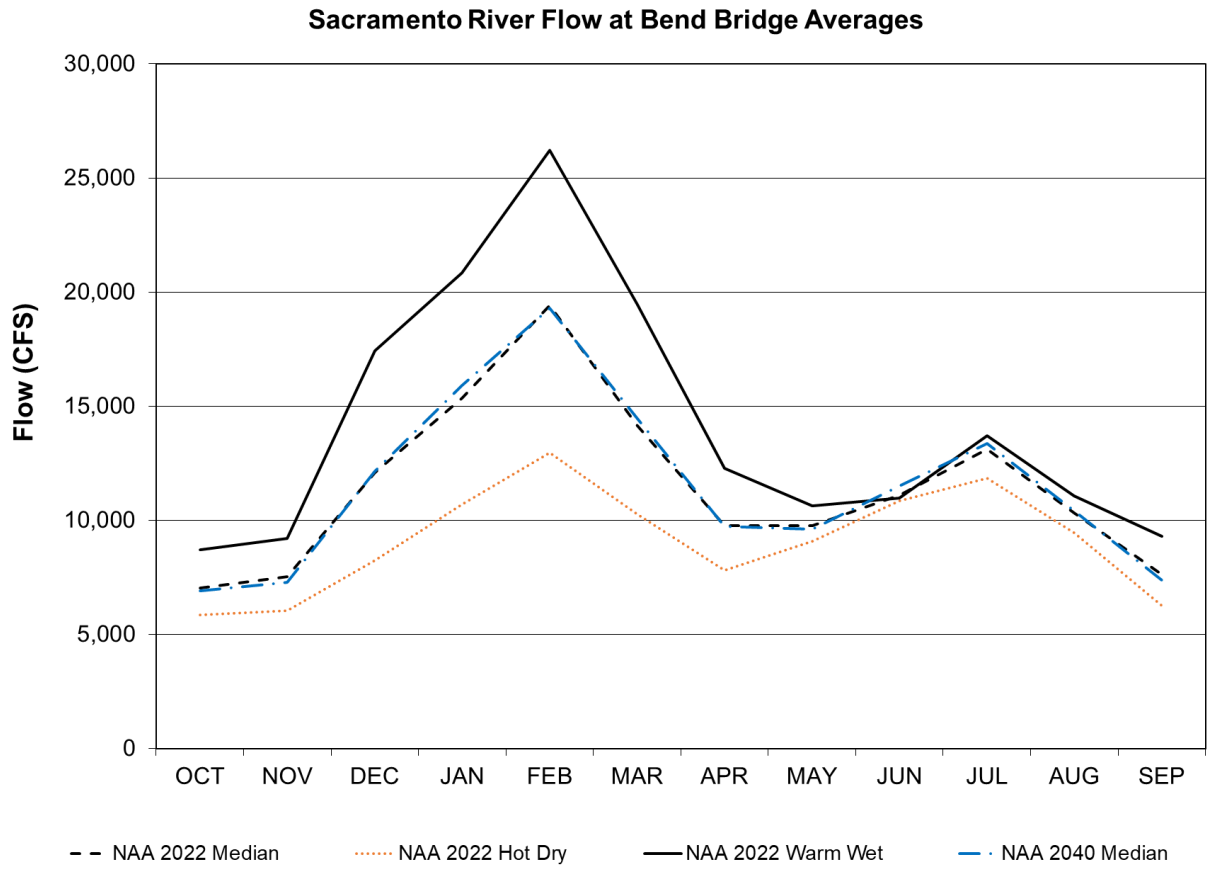

Figure F.2-1-4. Long-term Average Sacramento River flow at Bend Bridge

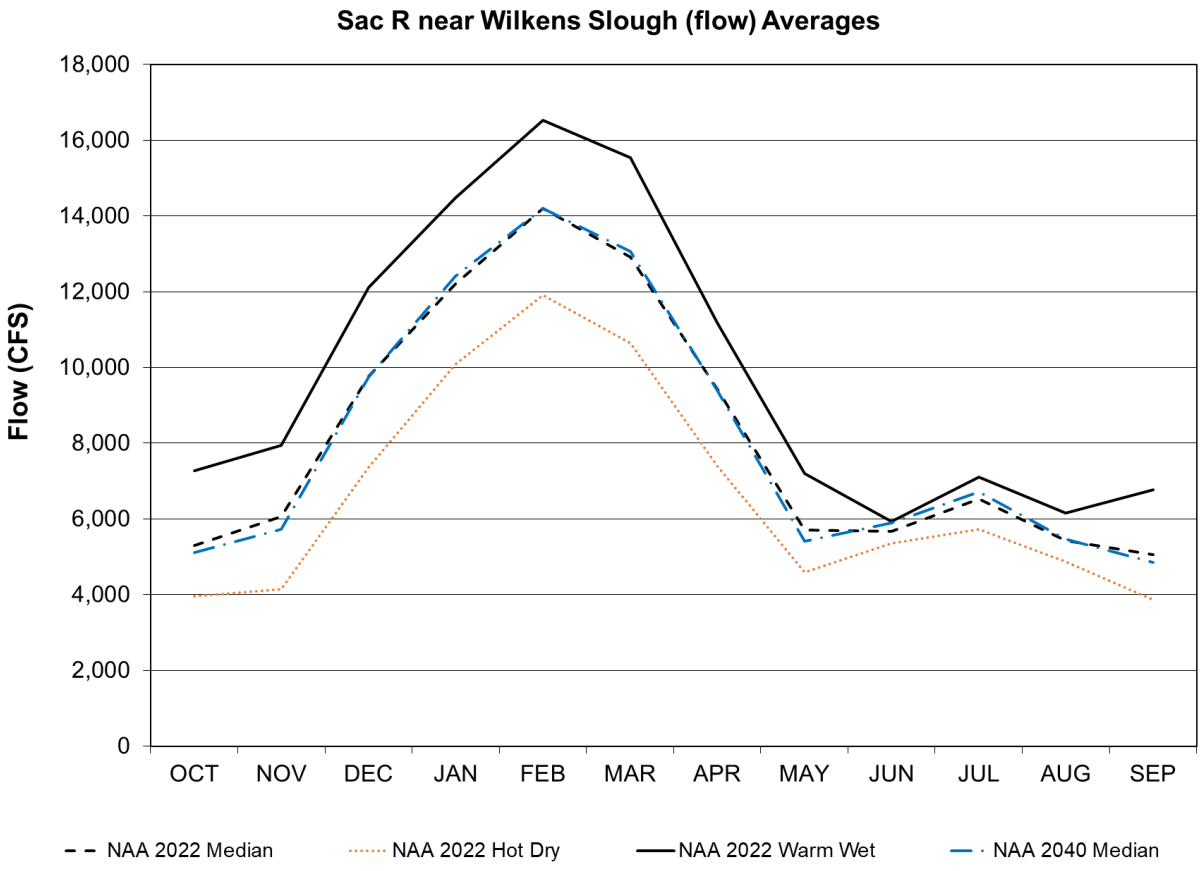

Figure F.2-1-5. Long-term Average Sacramento River flow near Wilkins Slough

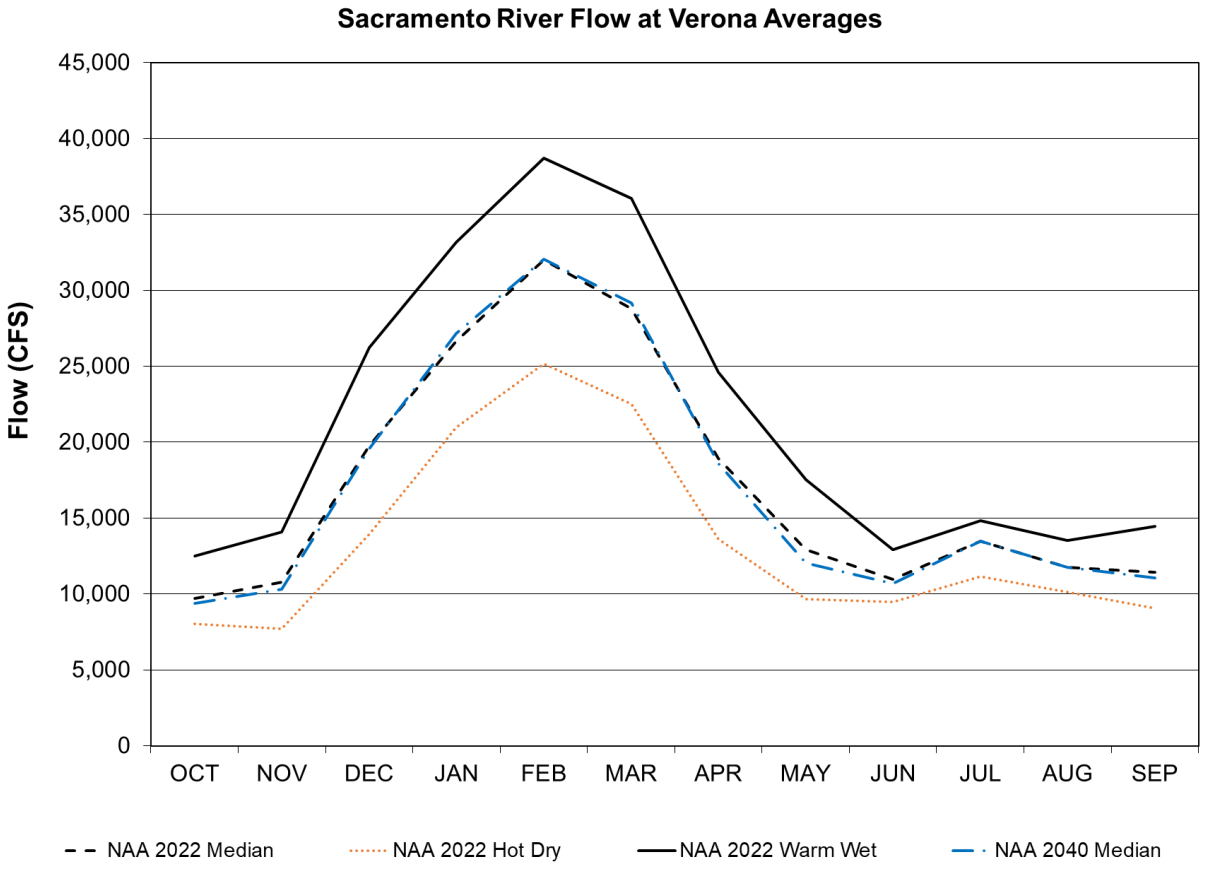

Figure F.2-1-6. Long-term Average Sacramento River flow at Verona

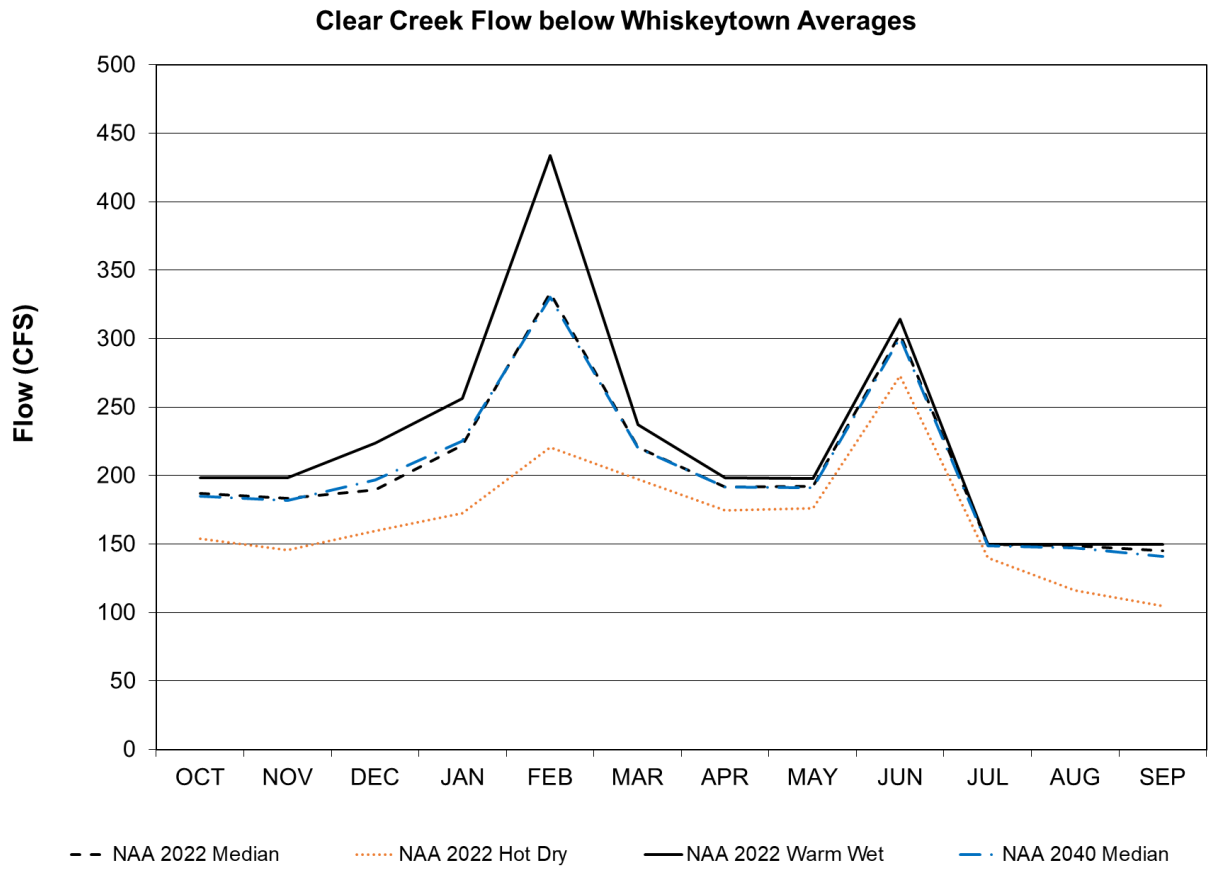

Figure F.2-1-7. Long-term Average Clear Creek flow below Whiskeytown

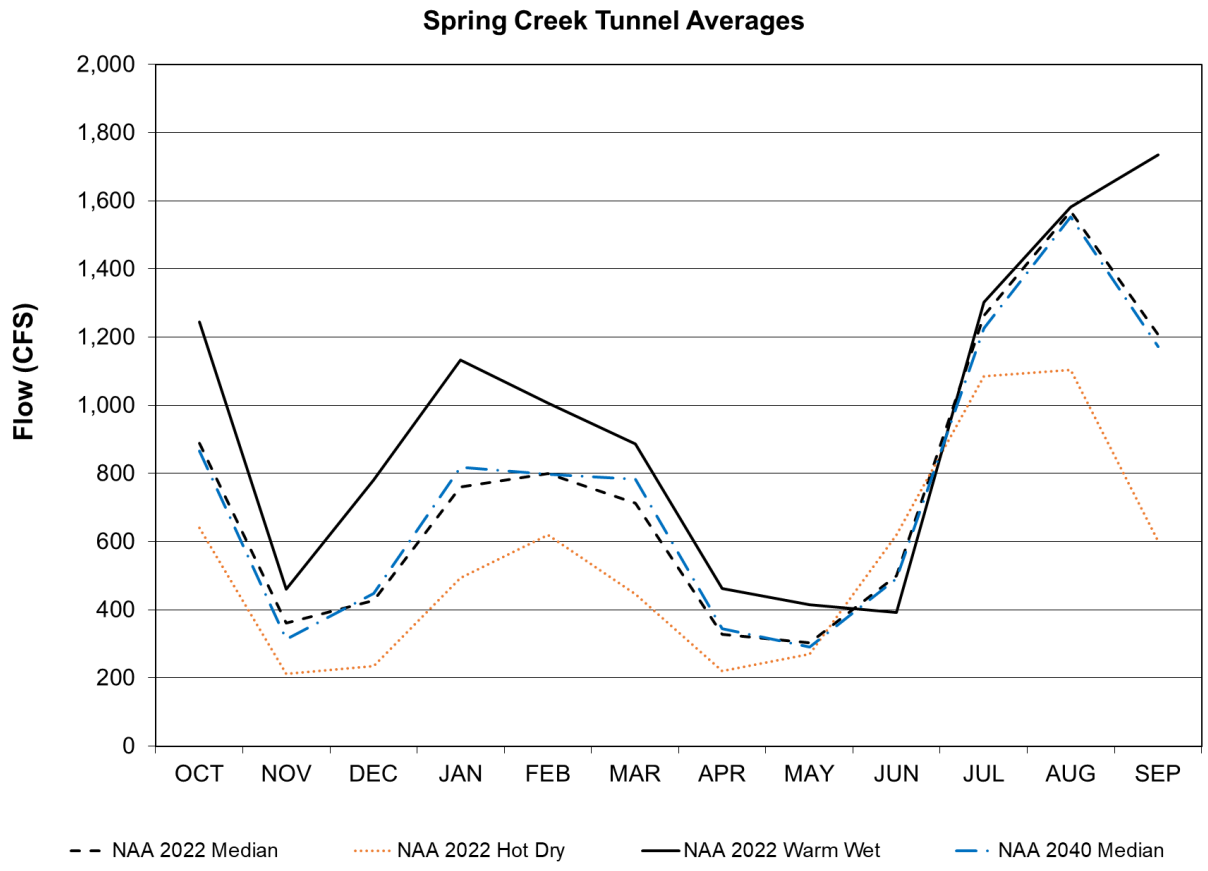

Figure F.2-1-8. Long-term Average Spring Creek Tunnel Flow

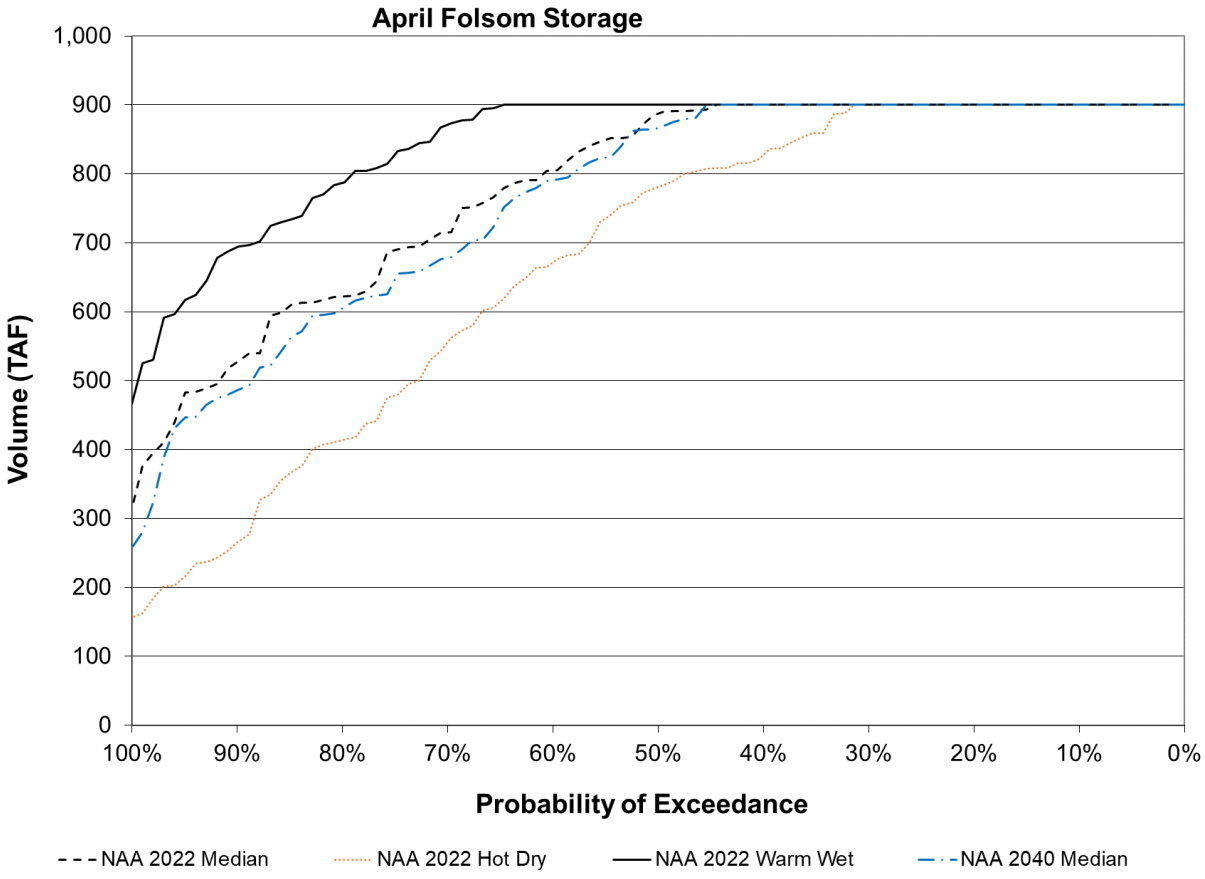

Figure F.2-1-9. End of April Folsom Storage

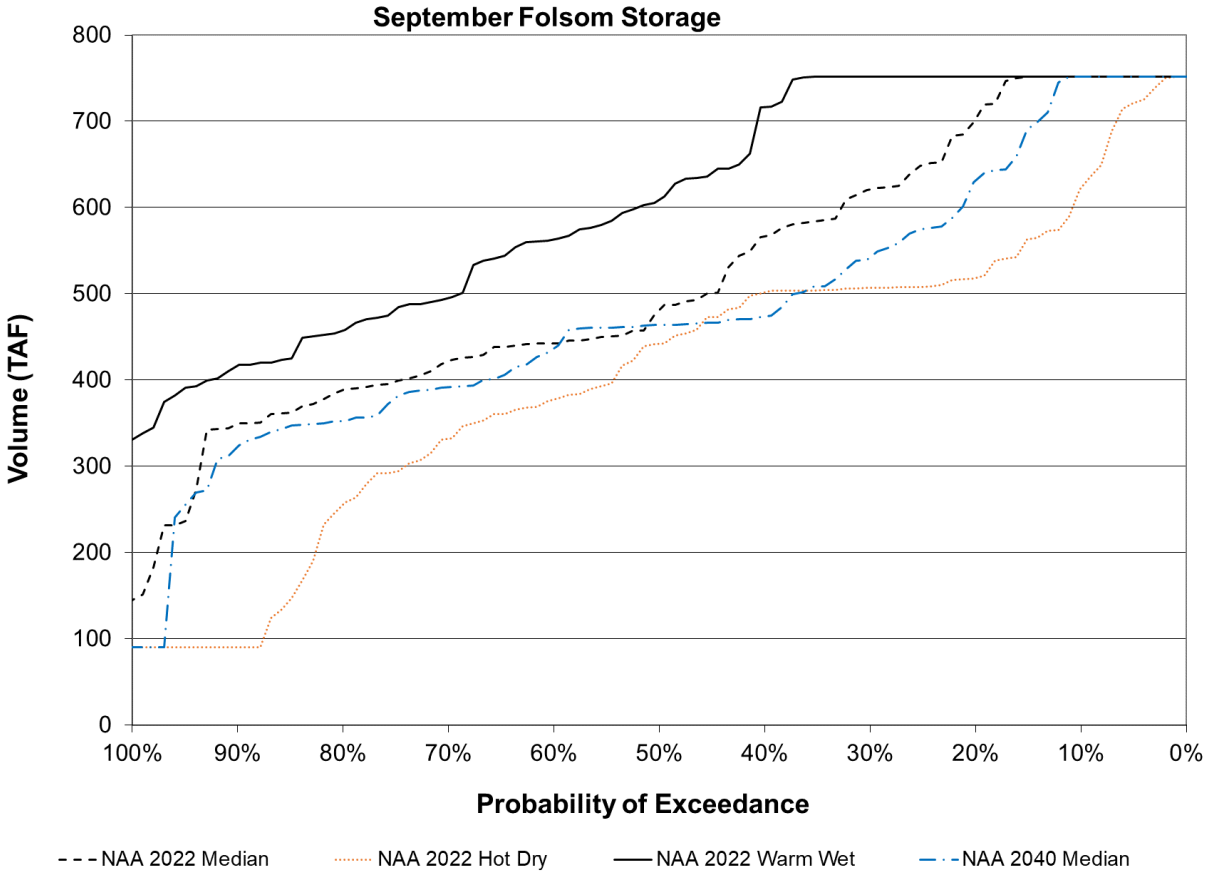

Figure F.2-1-10. End of September Folsom Storage

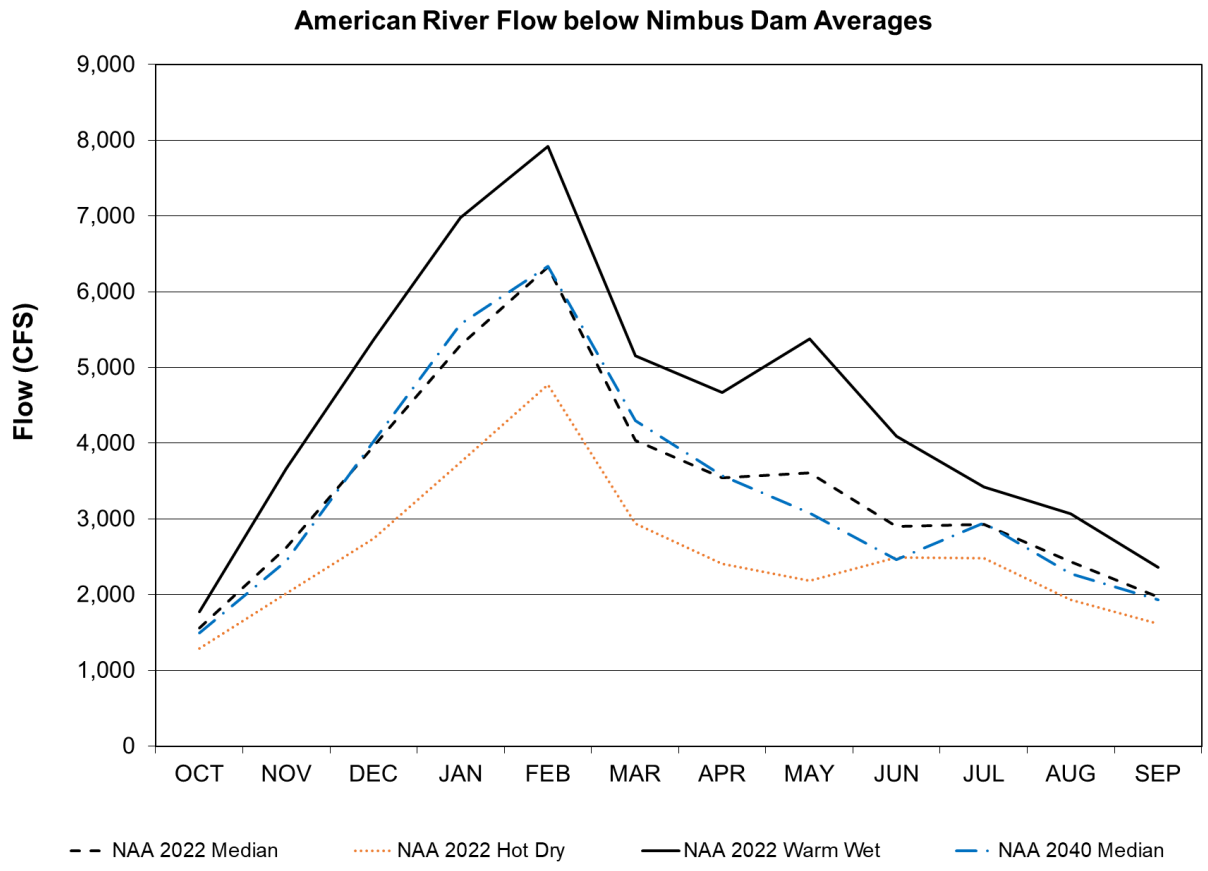

Figure F.2-1-11. Long-term Average American River flow below Nimbus Dam

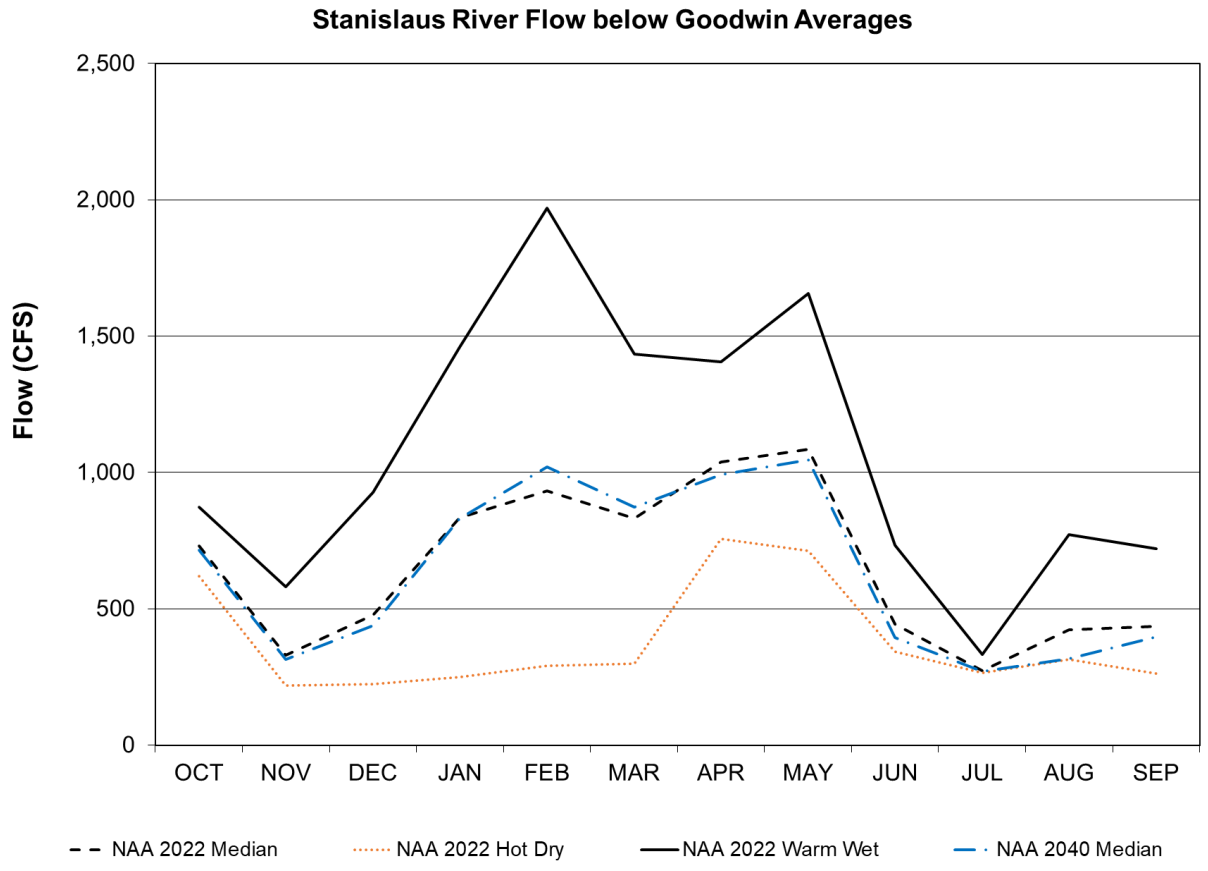

Figure F.2-1-12. Long-term Average Stanislaus River flow below Goodwin

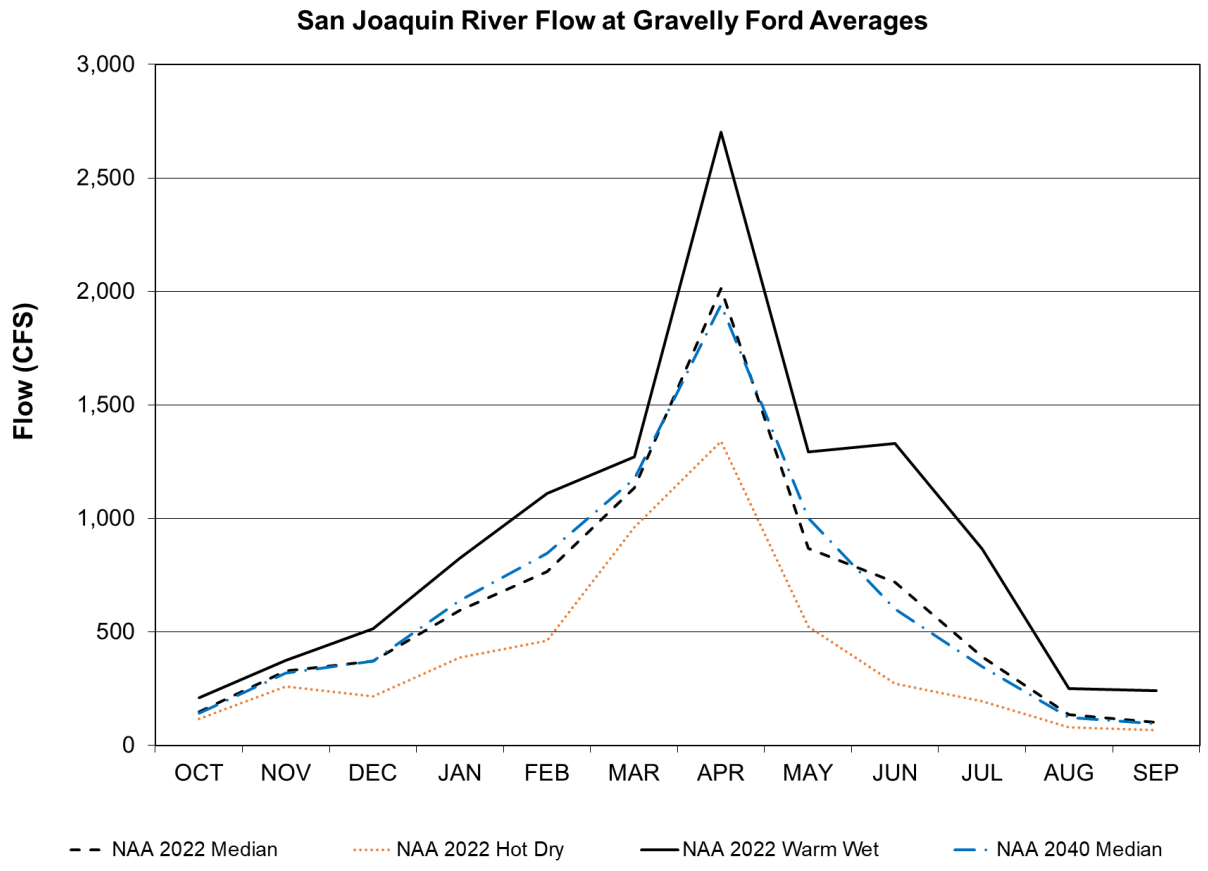

Figure F.2-1-13. Long-term Average San Joaquin River flow at Gravelly Ford

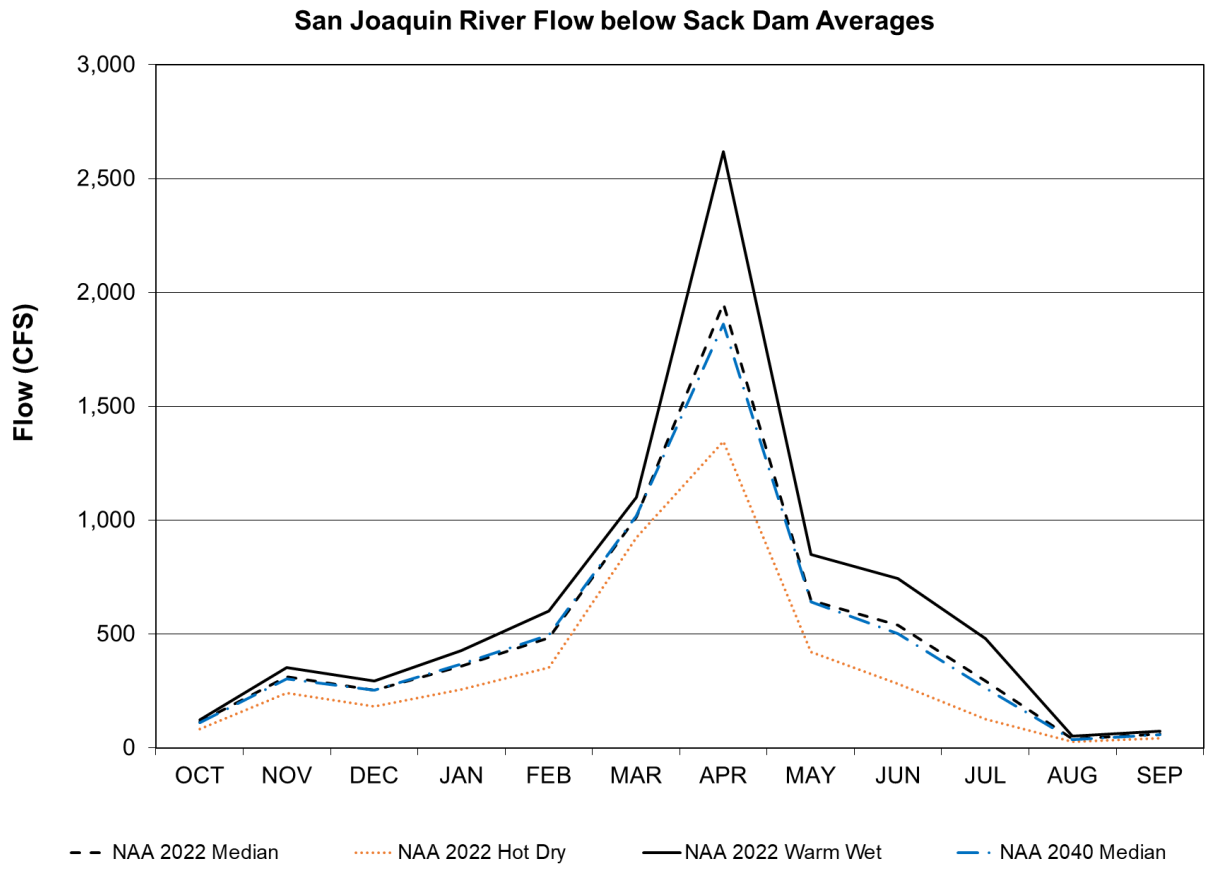

Figure F.2-1-14. Long-term Average San Joaquin River flow below Sack Dam

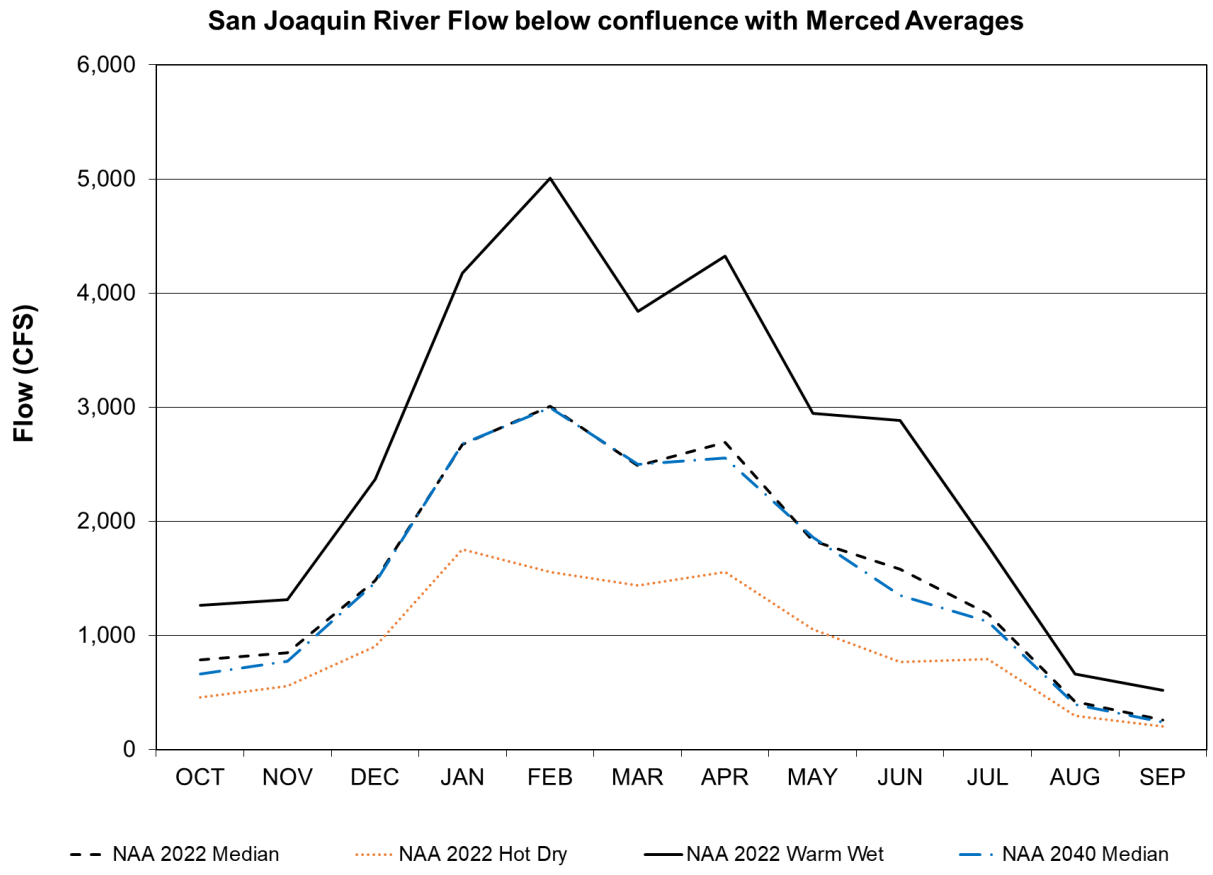

Figure F.2-1-15. Long-term Average San Joaquin River flow below Confluence with Merced River

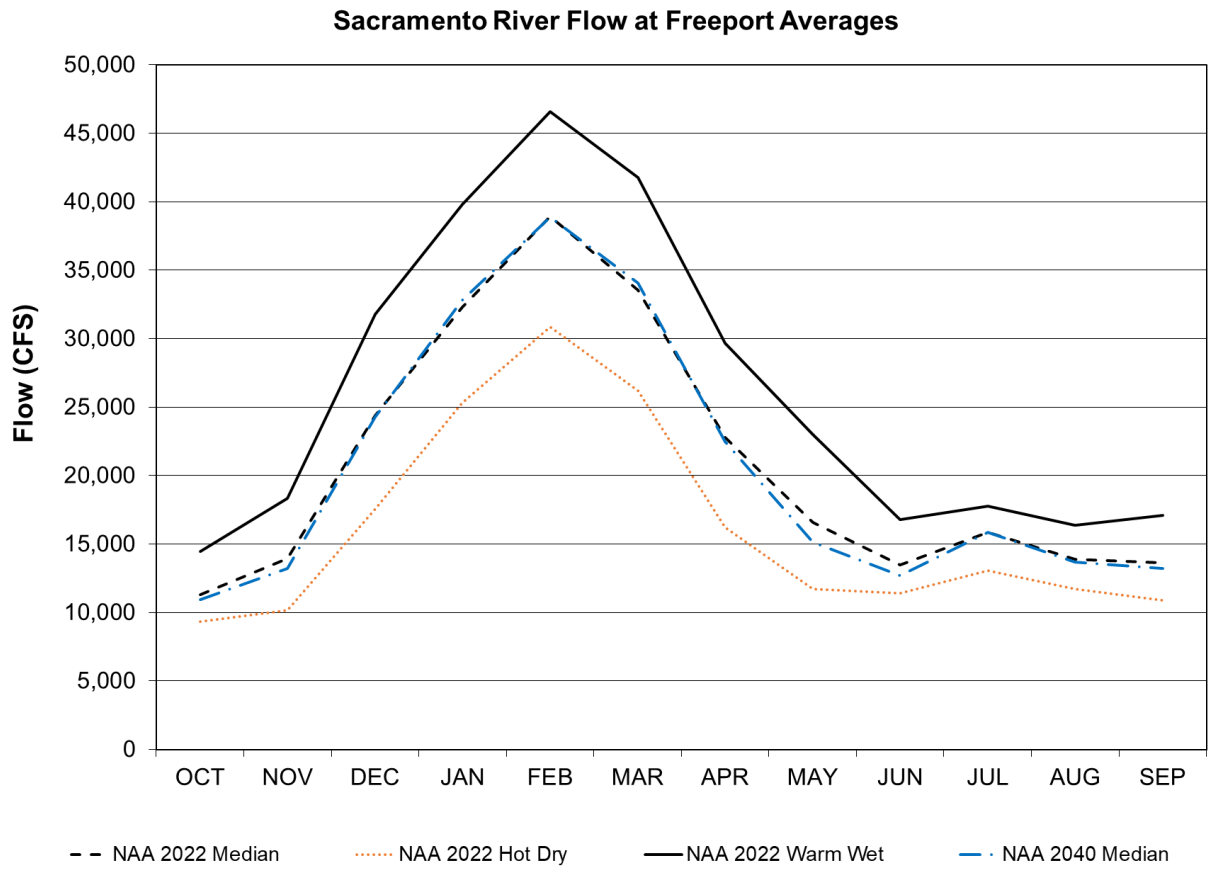

Figure F.2-1-16. Long-term Average Sacramento River flow at Freeport

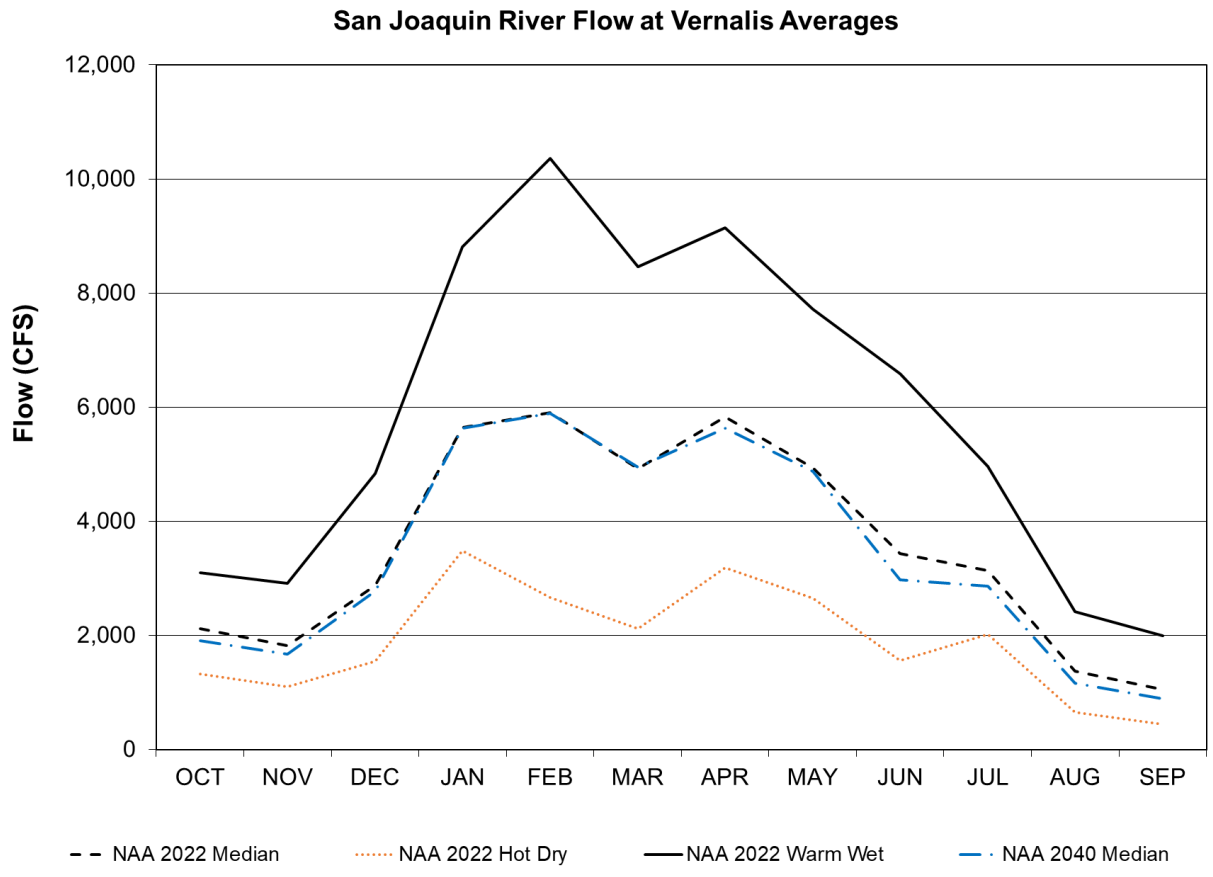

Figure F.2-1-17. Long-term Average San Joaquin River flow at Vernalis

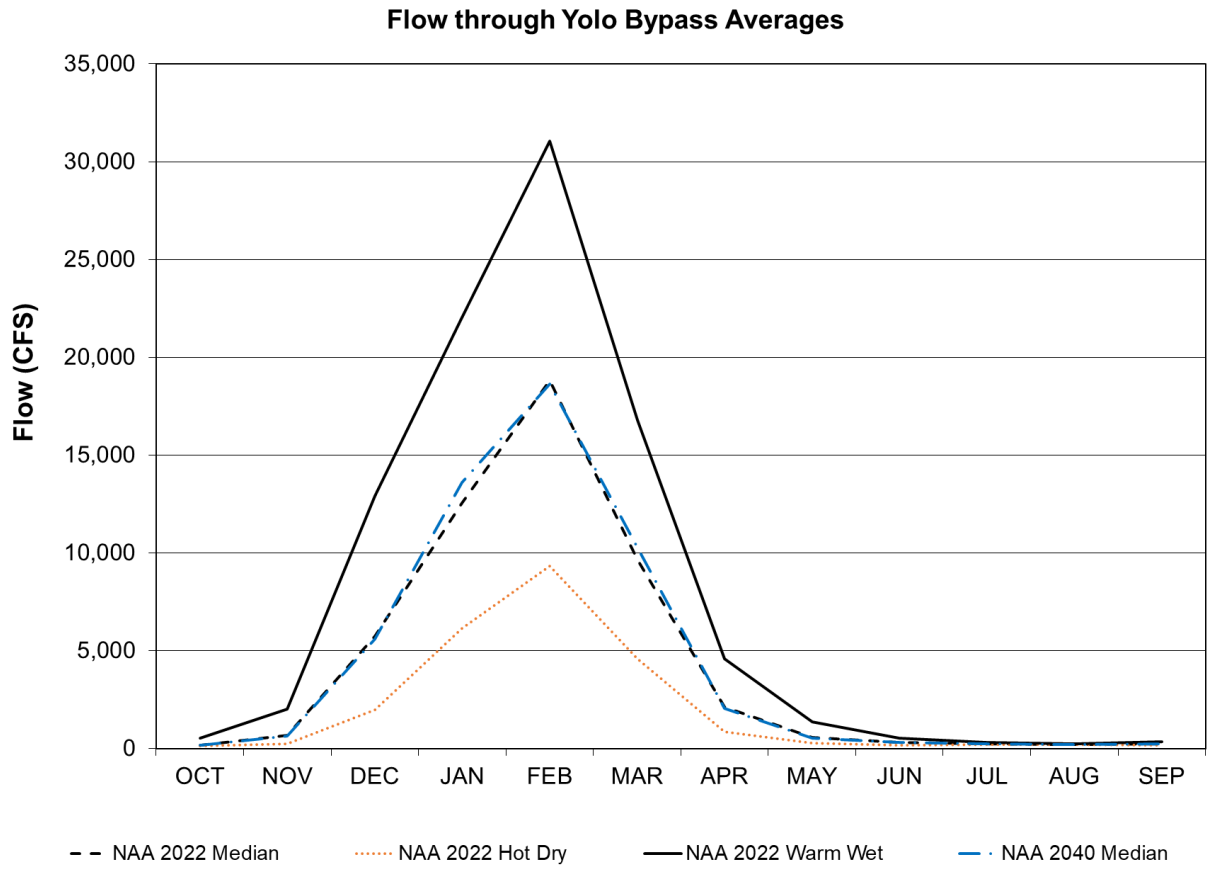

Figure F.2-1-18. Long-term Average Yolo Bypass Flow

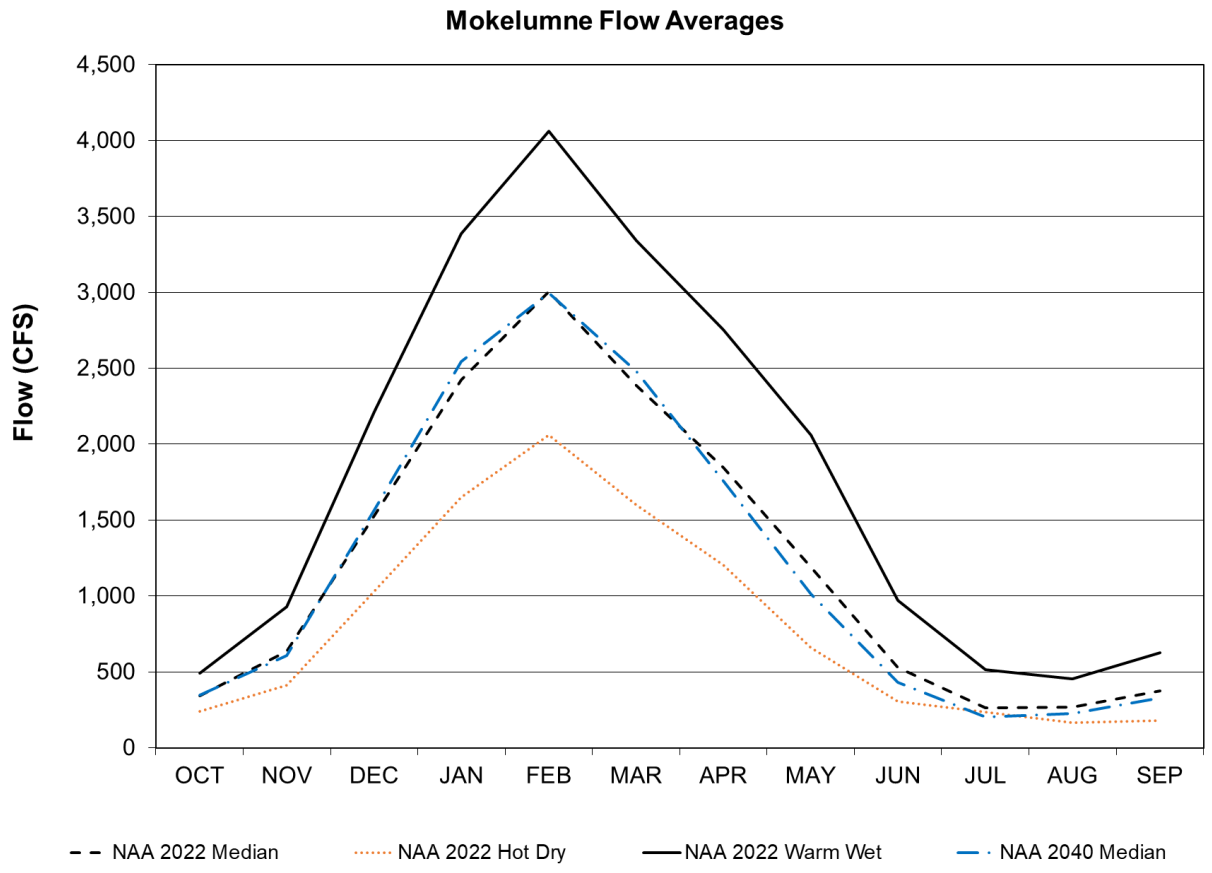

Figure F.2-1-19. Long-term Average Mokelumne River Flow

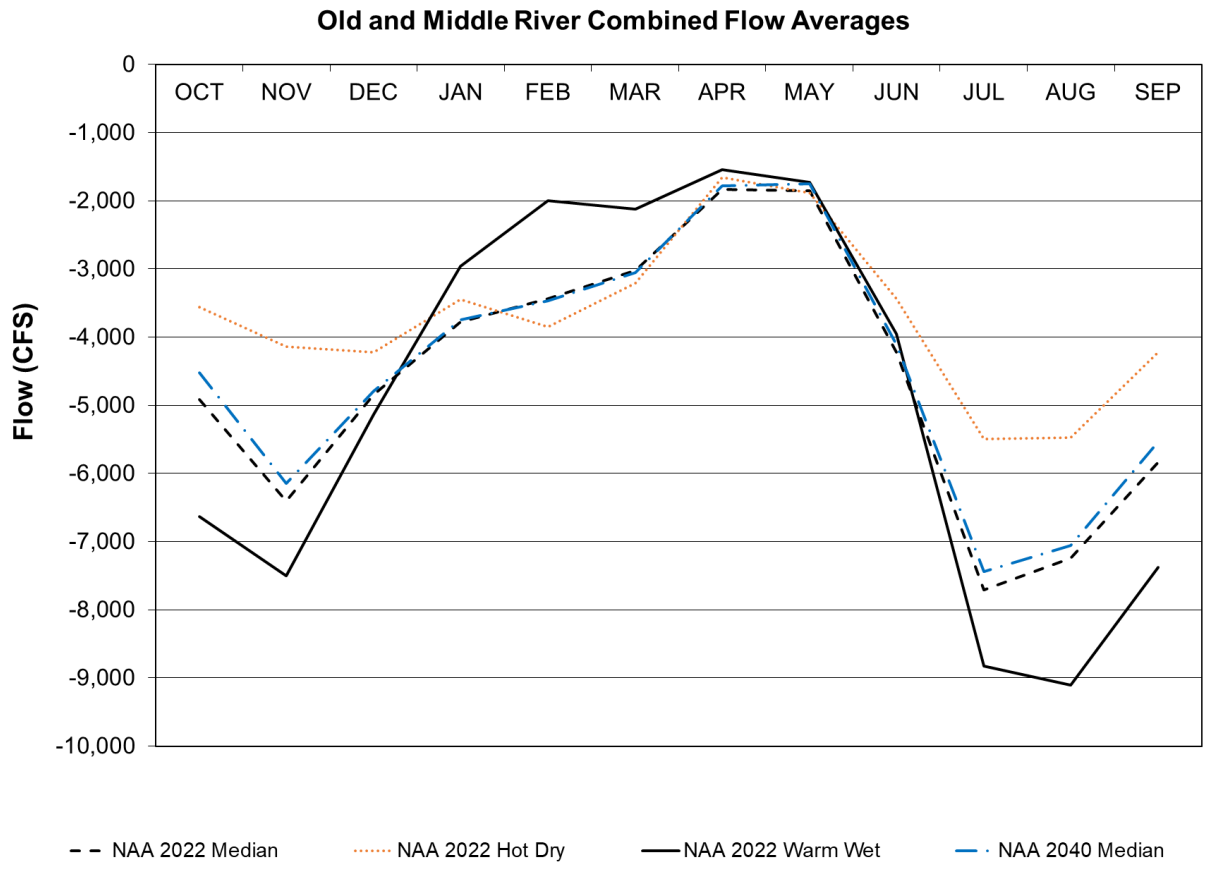

Figure F.2-1-20. Long-term Average Old and Middle River Combined Flow

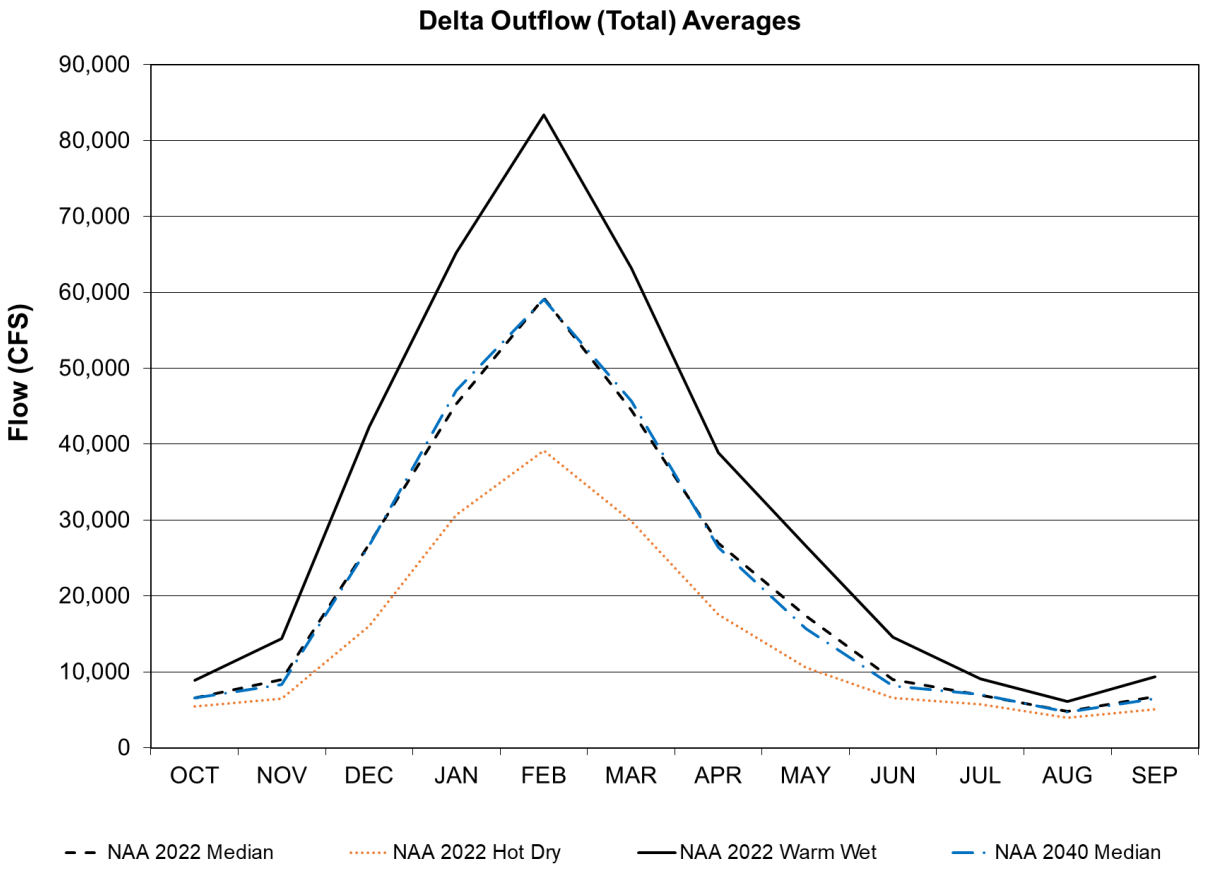

Figure F.2-1-21. Long-term Average Delta Outflo

F.2-1.1.1.2 HEC5Q

Sacramento River

Figure F.2-1-22 through Figure F.2-1-27 summarize temperature outcomes under the climate sensitivities for the NAA with the 2019 BiOp temperature logic. TDM was estimated using the standard LTO parameterization.

The NAA TDM estimate (Figure F.2-1-22) displays large climate variability. Under the 2022 Median climate scenario, TDM exceeds 60% in approximately 25% of the simulated years. The sharp shoulder in the TDM exceedance curve near the 25% exceedance is illustrative of the 2019 BiOp temperature targets not fully utilizing the available cold-water resource by misclassifying years into warmer target years than could have otherwise been achieved. The shoulder is preserved across all of the climate sensitivities as a fundamental characteristic of the 2019 BiOp temperature targets. However, under the 2022 Warm Wet condition that is cooler and wetter than the 2022 Median scenario, the shoulder is minimized with 60% TDM being exceeded less than approximately 5% of the time. Conversely, the 2022 Hot Dry Scenario that is warmer and drier than the 2022 Median scenario has large TDM values occur much more frequently with 60% TDM occurring in over 50% of the years. The 2040 Median scenario performs similarly to the 2022 Median scenario, albeit with an approximately 10% upward exceedance shift in the transition from high TDM to low TDM outcomes.

The NAA TDM values are driven by the Sacramento River temperatures from Clear Creek down to Red Bluff. Figure F.2-1-23 and Figure F.2-1-24 show the average and maximum May through end of October temperatures in the Sacramento River below Clear Creek with Figure F.2-1-25 and Figure F.2-1-26 providing the same information for Red Bluff. The scaling of TDM follows temperature outcomes with the 2022 Hot Dry scenario having the largest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest temperatures of the scenarios. While the scenarios have a clear incremental increase in average temperature, maximum temperatures above the 60% exceedance threshold are largely similar. An analogous trend is visible in Figure F.2-1-27 with the volume of water less than 52 °F at the end of April. More cold water correlates with lower TDMs across the climate scenarios. However, despite having generally similar cold-water volumes, the 2040 Median condition exhibits worse TDM outcomes than the 2022 Median, likely due to the roughly degree higher average temperatures under the 2040 Median scenario.

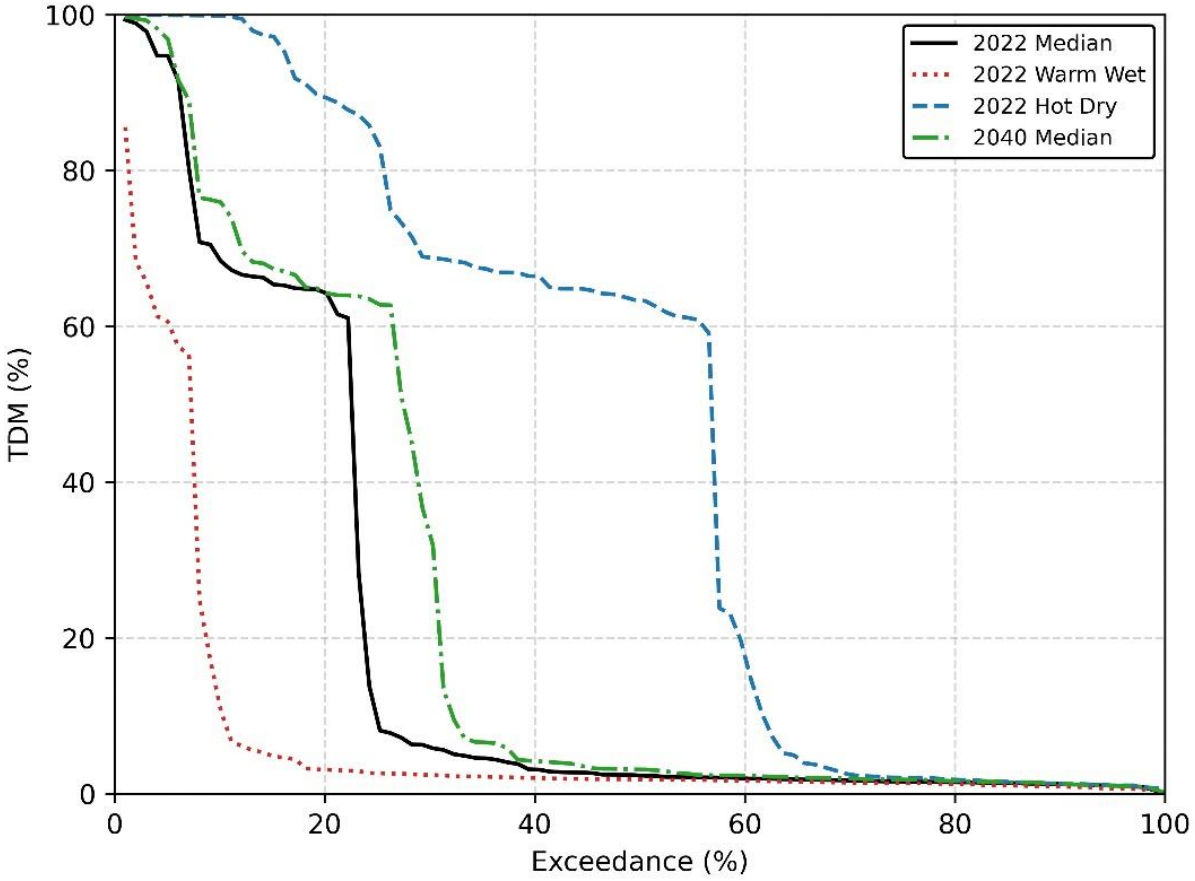

Figure F.2-1-22. Martin model TDM exceedance plot for the No Action alternative under various climate assumptions for water years 1922 through 2021

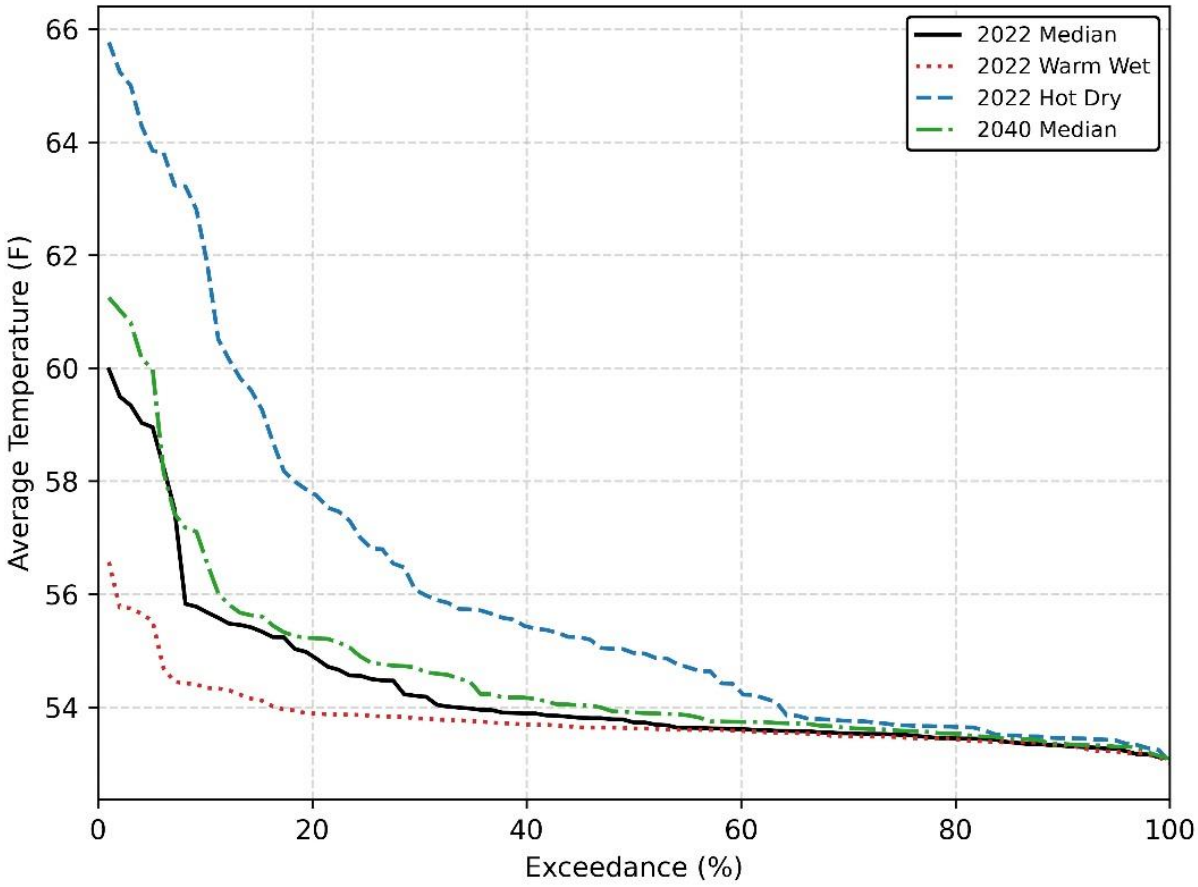

Figure F.2-1-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for the No Action alternative under various climate assumptions for water years 1923 through 2020

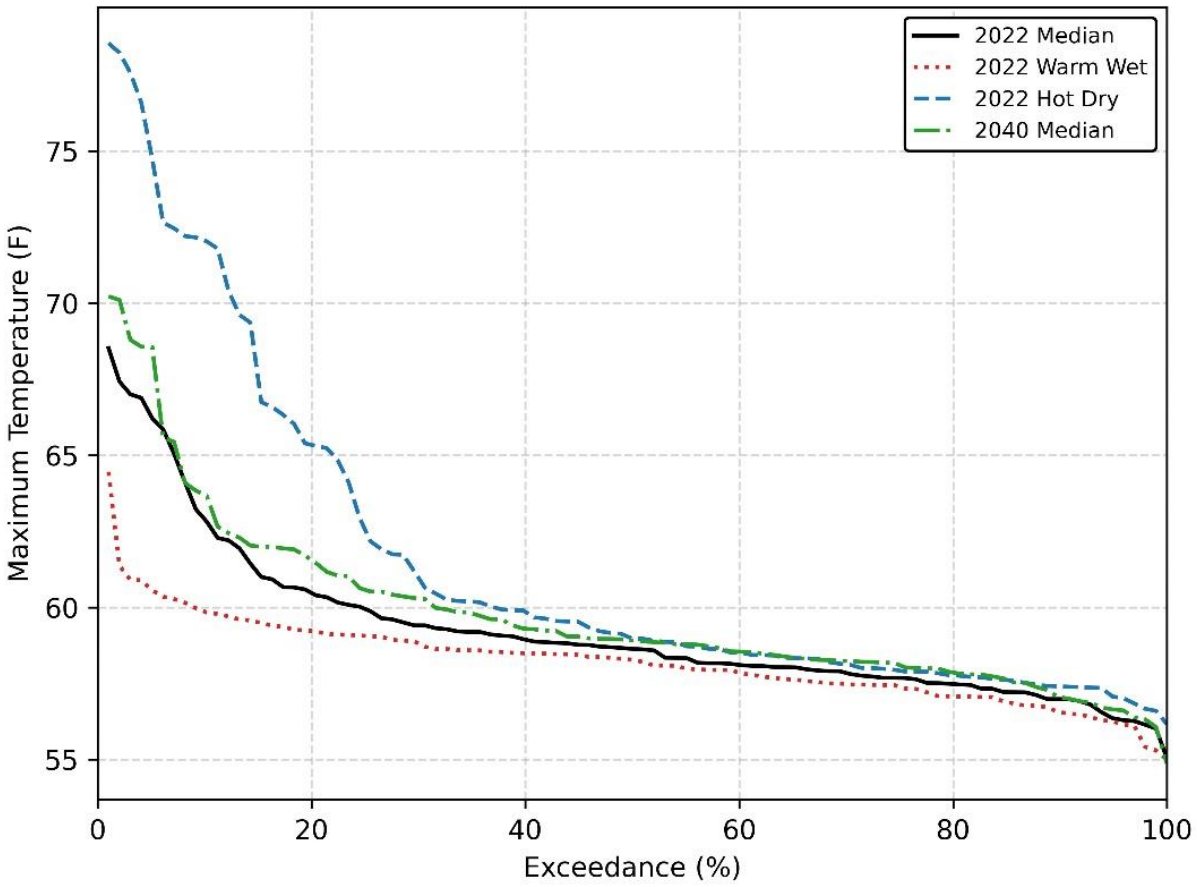

Figure F.2-1-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for the NAA under various climate assumptions for water years 1923 through 2020

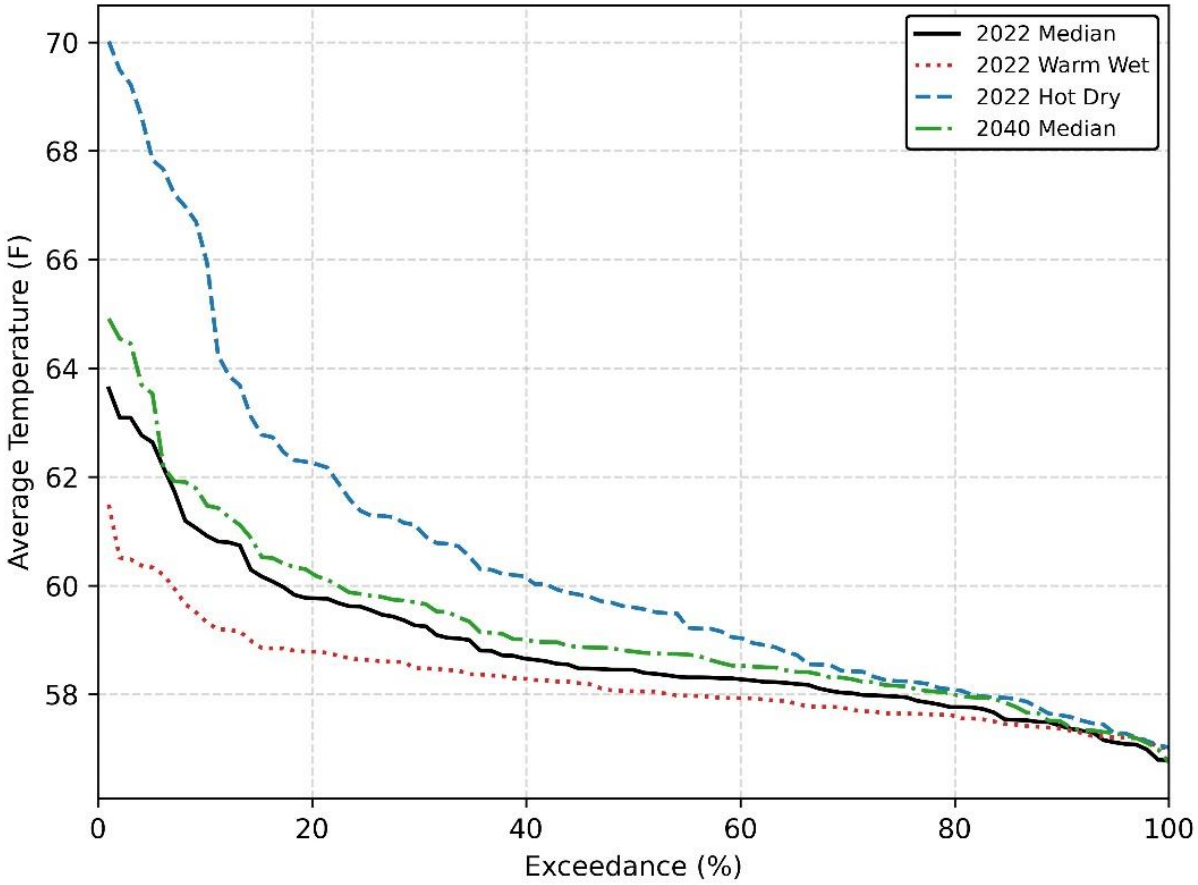

Figure F.2-1-25. Average water year temperatures on the Sacramento River at Red Bluff for the NAA under various climate assumptions from May through end of October for water years 1923 through 2020

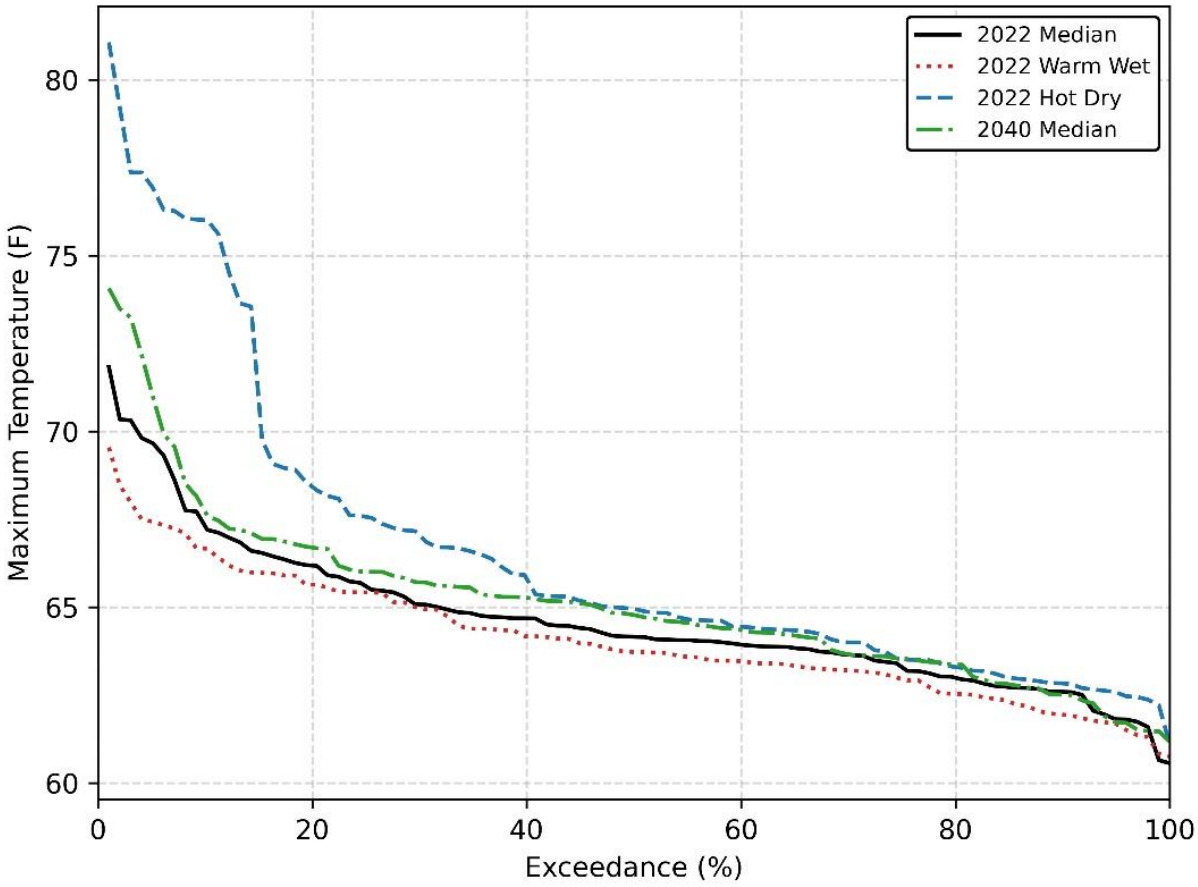

Figure F.2-1-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for the NAA under various climate assumptions for water years 1923 through 2020

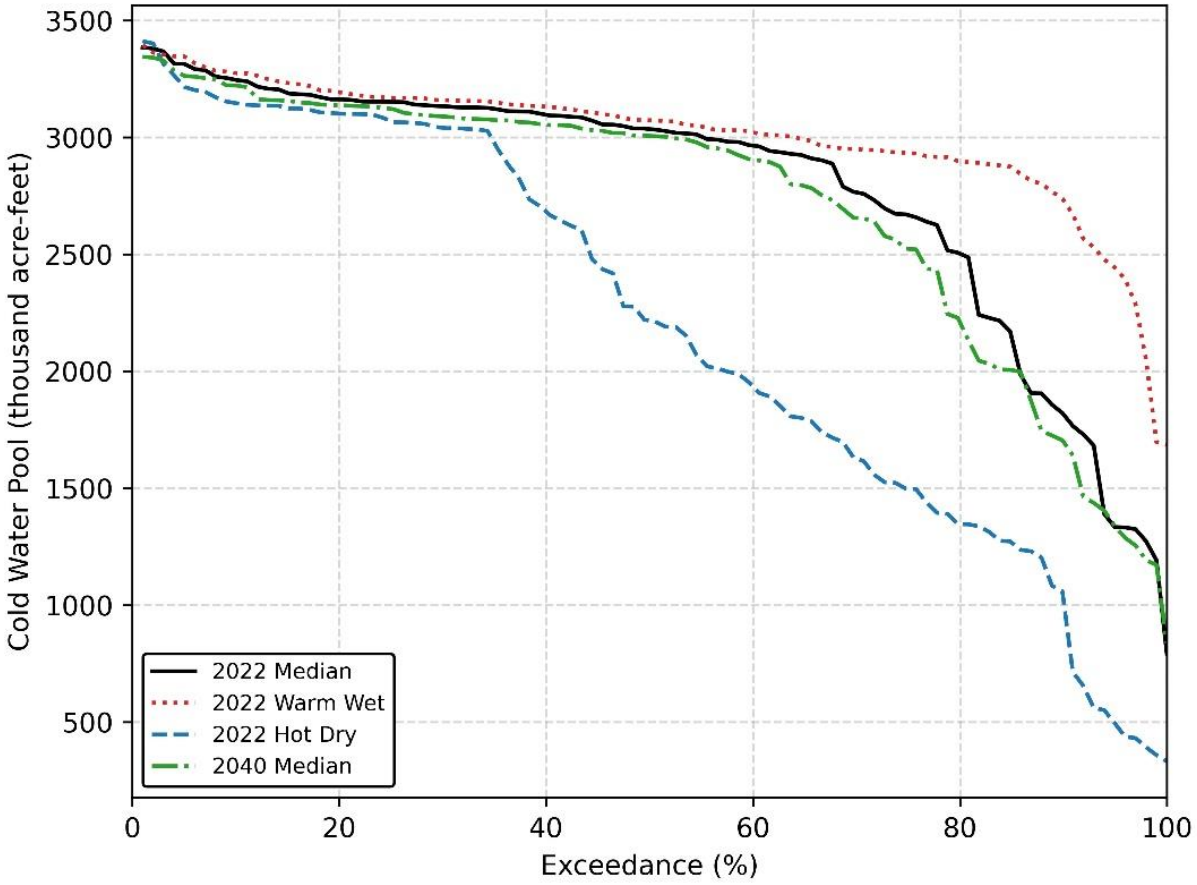

Figure F.2-1-27. Volume of water at the end of April less than 52 °F in Shasta Lake for the NAA under various climate assumptions for water years 1923 through 2021

American River

Figure F.2-1-22 through Figure F.2-1-27 focus on the American River basin. Average May through end of October temperatures (Figure F.2-1-22) at the Watt Avenue compliance location are higher in the 2022 Hot Dry and 2040 Median scenarios as compared to the 2022 Median condition. Interestingly, although the 2022 Hot Dry scenario is hotter than the 2040 Median at the highest temperatures, the differences in the scenarios are minimal at the coolest temperatures. The 2022 Warm Wet scenario, with generally more water available in the system and cooler temperatures, has lower May through end of October temperatures than the 2022 Median scenario. This scaling is maintained through the maximum May through end of October temperatures as well.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. The 2022 Warm Wet scenario has meaningfully larger end of April cold water pool (52 °F) as compared to the 2022 Median condition. Conversely, the 2022 Hot Dry scenario has meaningfully less cold water available than the 2022 Median. The availability of cold water is translated into temperature performance at Watt Avenue and compounded by the in-stream warming. The 2022 Median and 2040 Median scenarios have similar end of April cold-water pool resources; however, the 2040 Median condition performs about a degree warmer than the 2022 Median. This difference is due in part to the greater in-stream warming as well as greater warming in the reservoir proper to reduce the cold water available in the temperature management season that is present under the 2040 Median scenario.

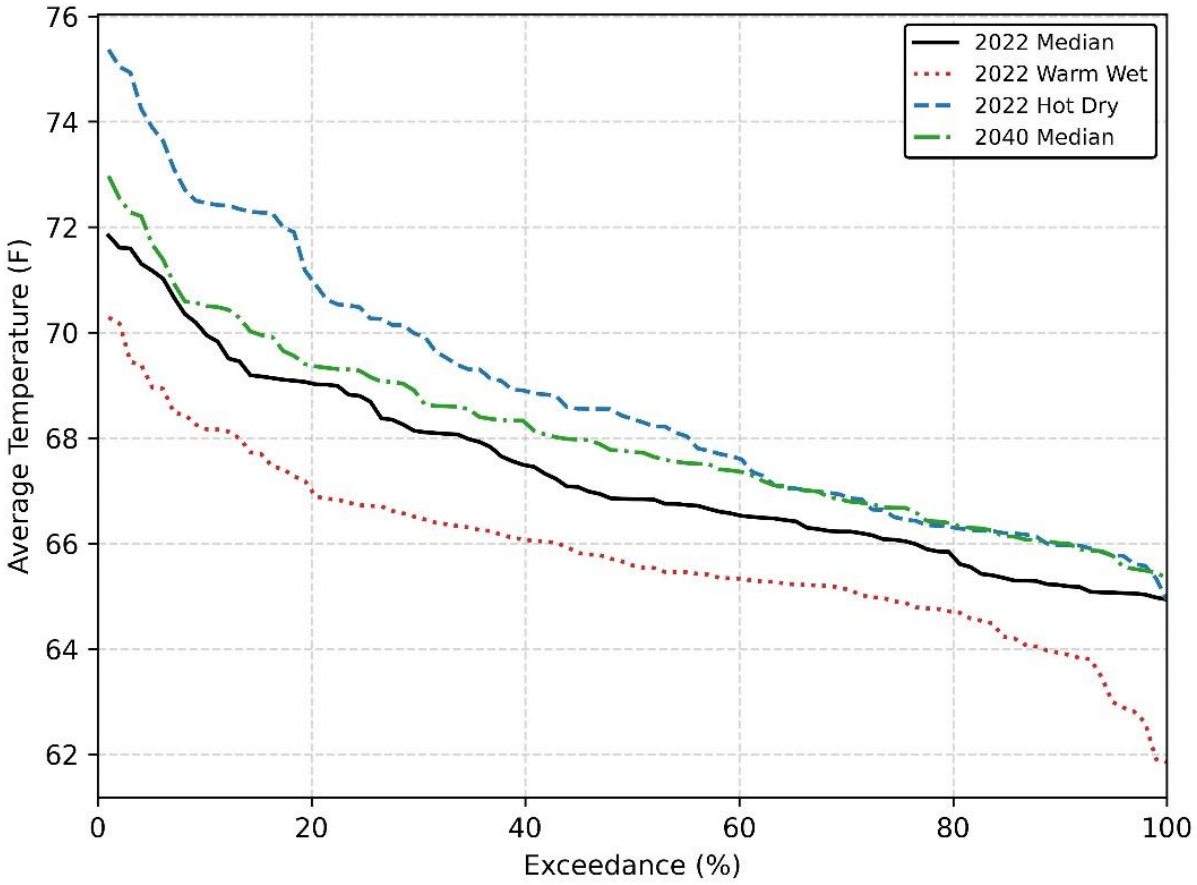

Figure F.2-1-28. Average May through end of October temperatures on the American River at Watt Avenue for the NAA under various climate assumptions for water years 1923 through 2020

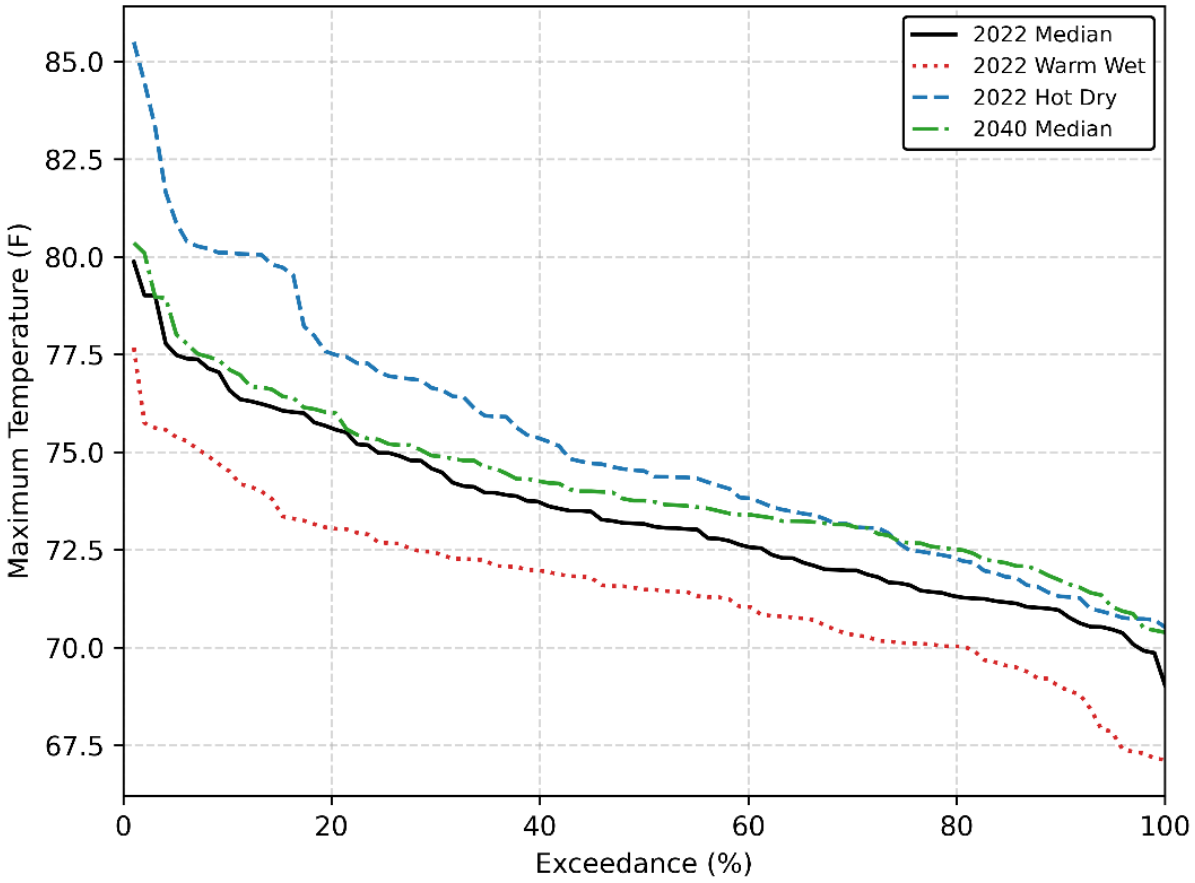

Figure F.2-1-29. Maximum May through end of October temperatures on the American River at Watt Avenue for the NAA under various climate assumptions for water years 1923 through 2020

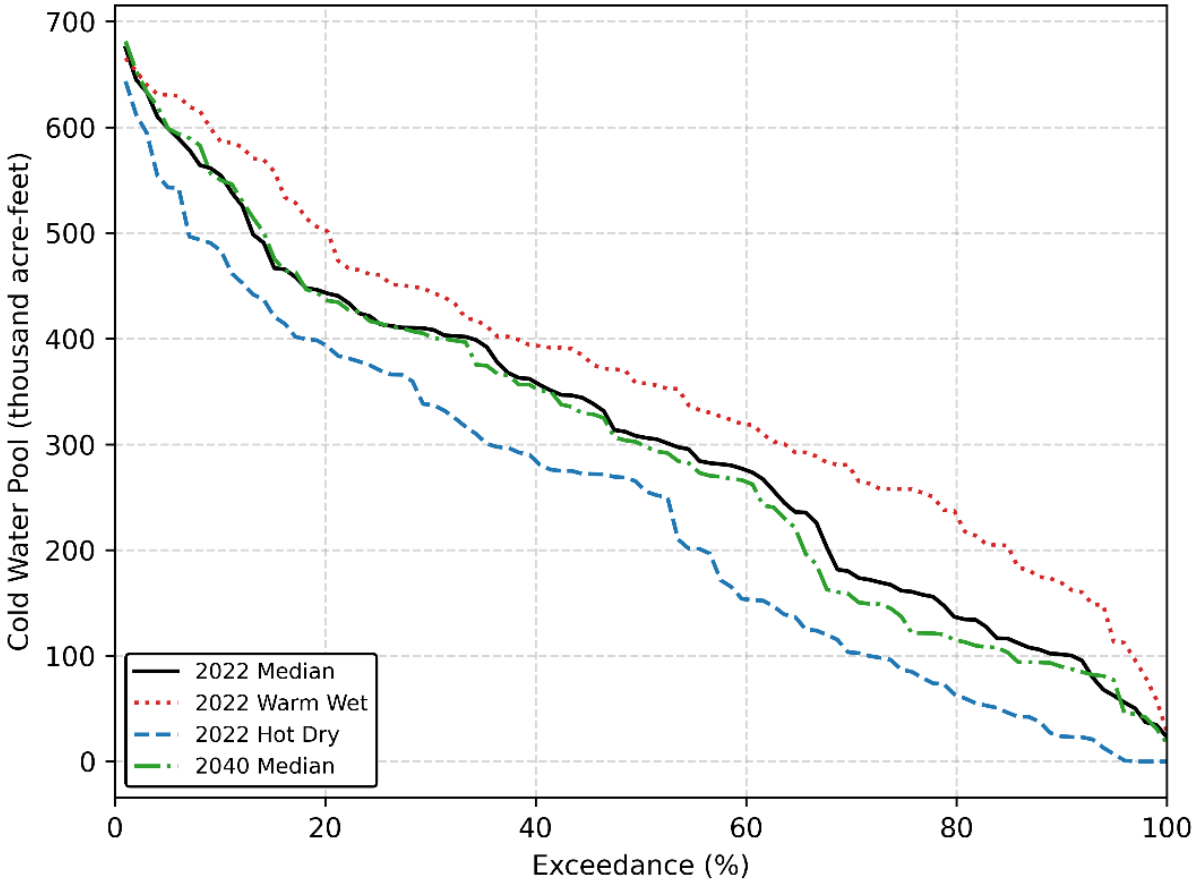

Figure F.2-1-30. Volume of water at the end of April less than 52 °F in Folsom Lake for the NAA under various climate assumptions for water years 1923 through 2021

Stanislaus River

Figure F.2-1-31 and Figure F.2-1-32 summarize the temperature outcomes under the climate sensitivities for the NAA in the Stanislaus basin. Average May through end of October temperatures at the Orange Blossom Bridge compliance location is hotter for the 2022 Hot Dry and 2040 Median scenarios when compared to the 2022 Median scenario. The 2022 Hot Dry scenario is hotter than the 2040 Median scenarios for all exceedances and the difference in temperatures between the two grows as the temperatures increase. The 2022 Warm Wet scenario average May through end of October temperatures at the Orange Blossom Bridge compliance location is cooler than the 2022 Median scenario due to generally more water available in the system and cooler temperatures. At high temperatures, the maximum May through October temperatures at the Orange Blossom Bridge compliance location follow a similar trend as the average May through October temperatures. At low temperatures, the 2022 Median, 2022 Hot Dry, and 2040 Median scenarios have similar maximum temperatures. The 2022 Warm Wet scenario has lower maximum temperatures at low temperatures when compared to the other scenarios.

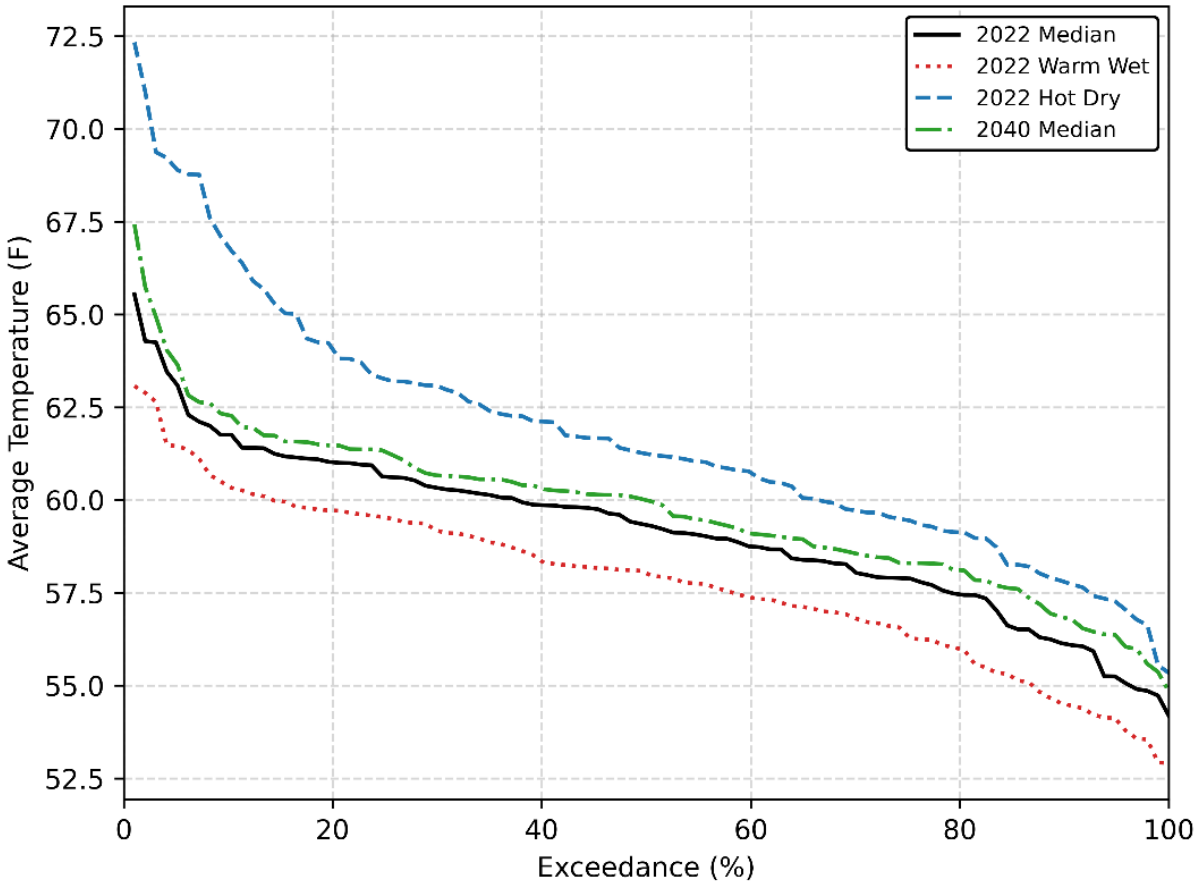

Figure F.2-1-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom Bridge for the NAA under various climate assumptions for water years 1923 through 2019

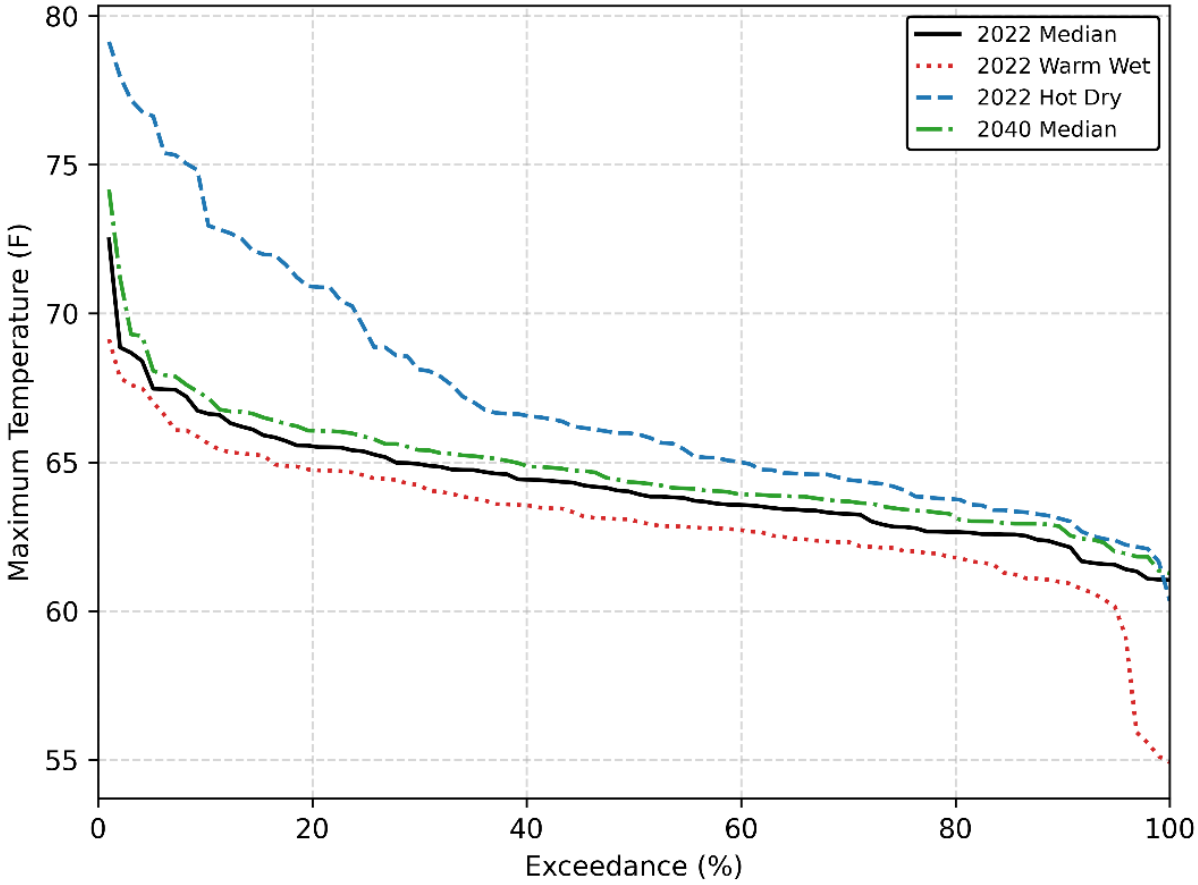

Figure F.2-1-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom Bridge for the NAA under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Appendix F.2-2 Climate Sensitivity Analysis, Alternative 1

F.2-2.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative 1 under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-2.2 Climate Change Comparison

F.2-2.2.1 CalSim 3

Figure F.2-2-1 through Figure F.2-2-21 show CalSim 3 simulation results for Alternative 1. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 1 were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough
- Sacramento River at Verona
- Sacramento River at Freeport
- Flow though Yolo Bypass

- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-2-1) and end of September (Figure F.2-2-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 22% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows (Figure F.2-2-3 through Figure F.2-2-8), long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of the reservoir management season, the differences are less notable. In the summer months, river flows are due primarily to releases from storage instead of runoff events. Flows under the 2040 Median climate scenario are similar to flows under 2022 Median climate scenario.

Clear Creek below Whiskeytown (Figure F.2-2-9) shows flow differences along the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall and winter months, though all scenarios are similar in spring as well as summer months. For Spring Creek inflow to Keswick Reservoir (Figure F.2-2-10), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-2-11) and end of September (Figure F.2-2-12) Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-2-13), changes to flow are similar to the changes in

the Sacramento watershed. In all months, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May and June due to lower Folsom inflows in spring months. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. As compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in 2040 Median conditions for the month of January due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-2-14), flow differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. Flows across all climate conditions are similar in June and July, months when releases consist of stored water.

For long-term monthly average San Joaquin River flows, differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. San Joaquin River at Gravelly Ford (Figure F.2-2-15) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam (Figure F.2-2-16) are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced (Figure F.2-2-17).

For long-term monthly average flows in the Delta (Figure F.2-2-18 through Figure F.2-2-21), flow differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. Flows across all climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure F.2-2-20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

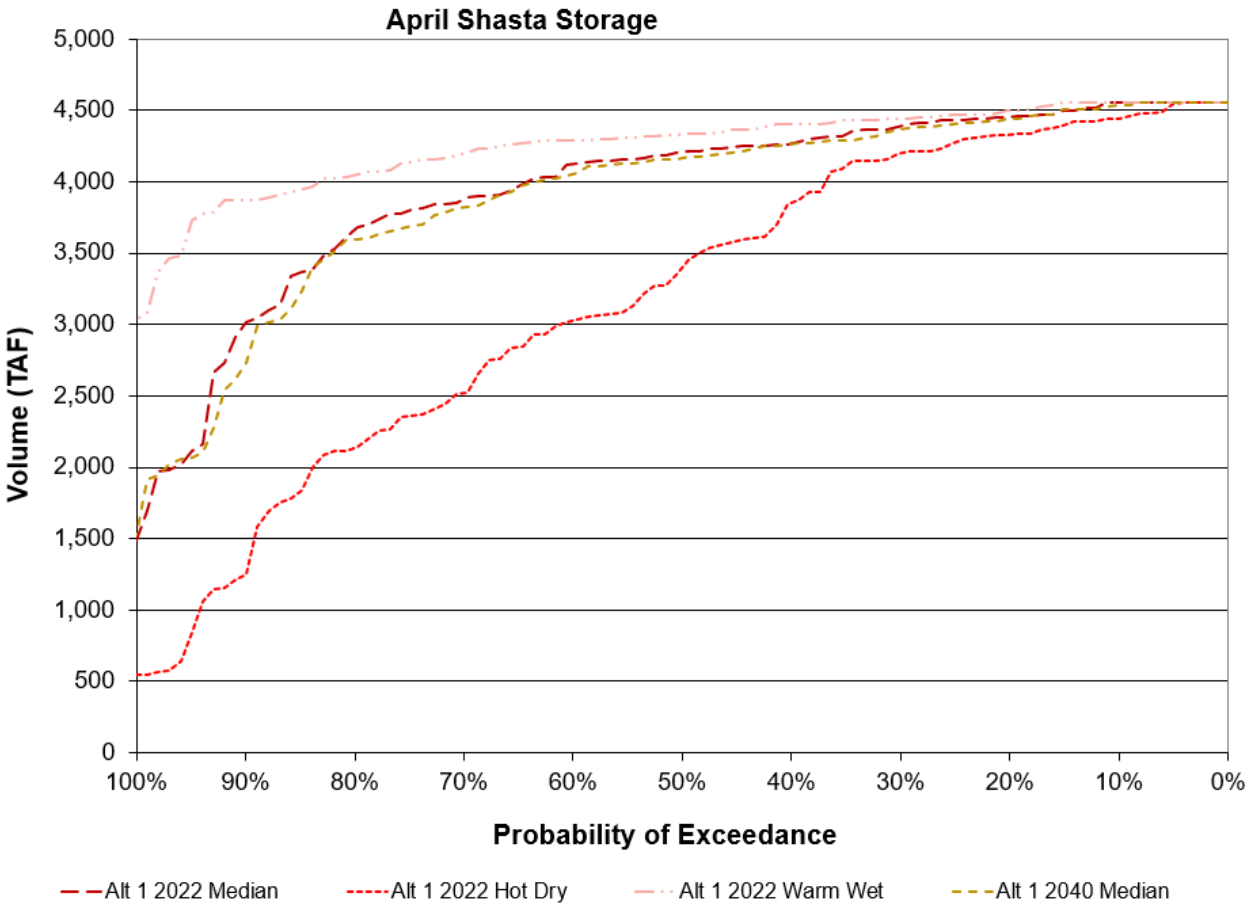

Figure F.2-2-1. End of April Shasta Storage

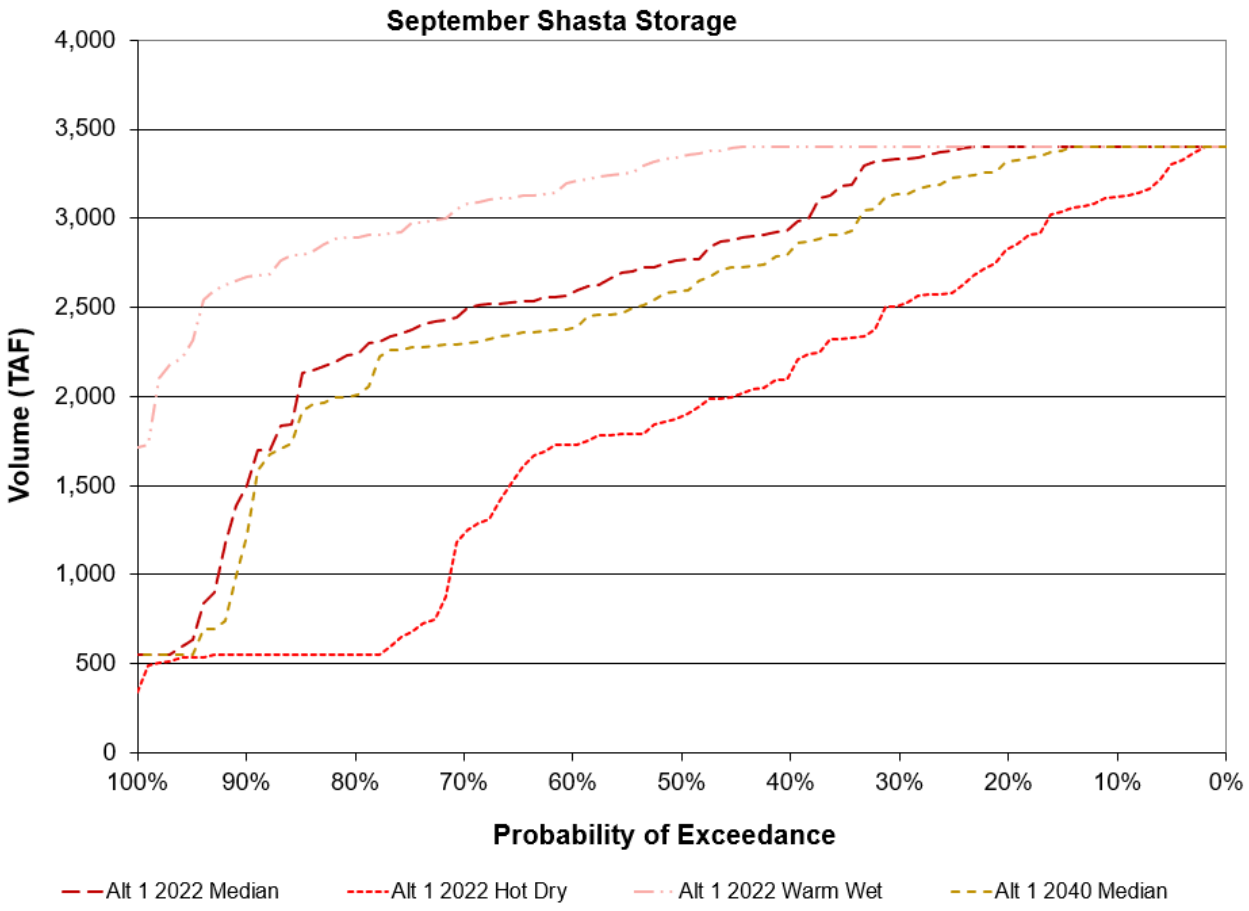

Figure F.2-2-2. End of September Shasta Storage

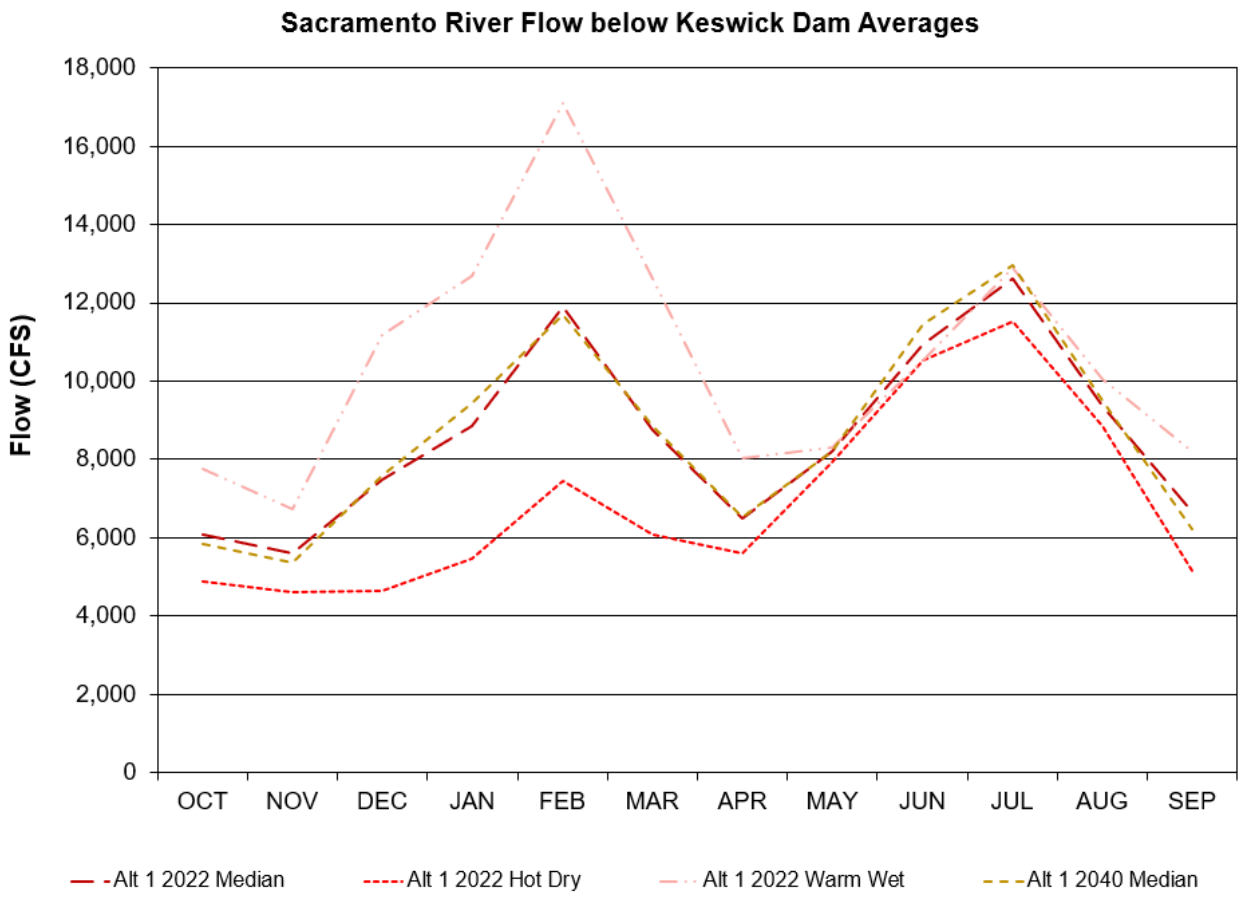

Figure F.2-2-3. Long-term Average Sacramento River flow below Keswick Dam

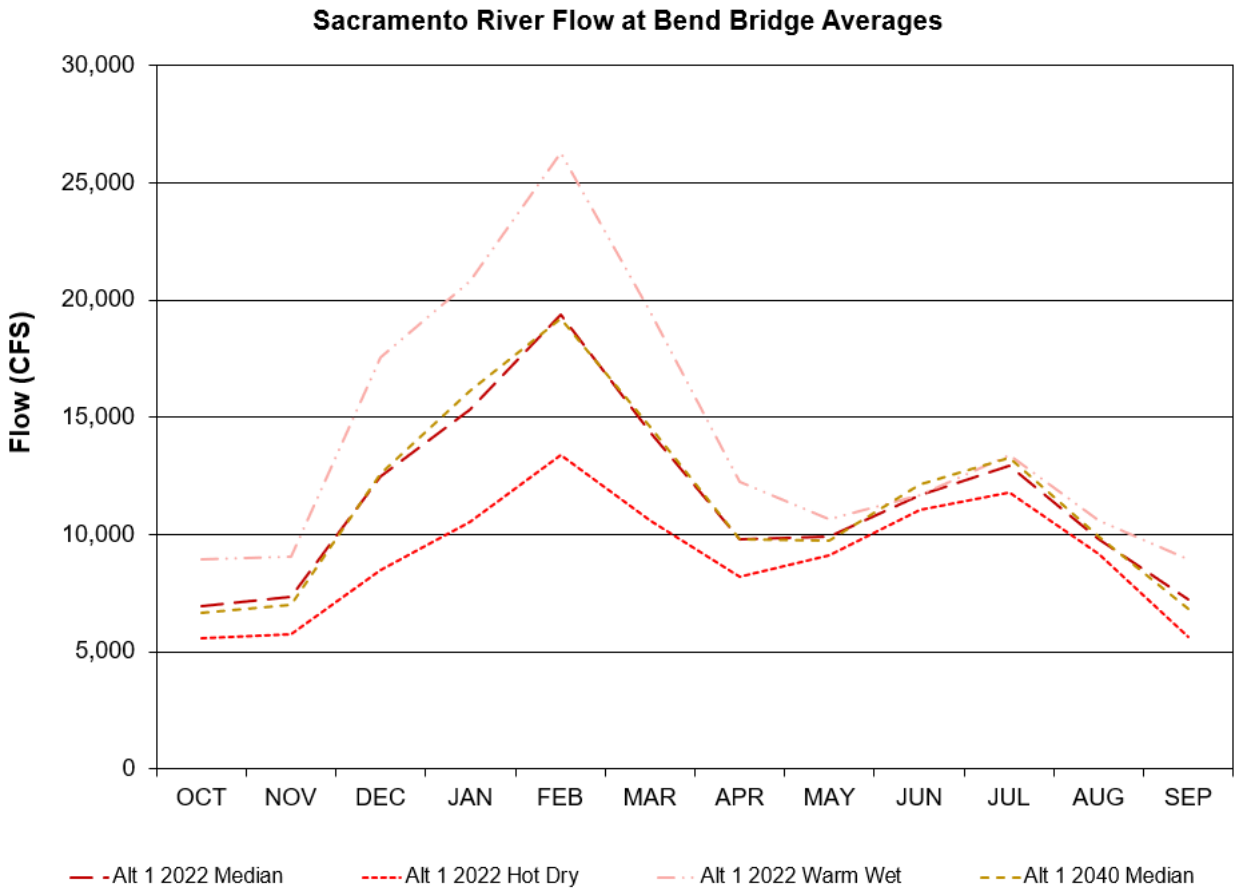

Figure F.2-2-4. Long-term Average Sacramento River flow at Bend Bridge

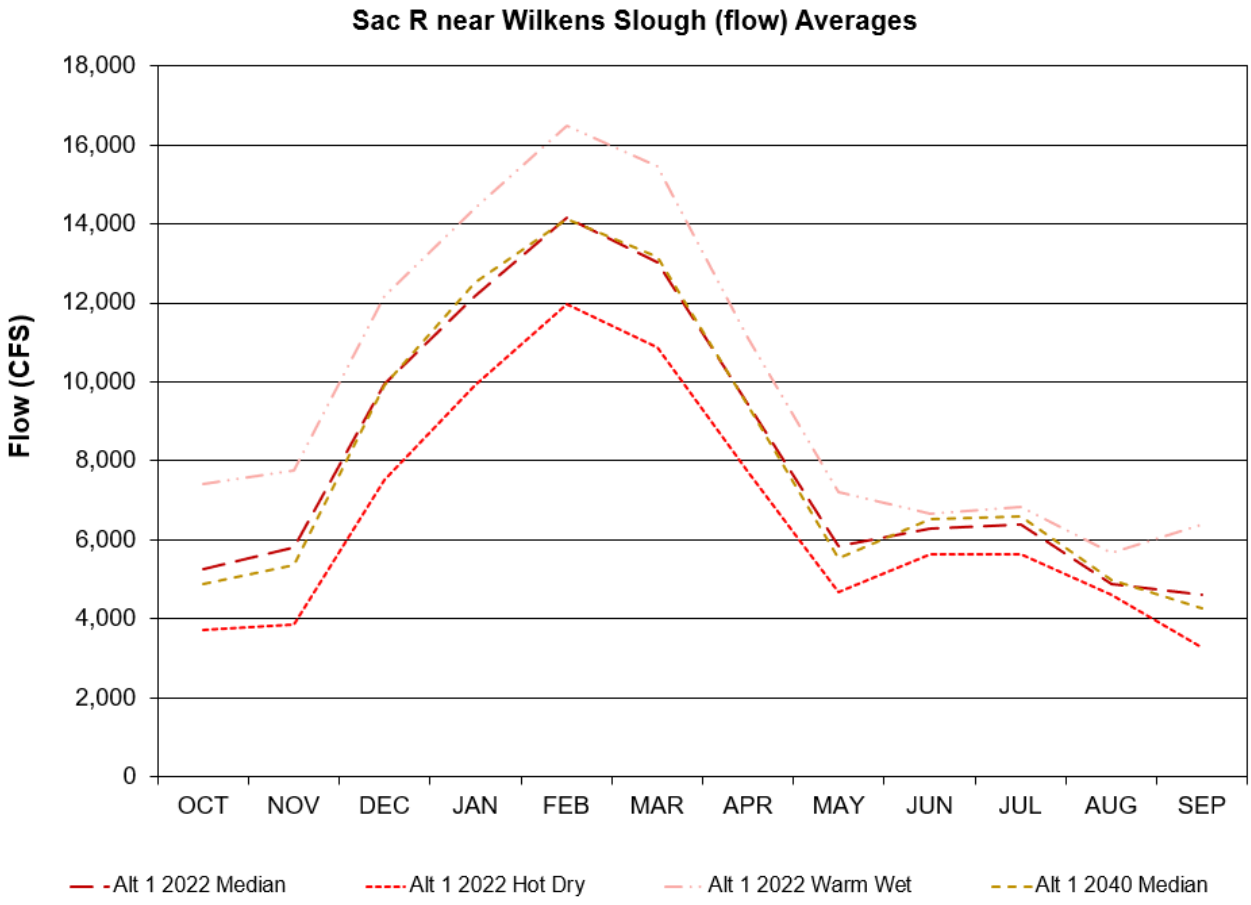

Figure F.2-2-5. Long-term Average Sacramento River flow near Wilkins Slough

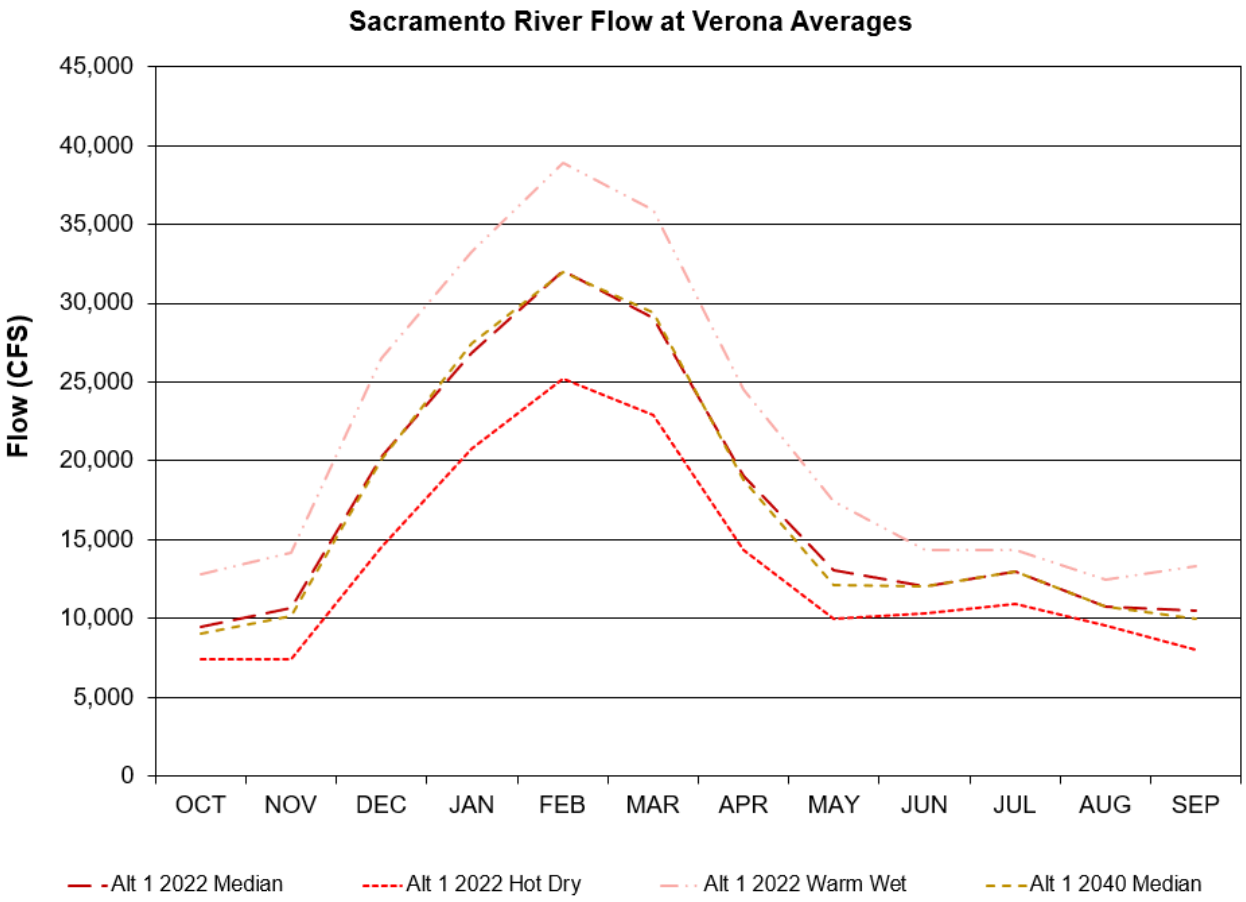

Figure F.2-2-6. Long-term Average Sacramento River flow at Verona

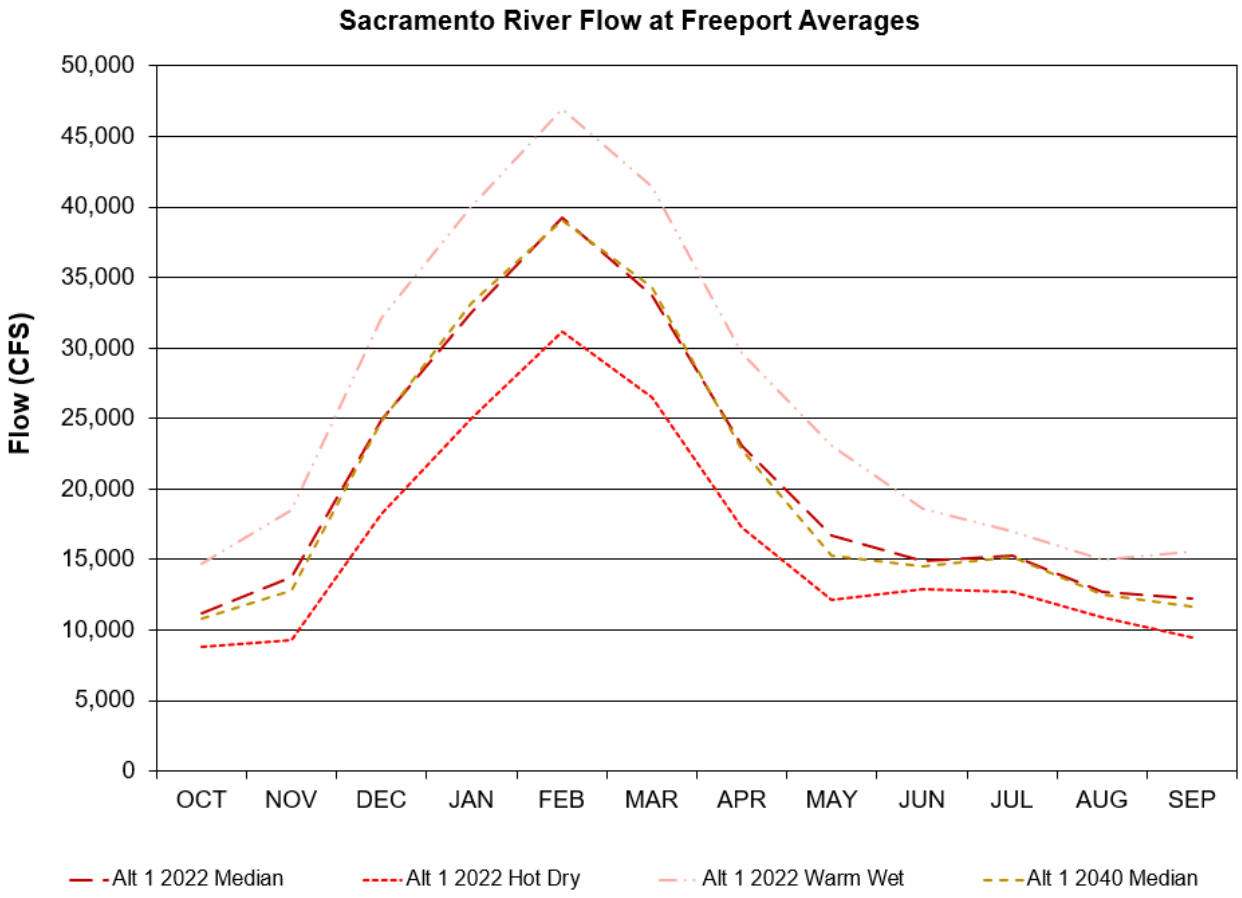

Figure F.2-2-7. Long-term Average Sacramento River flow at Freeport

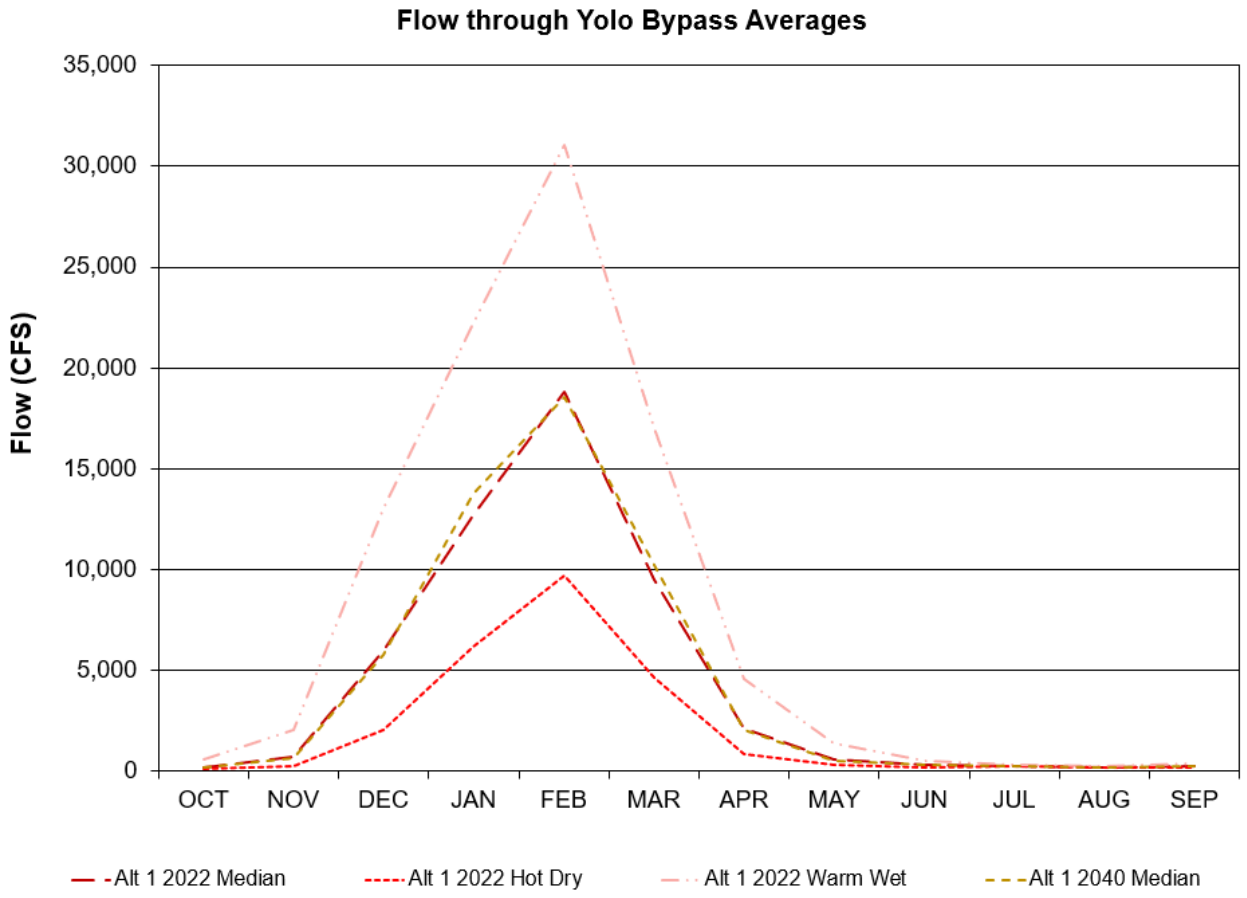

Figure F.2-2-8. Long-term Average Yolo Bypass Flow

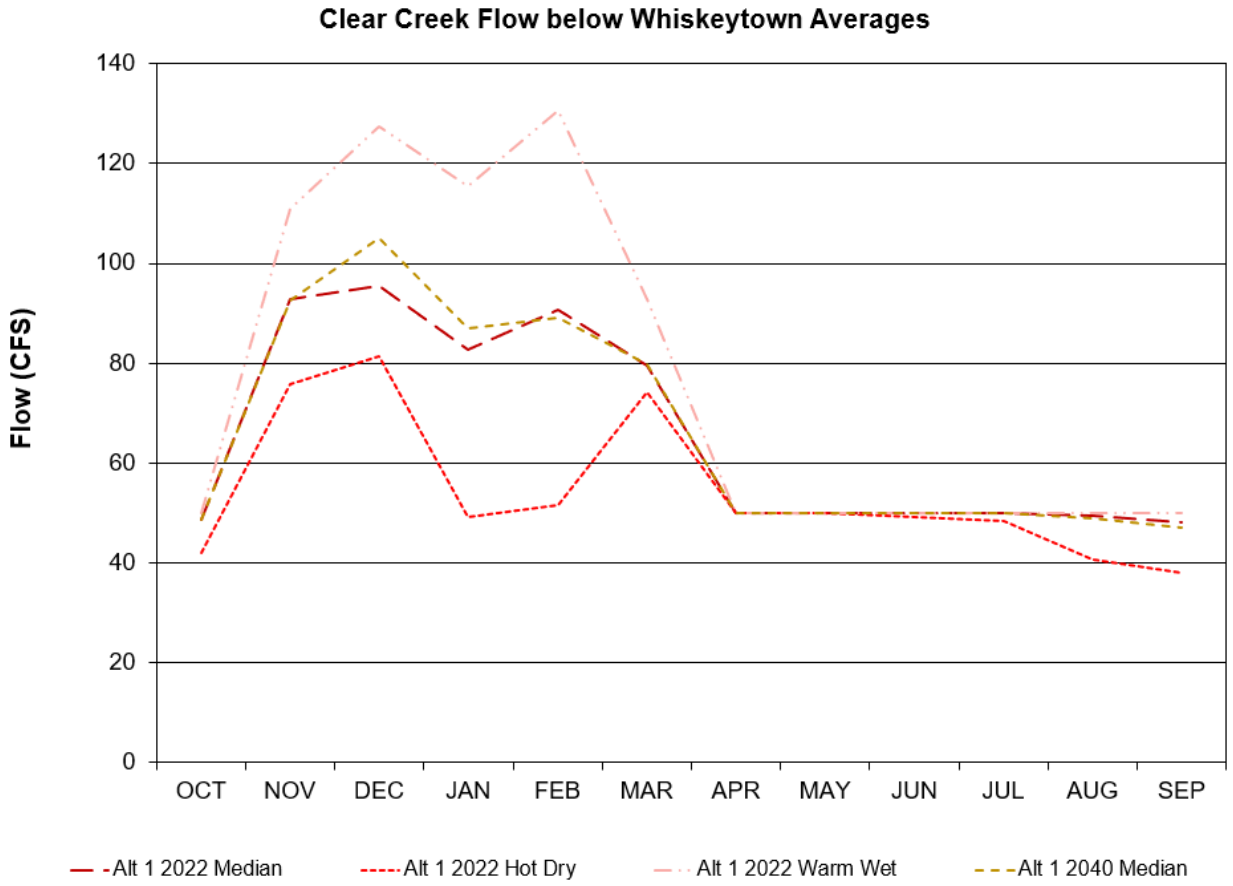

Figure F.2-2-9. Long-term Average Clear Creek flow below Whiskeytown

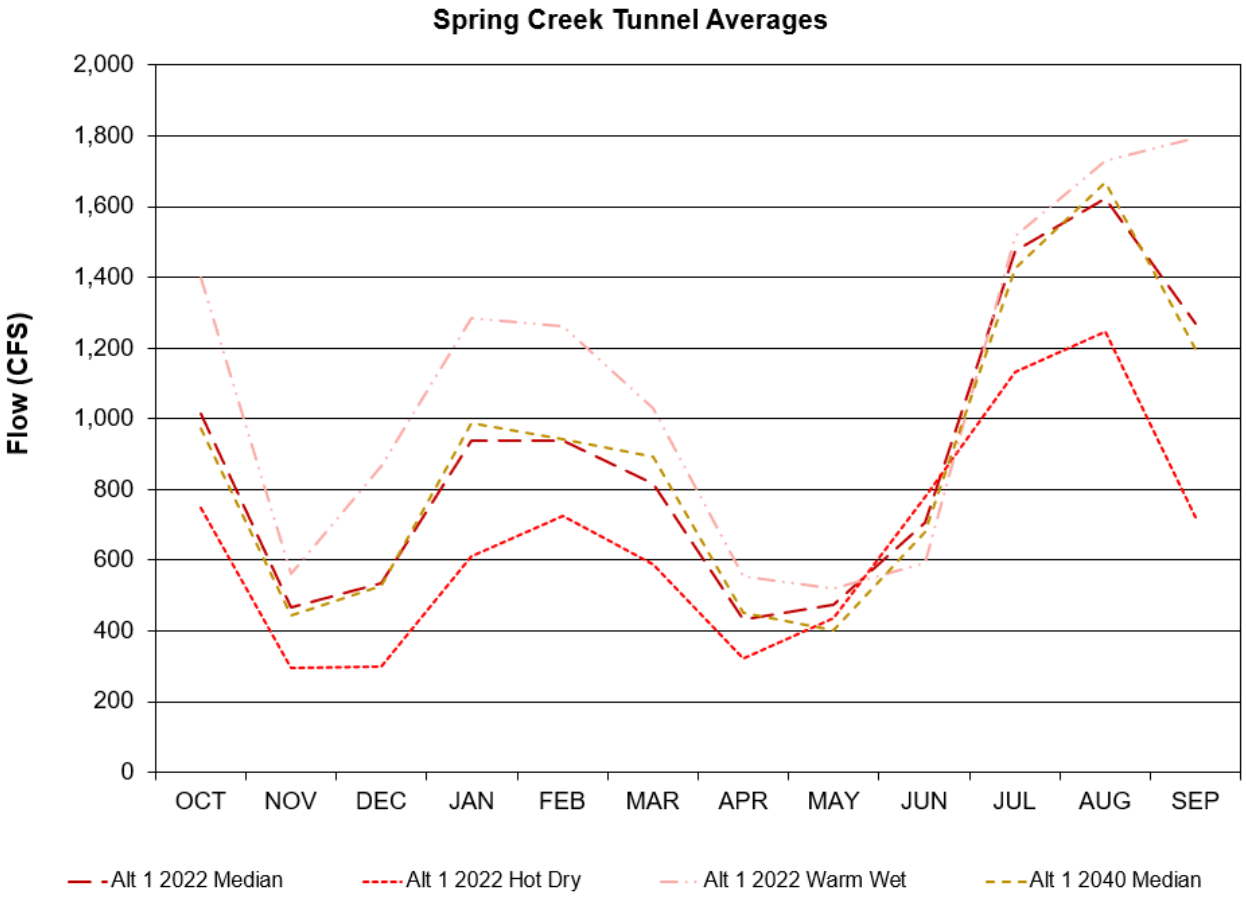

Figure F.2-2-10. Long-term Average Spring Creek Tunnel Flow

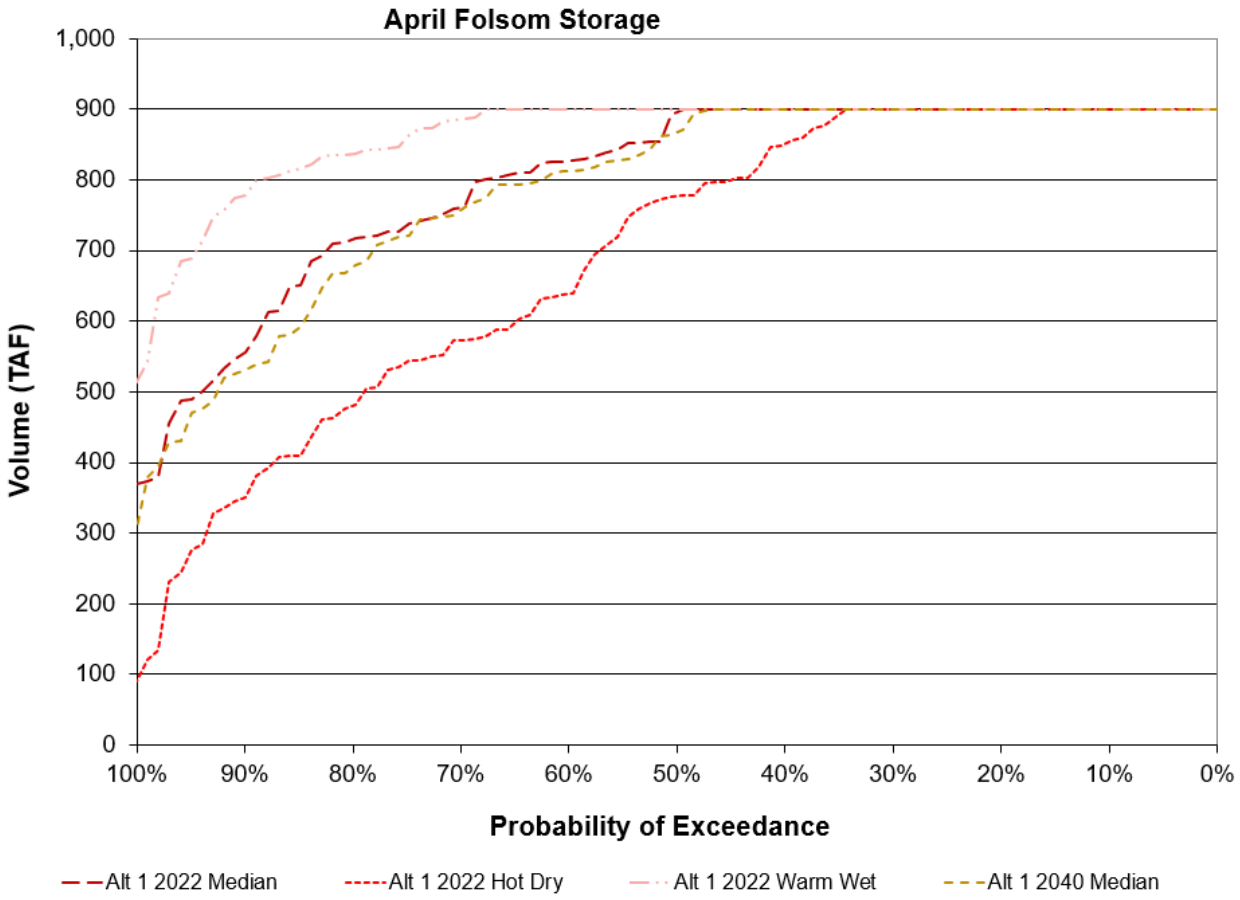

Figure F.2-2-11. End of April Folsom Storage

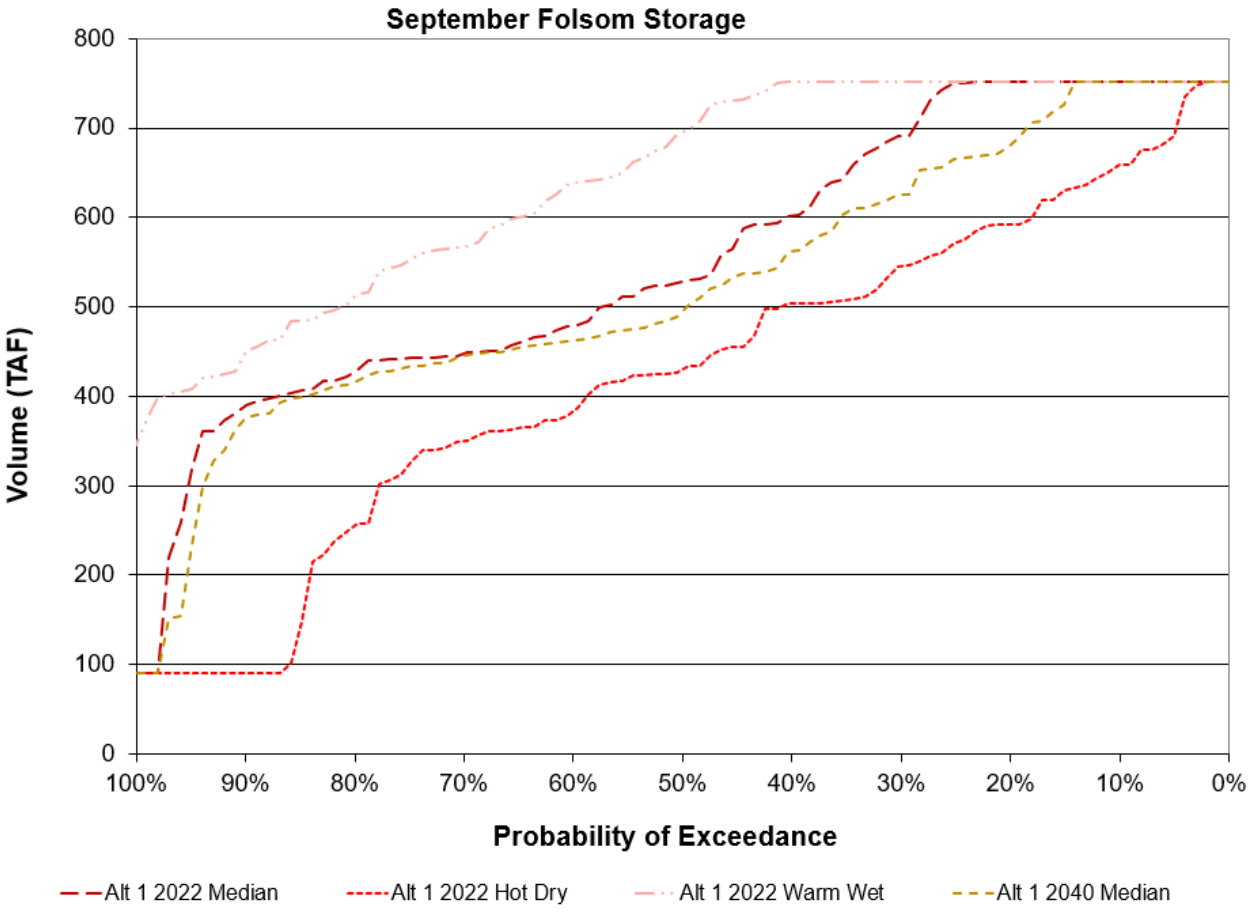

Figure F.2-2-12. End of September Folsom Storage

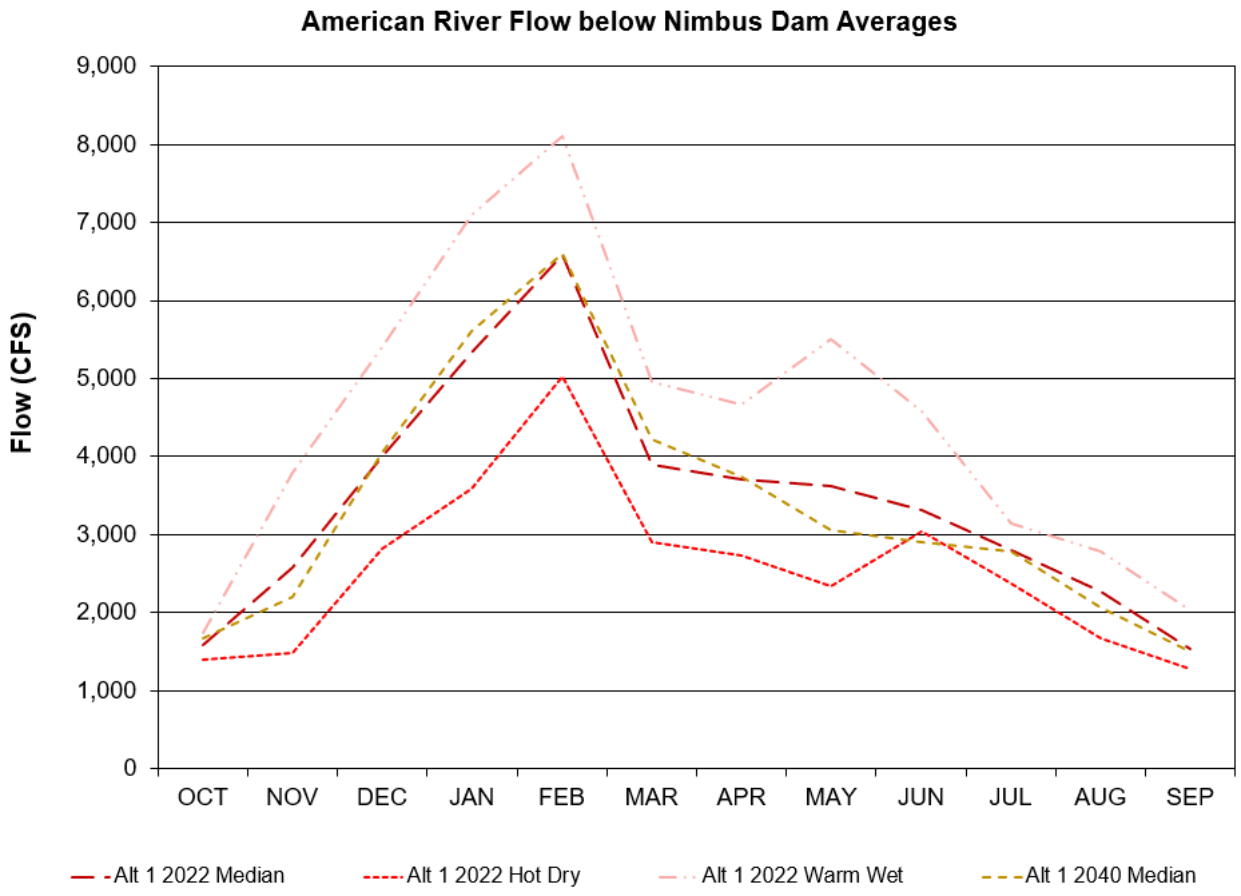

Figure F.2-2-13. Long-term Average American River flow below Nimbus Dam

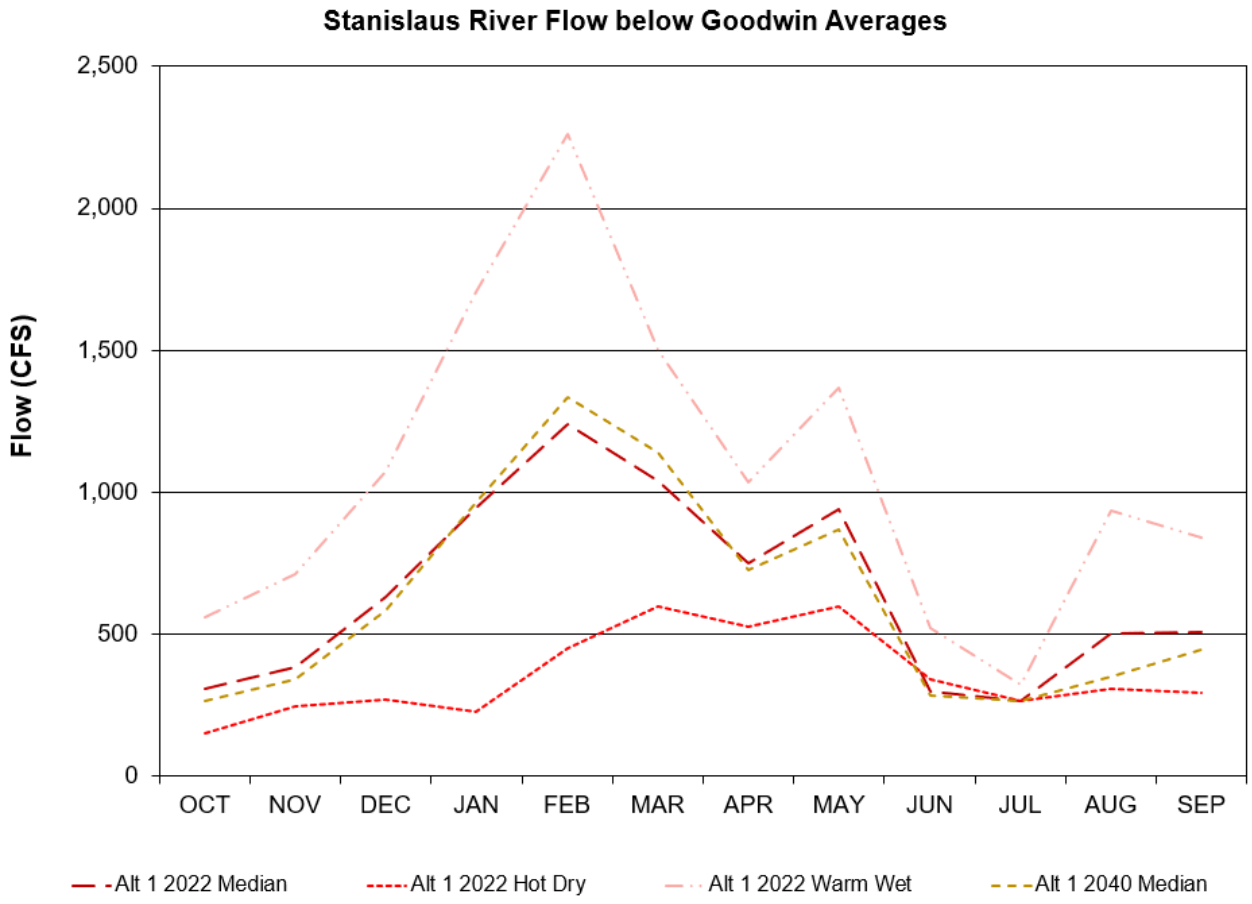

Figure F.2-2-14. Long-term Average Stanislaus River flow below Goodwin

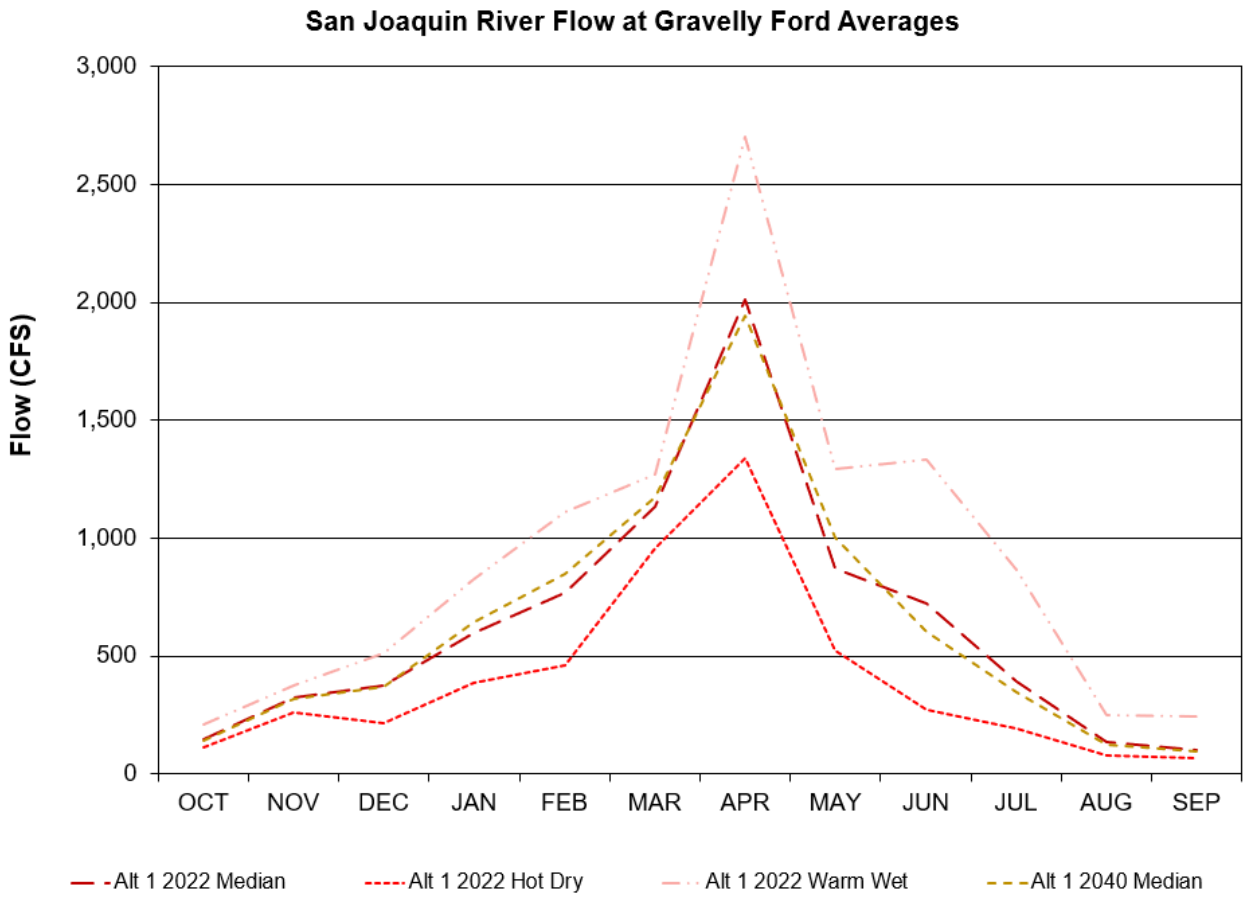

Figure F.2-2-15. Long-term Average San Joaquin River flow at Gravelly Ford

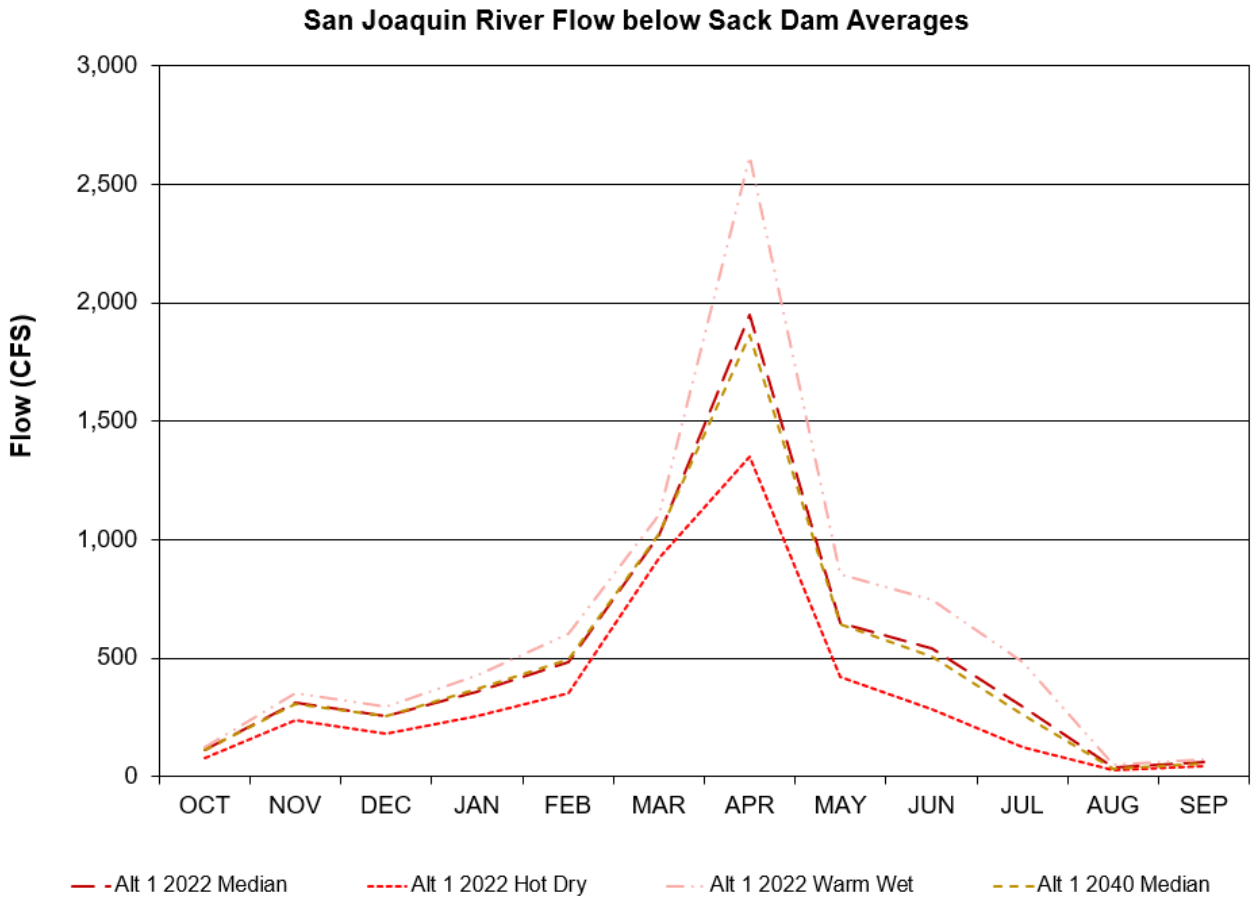

Figure F.2-2-16. Long-term Average San Joaquin River flow below Sack Dam

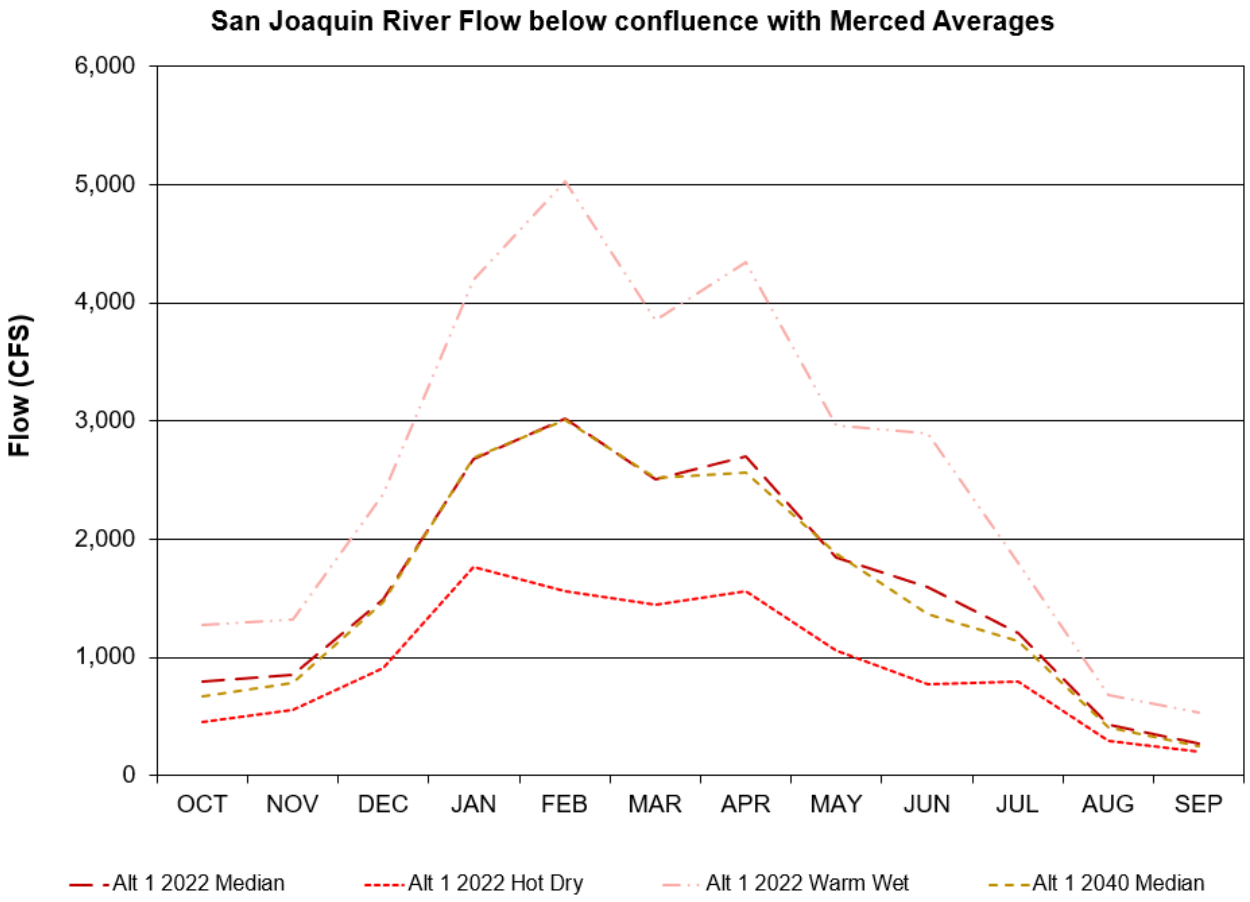

Figure F.2-2-17. Long-term Average San Joaquin River flow below Confluence with Merced River

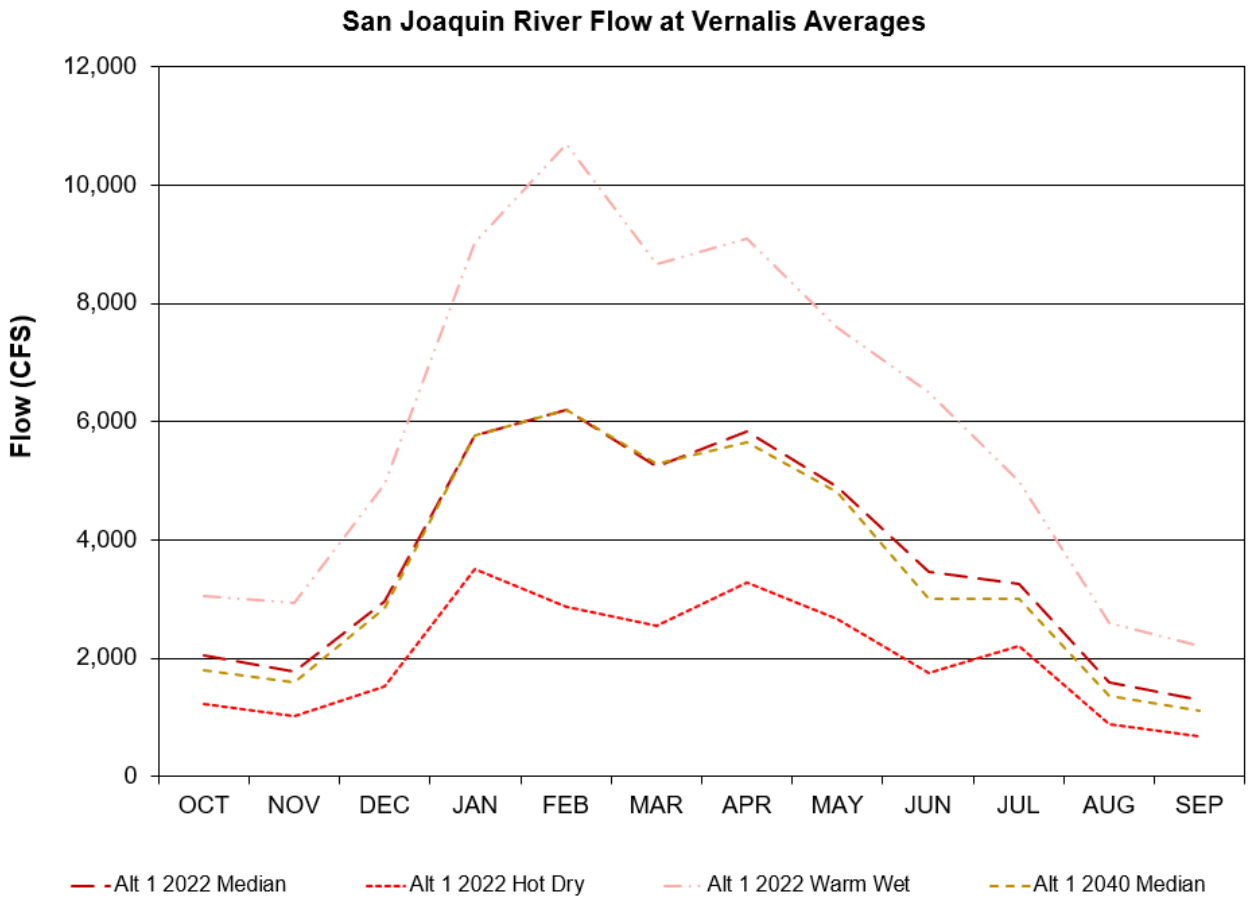

Figure F.2-2-18. Long-term Average San Joaquin River flow at Vernalis

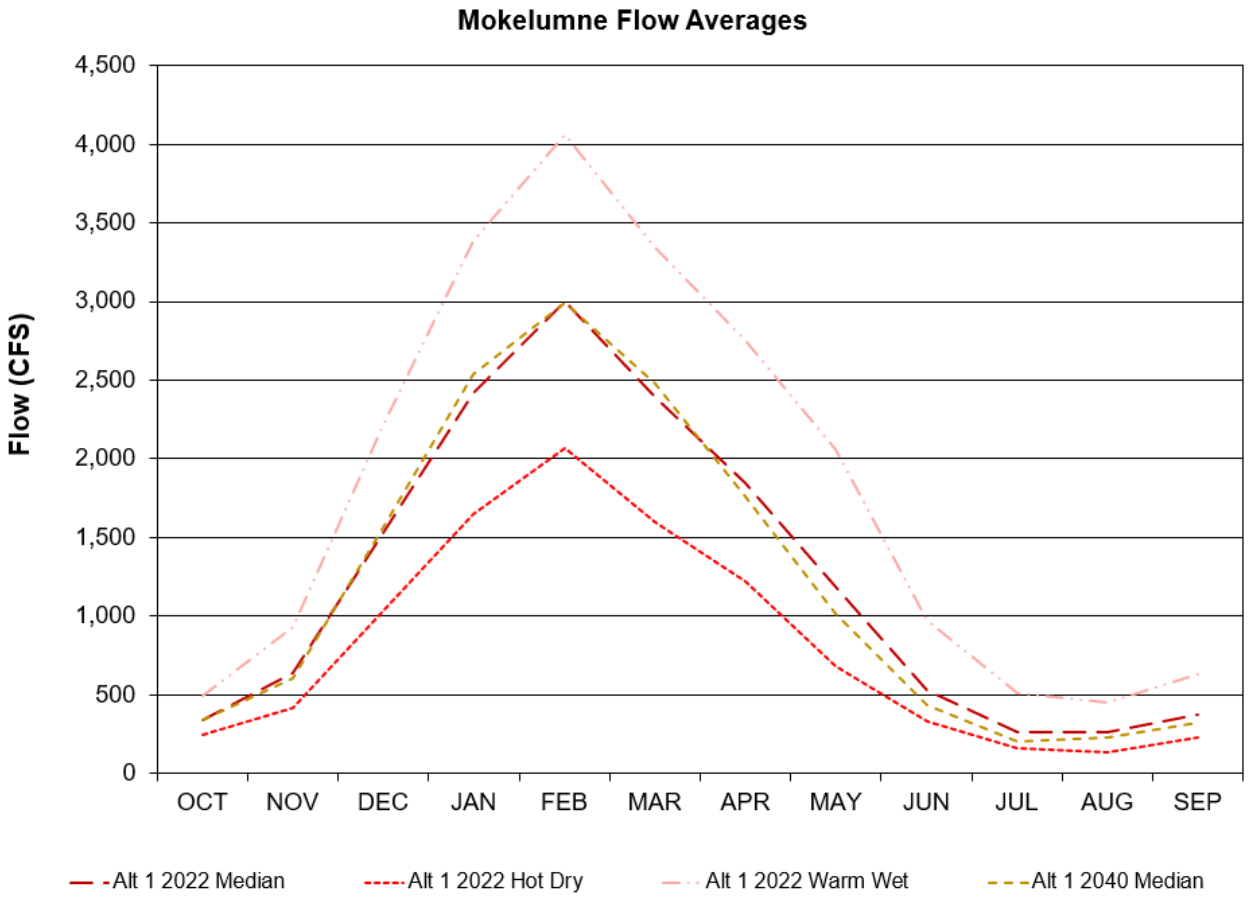

Figure F.2-2-19. Long-term Average Mokelumne River Flow

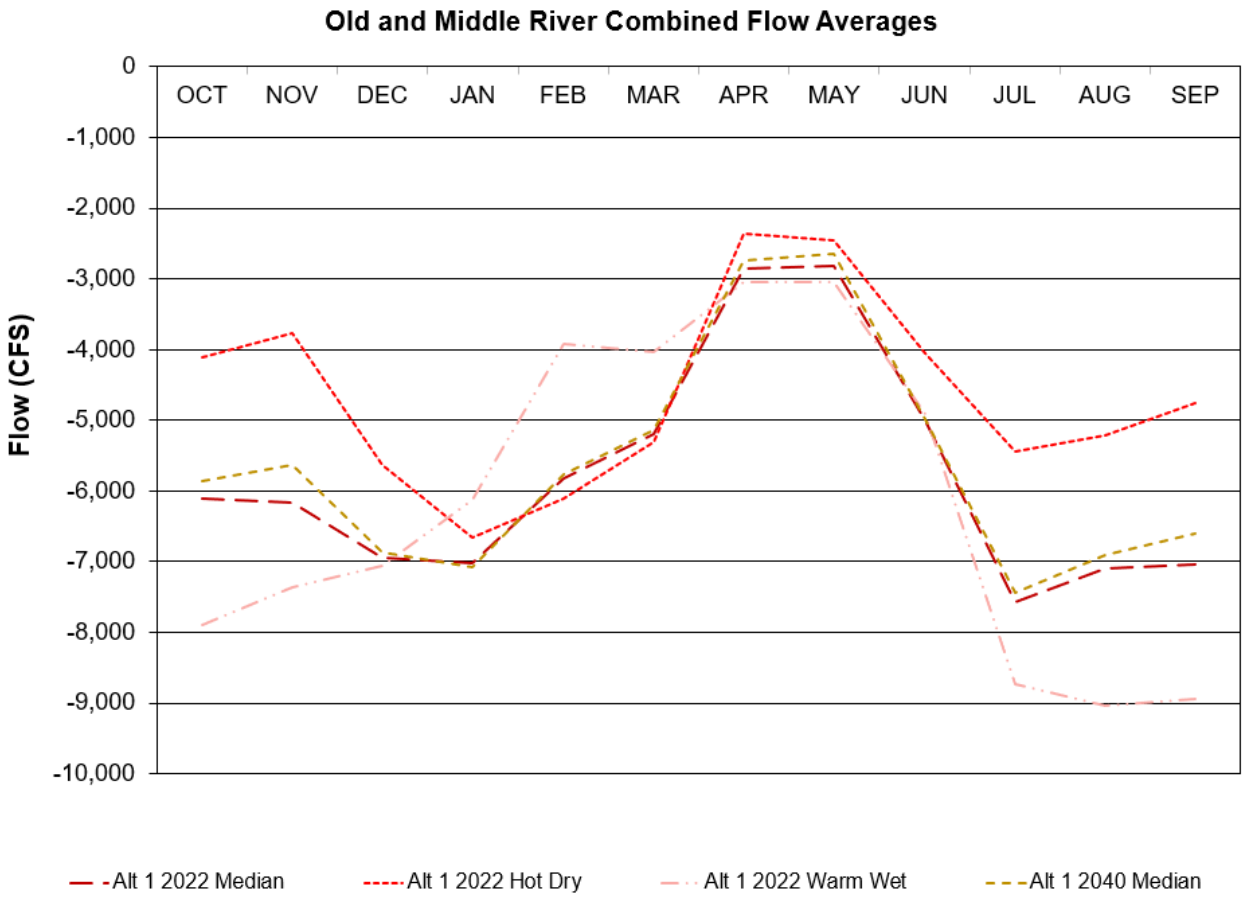

Figure F.2-2-20. Long-term Average Old and Middle River Combined Flow

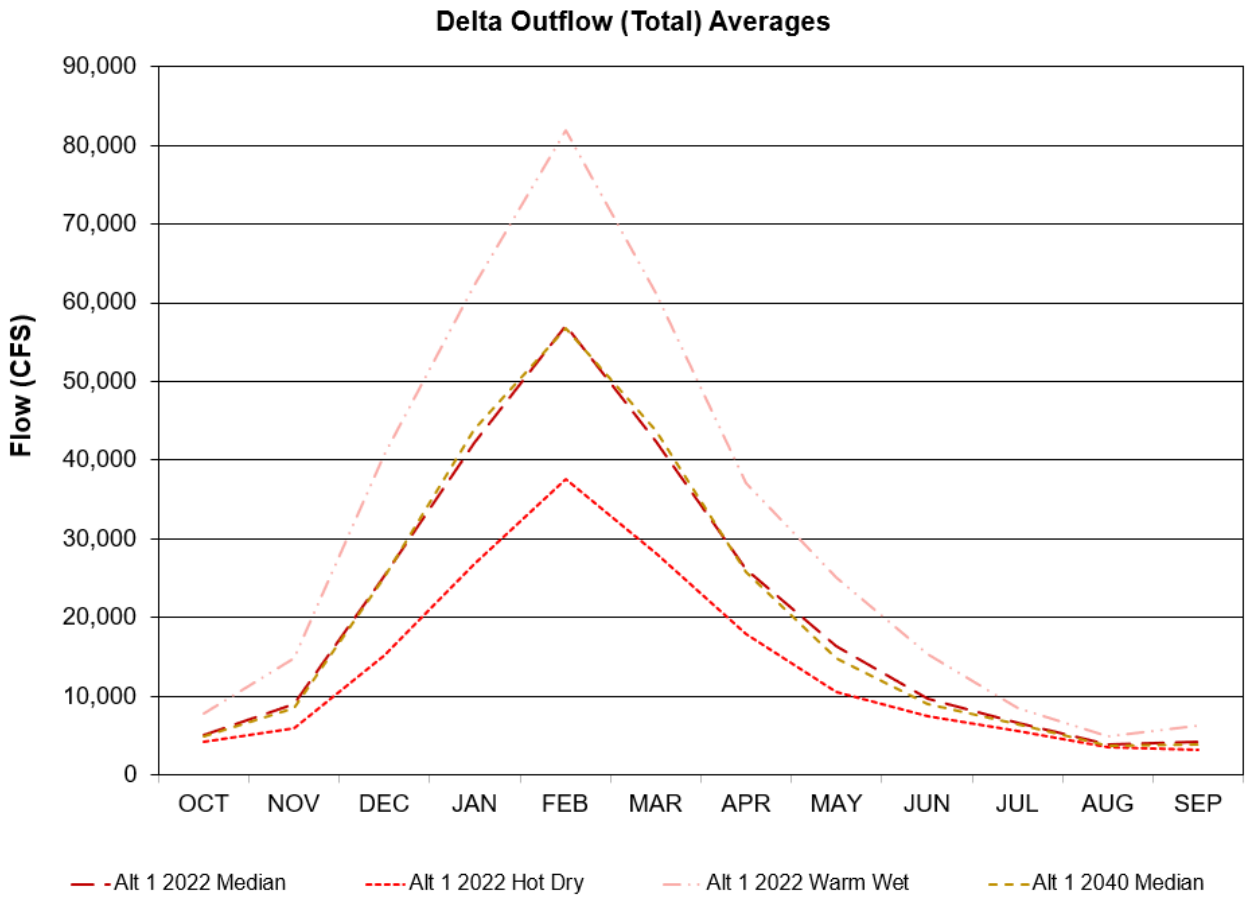

Figure F.2-2-21. Long-term Average Delta Outflow

F.2-2.2.2 HEC5Q

F.2-2.2.2.1 ***Sacramento***

Figure F.2-2-22 through Figure F.2-2-27 evaluate the temperature outcomes in the Sacramento River under the climate sensitivities using the Alternative 1 logic. Temperature dependent mortality (TDM) was calculated using the standard LTO parameterization.

The Alternative 1 TDM estimate shown in Figure F.2-2-22 demonstrates substantial climate variability. Under the 2022 Median climate scenario, TDM exceeds 60% in less than 10% of the simulated years. Under the 2022 Warm Wet climate scenario which is cooler and wetter than the 2022 Median climate scenario, TDM exceeds 60% in approximately 5% of the simulated years. Conversely, the 2022 Hot Dry climate scenario which is warmer and drier than the 2022 Median scenario has large TDM values occur more frequently with 60% TDM occurring in approximately 25% of the simulated years. The 2040 Median scenario performs similarly to the 2022 Median scenario, albeit with an approximately 10% upward exceedance shift surrounding the 20% exceedance threshold.

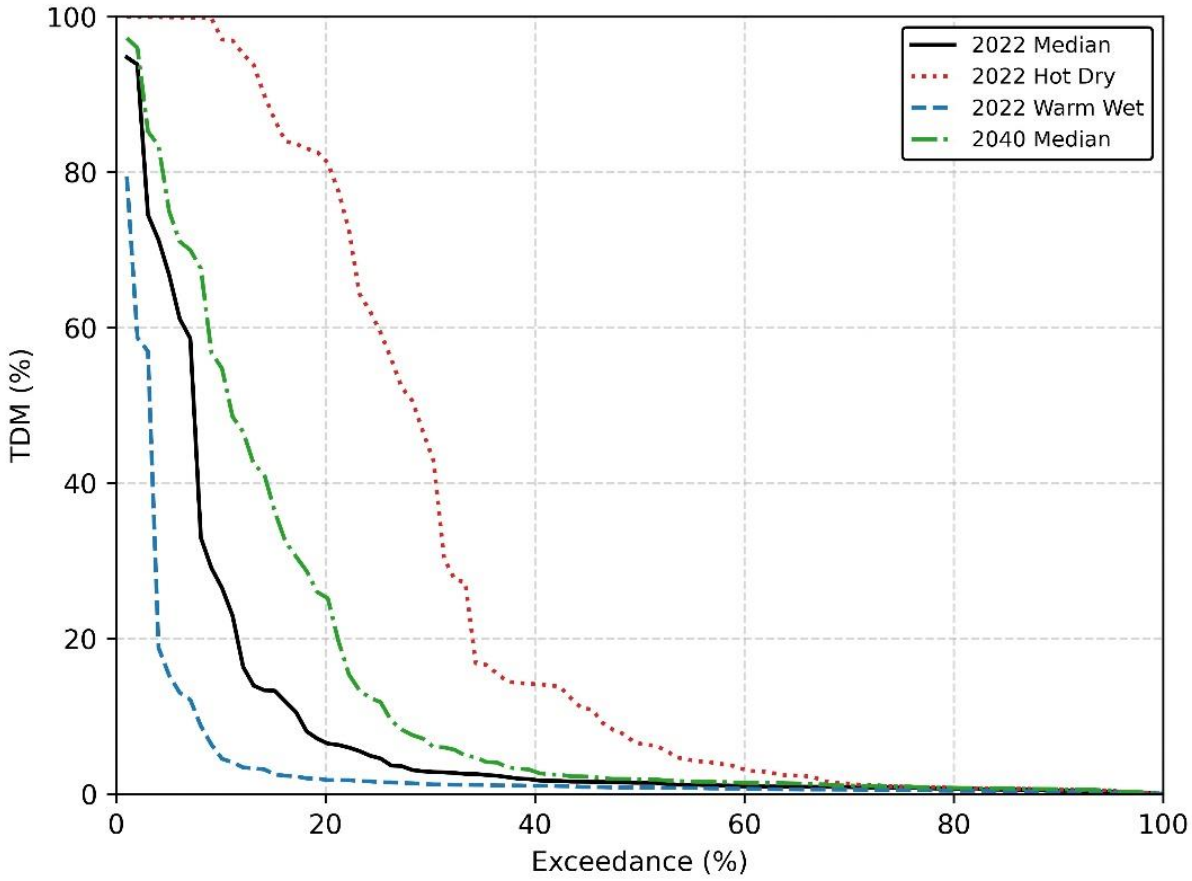

Figure F.2-2-22. Martin model TDM exceedance plot for Alternative 1 under various climate assumptions for water years 1922 through 2021

The Alternative 1 TDM values are driven by the Sacramento River temperatures from Clear Creek down to Red Bluff. Figure F.2-2-23 and Figure F.2-2-24 show the average and maximum May through end of October temperature in the Sacramento River below Clear Creek with Figure F.2-2-25 and Figure F.2-2-26 providing the same information for Red Bluff.

The scaling of TDM follows temperature outcomes with the 2022 Hot Dry scenario having the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest temperatures of the scenarios. While the scenarios have a clear incremental increase in average temperature, temperatures above the 60% exceedance threshold are largely similar. An analogous trend is visible in Figure F.2-2-27 with the volume of water less than 52 degrees Fahrenheit (°F) at the end of April. More cold water correlates with lower TDMs across the climate scenarios. However, despite having generally similar cold-water volumes, the 2040 Median condition exhibits worse TDM outcomes than the 2022 Median, likely due to the roughly degree higher average temperatures under the 2040 Median scenario. The higher average temperatures under the 2040 Median scenario are likely due in part to the greater in-stream and reservoir warming.

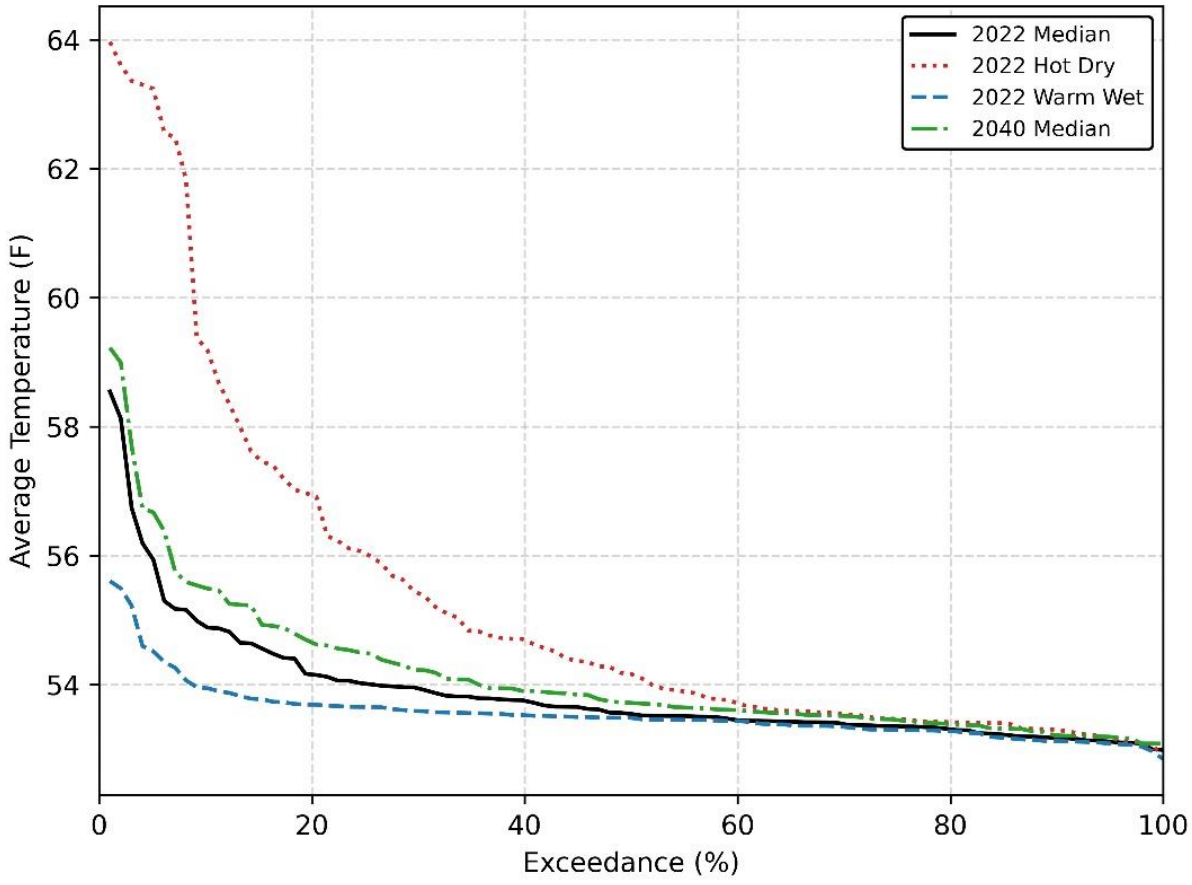

Figure F.2-2-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 1 under various climate assumptions for water years 1923 through 2020

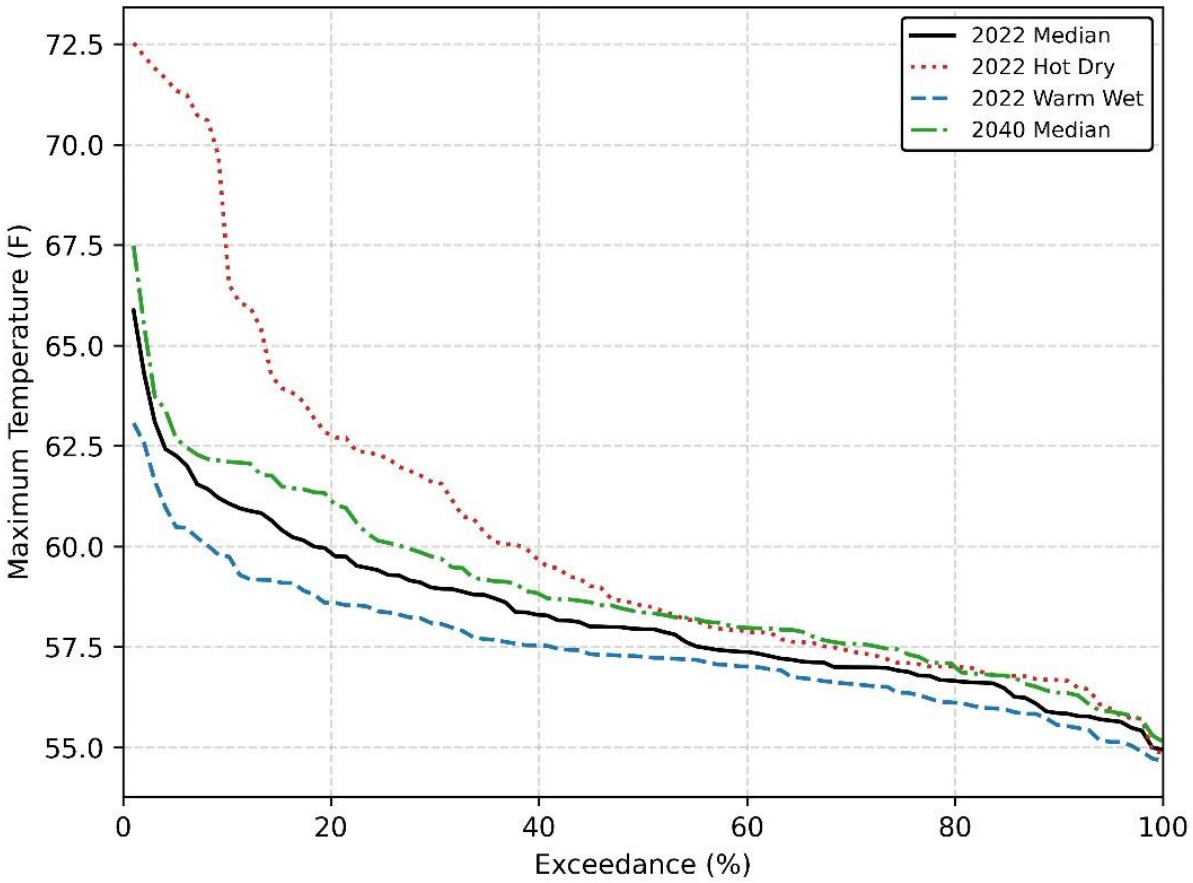

Figure F.2-2-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 1 under various climate assumptions for water years 1923 through 2020

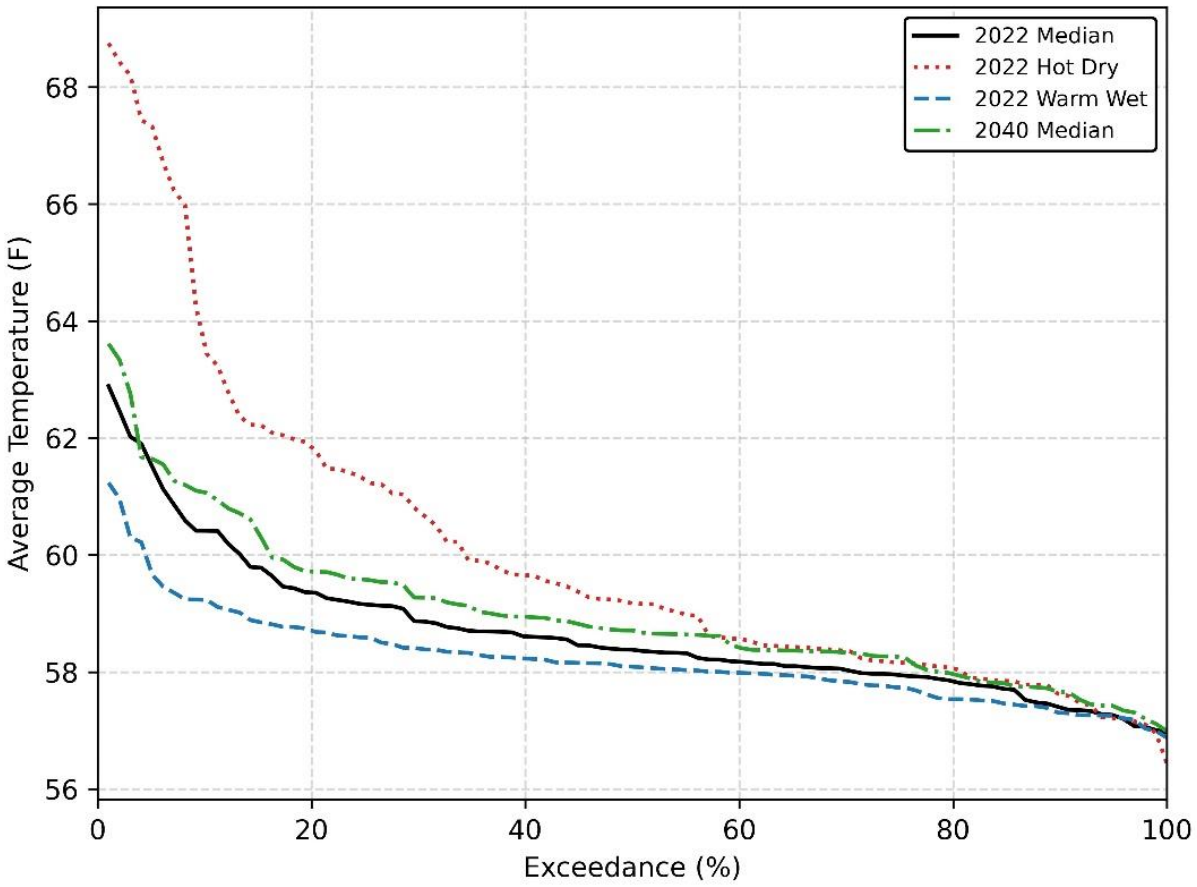

Figure F.2-2-25. Average May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 1 under various climate assumptions for water years 1923 through 2020

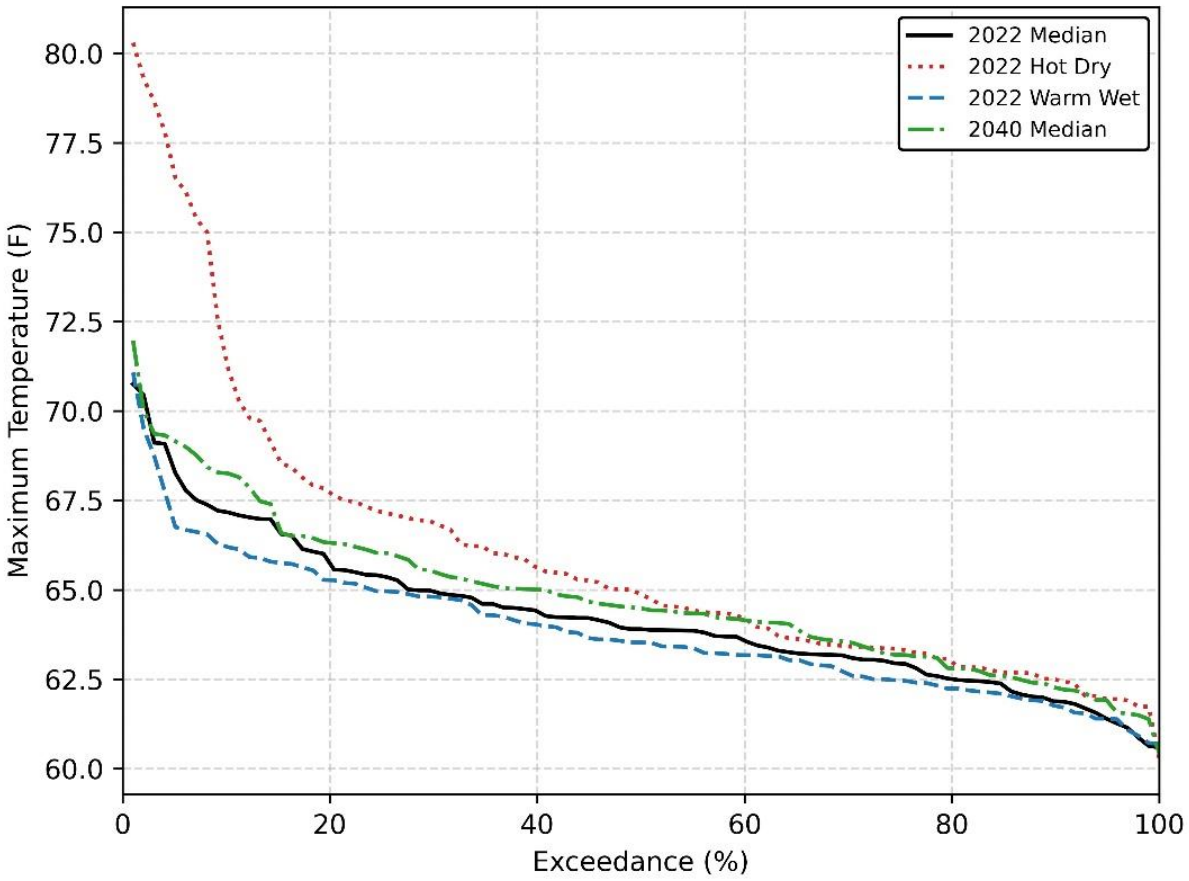

Figure F.2-2-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 1 under various climate assumptions for water years 1923 through 2020

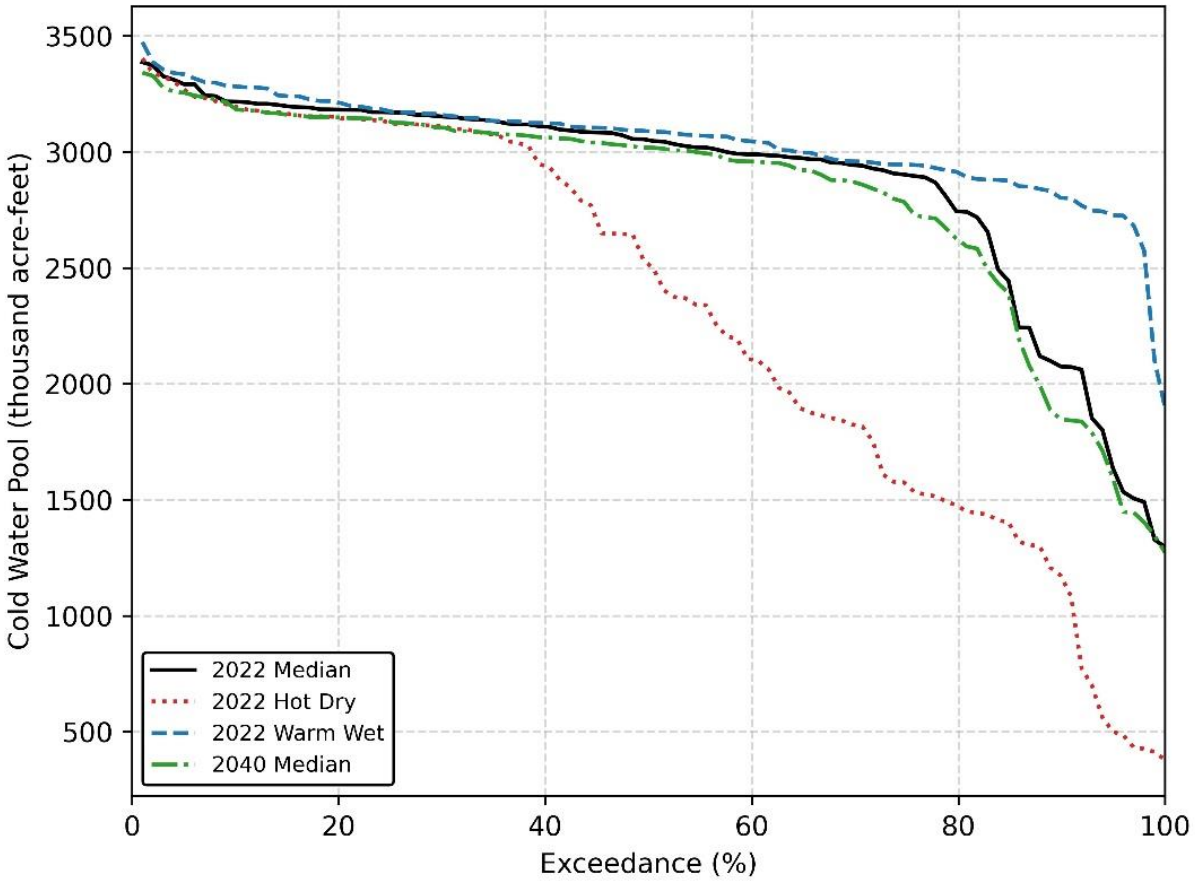

Figure F.2-2-27. Volume of water at the end of April less than 52°F in Shasta Lake for Alternative 1 under various climate assumptions for water years 1923 through 2021

F.2-2.2.2.2 ***American***

Figure F.2-2-28 through Figure F.2-2-30 evaluate the temperature outcomes in the American River under the climate sensitivities using the Alternative 1 logic. The 2022 Hot Dry scenario has the highest average and maximum temperatures at low exceedances. At high exceedances, both the 2022 Hot Dry and 2040 Median scenarios perform similarly and have the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. Figure F.2-2-30 shows the volume of water less than 52 °F at the end of April in Folsom Lake. The 2022 Hot Dry scenario has the lowest volumes of cold-water and the 2022 Warm Wet scenario has the highest volumes of cold-water. Despite the 2022 Median and 2040 Median having similar volumes of cold-water, the 2040 scenario exhibits higher average and maximum temperatures likely due in part to the greater in-stream and reservoir warming.

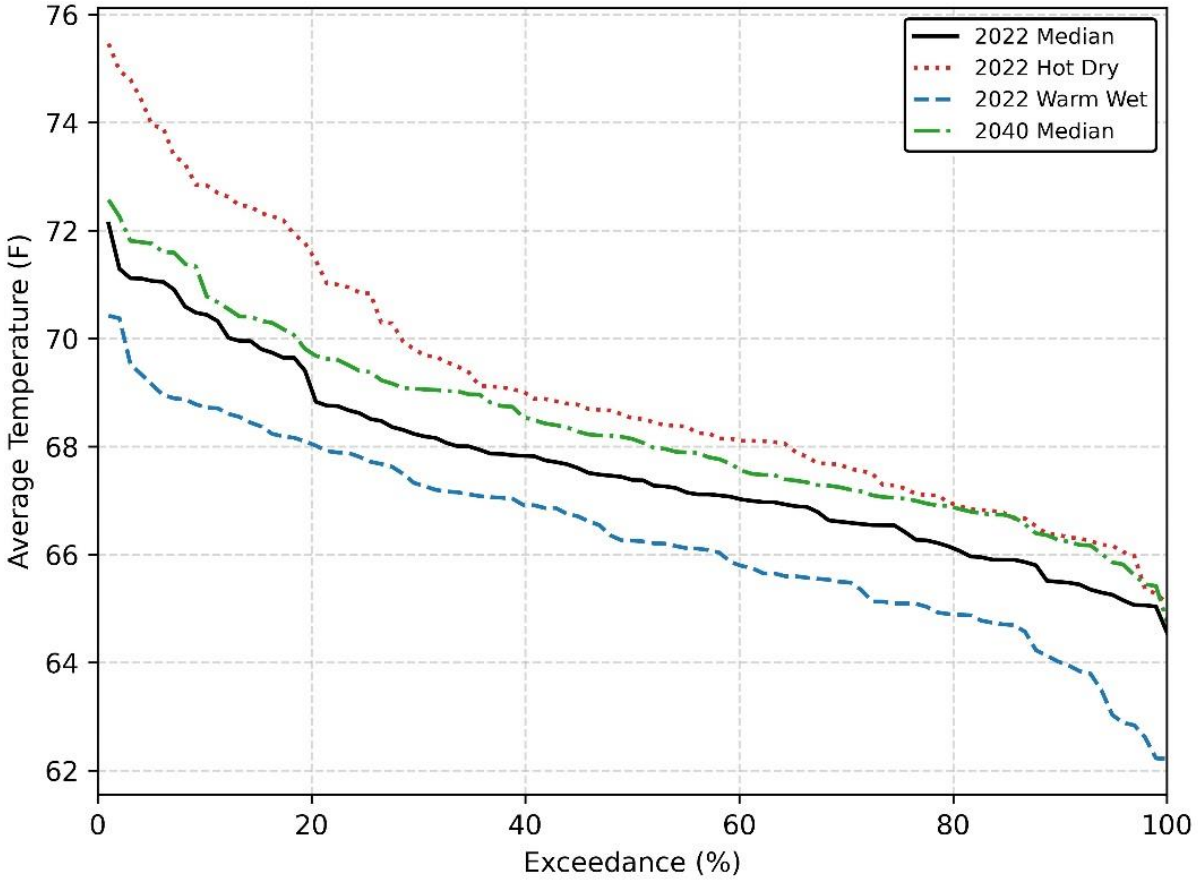

Figure F.2-2-28. Average May through end of October temperatures on the American River at Watt Avenue for Alternative 1 under various climate assumptions for water years 1923 through 2020

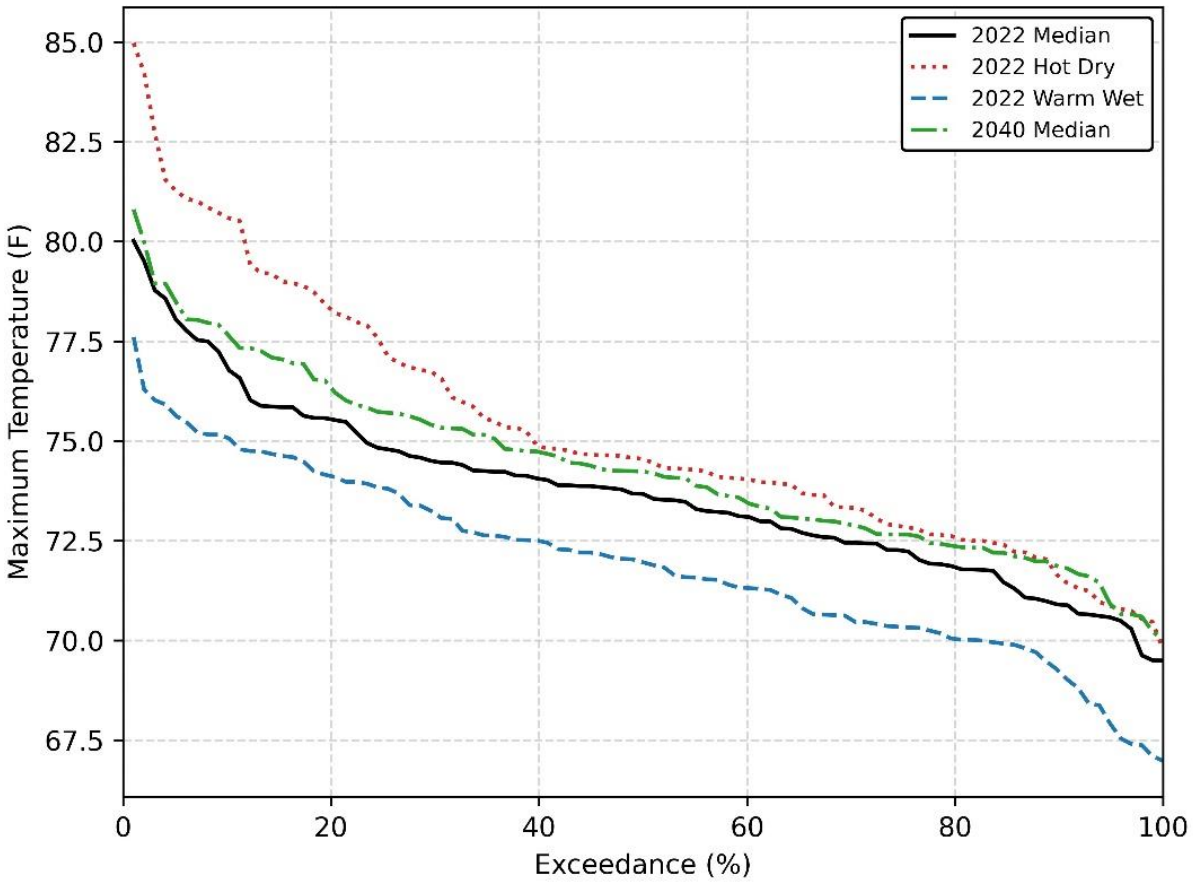

Figure F.2-2-29. Maximum May through end of October temperatures on the American River at Watt Avenue for Alternative 1 under various climate assumptions for water years 1923 through 2020

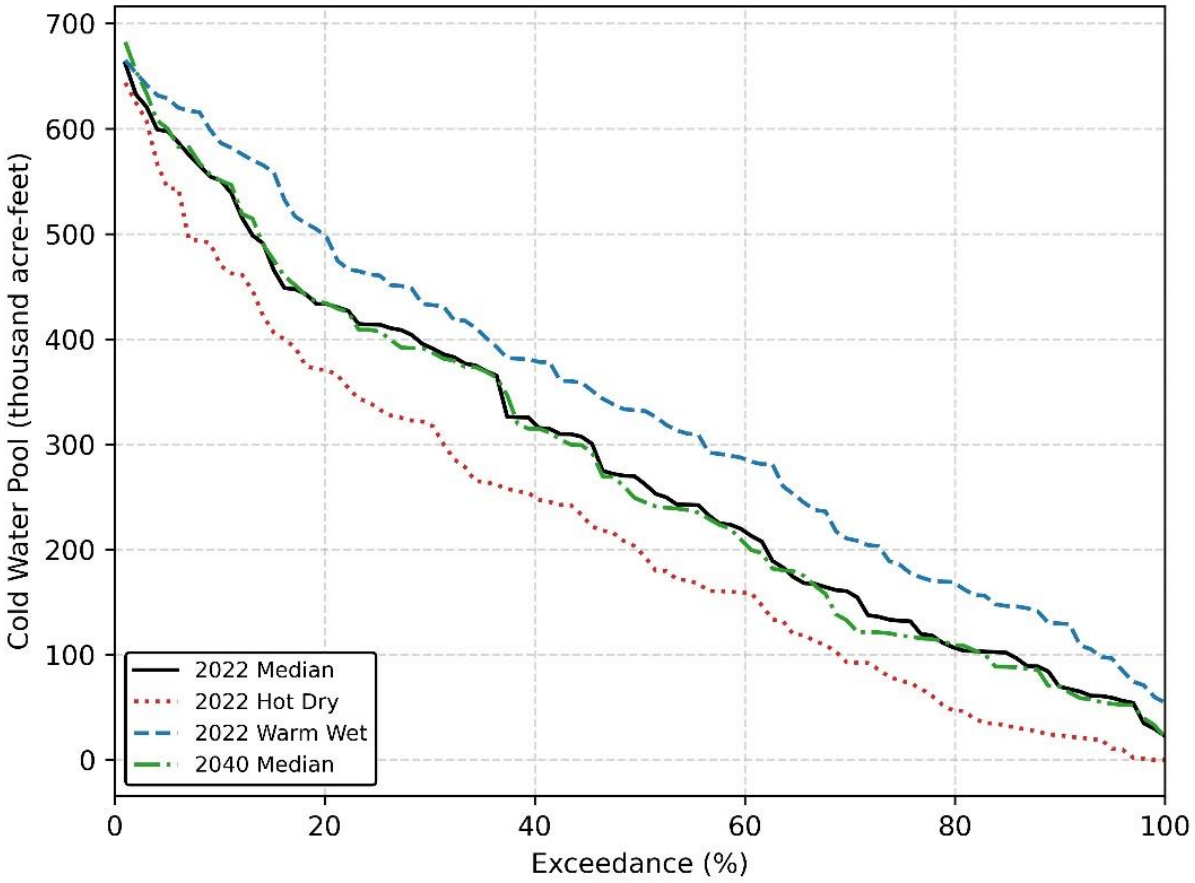

Figure F.2-2-30. Volume of water at the end of April less than 52 °F in Folsom Lake for Alternative 1 under various climate assumptions for water years 1923 through 2021

F.2-2.2.2.3 ***Stanislaus***

Figure F.2-2-31 and Figure F.2-2-32 evaluate the temperature outcomes in the Stanislaus River under the climate sensitivities using the Alternative 1 logic. The 2022 Hot Dry scenario has the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures. The 2040 Median temperatures are slightly higher than the 2022 Median due to instream warming.

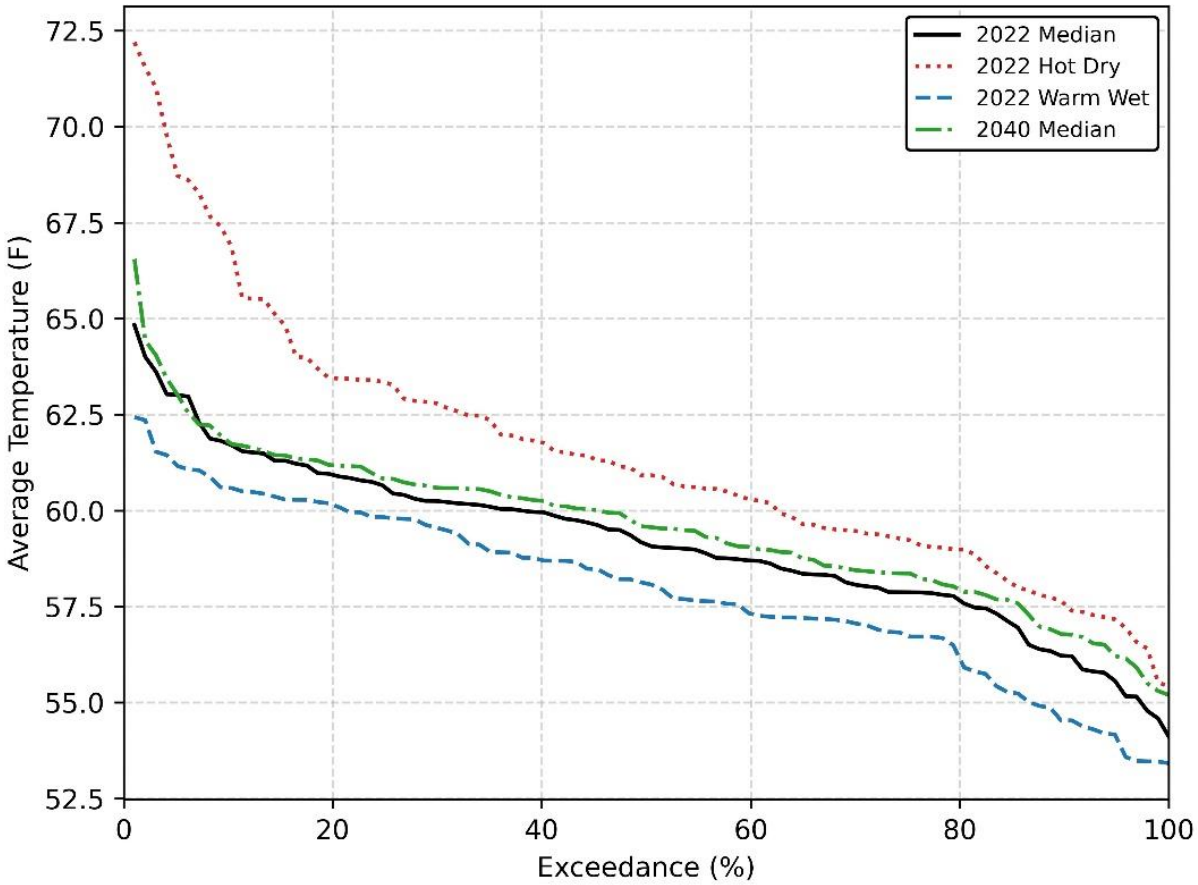

Figure F.2-2-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 1 under various climate assumptions for water years 1923 through 2019

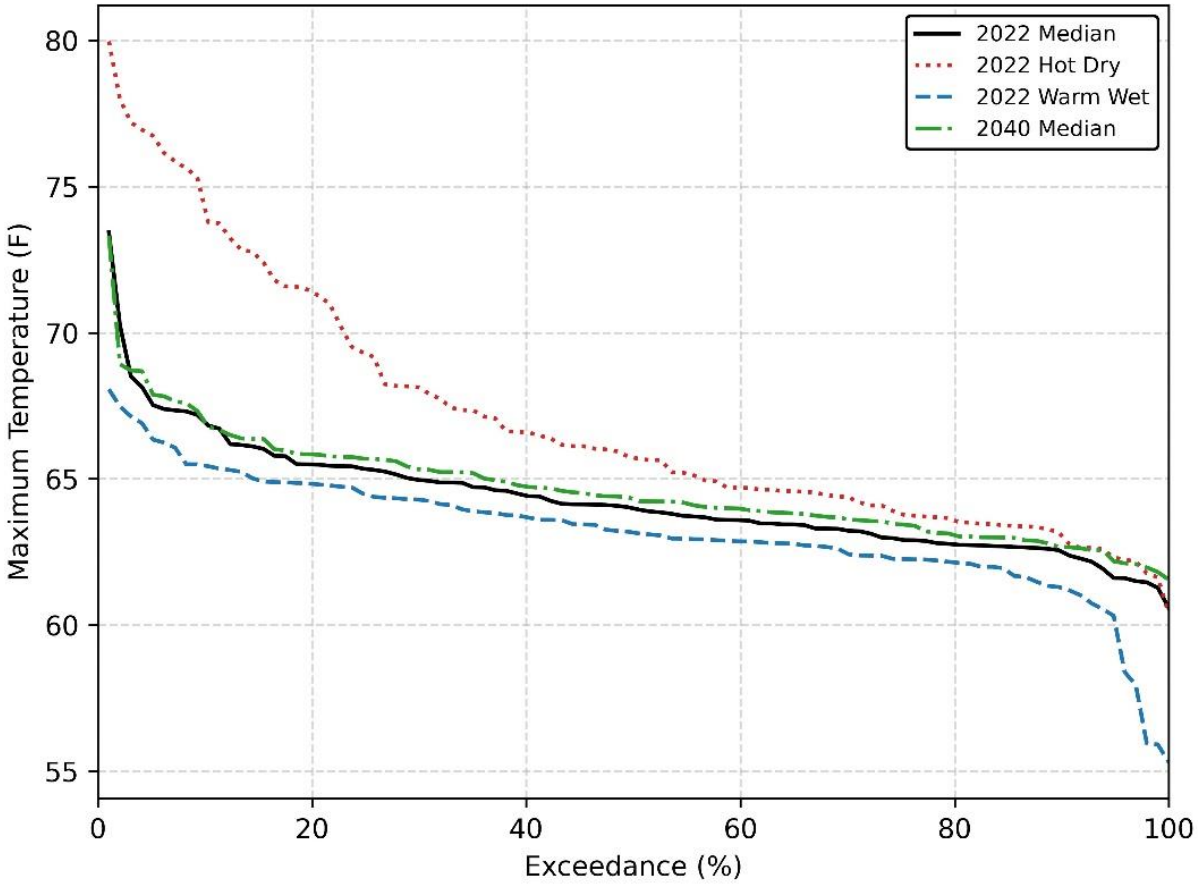

Figure F.2-2-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 1 under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Appendix F.2-3 Climate Sensitivity Analysis, Alternative 2 without TUCP

F.2-3.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative 2 without Voluntary Agreements and without TUCPs (Alt 2v1 wo TUCP) under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-3.2 Climate Change Comparison

F.2-3.2.1 CalSim 3

Figures 1 through 21 show CalSim 3 simulation results for Alternative 2v1 wo TUCP. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 2v1 wo TUCP were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough
- Sacramento River at Verona
- Sacramento River at Freeport

- Flow though Yolo Bypass
- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure 1) and end of September (Figure 2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 20% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows, long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of reservoir management season, the differences are less notable. Summer months are commonly when river flows are due primarily to releases from storage instead of runoff events. Flows under 2040 Median climate are similar to flows under 2022 Median climate.

Clear Creek below Whiskeytown (Figure 9) flow changes are similar to the changes observed in the Sacramento River watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in fall and winter months. For Spring Creek inflow to Keswick Reservoir (Figure 10), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure 11) and end of September (Figure 12) Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure 13), changes to flow are similar to the changes in the Sacramento watershed. In all months, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are

lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May and June due to lower Folsom inflows in spring months. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. As compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in January of 2040 Median conditions due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure 14), changes are similar to the changes in the Sacramento watershed. Flows across all climate conditions are most in June and July, months when releases consist of stored water. Otherwise, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows.

For long-term monthly average San Joaquin River flows, changes to flow are similar to the changes in the Sacramento watershed. San Joaquin River at Gravelly Ford (Figure 15) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam (Figure 16) are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced (Figure 17).

For long-term monthly average flows in the Delta (Figure 18 through 21), changes are generally similar to the changes in the Sacramento watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows. Flows across all climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure 20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

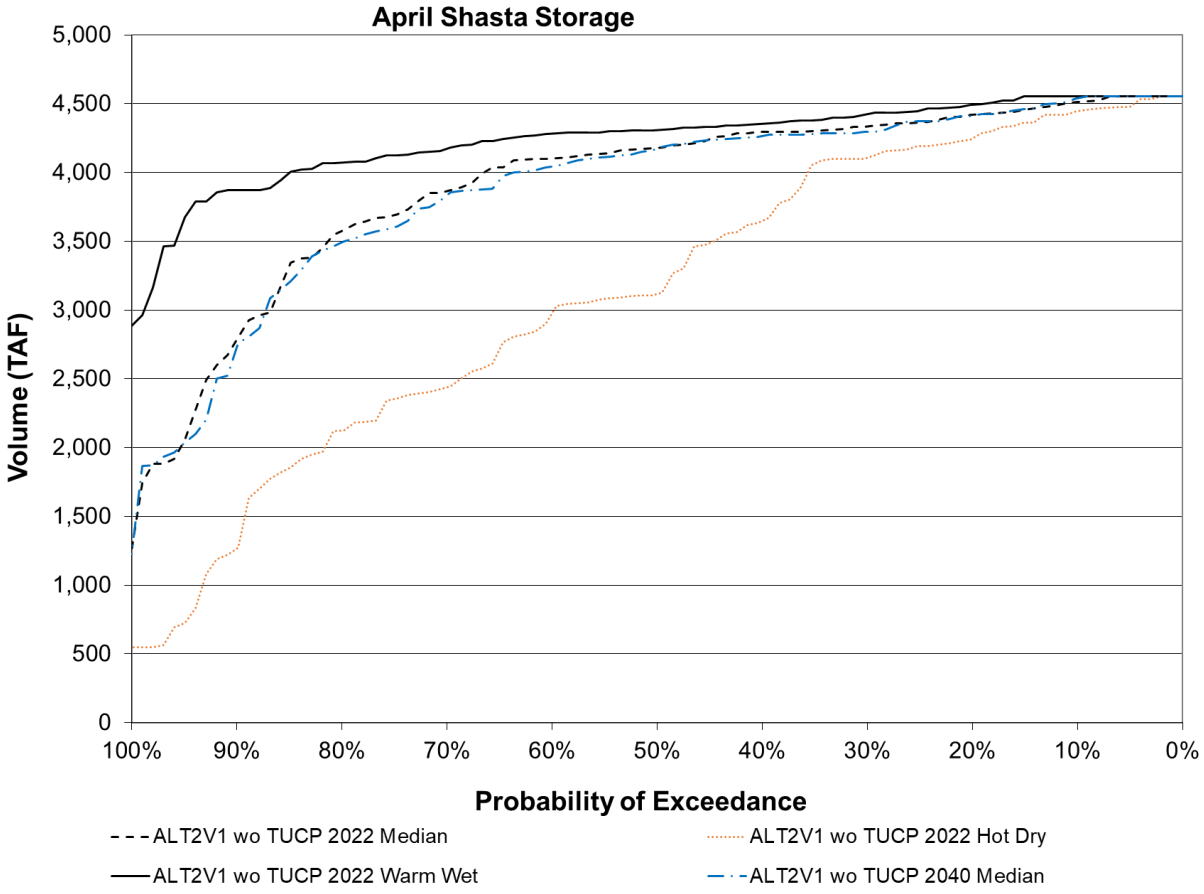

Figure 1. End of April Shasta Storage

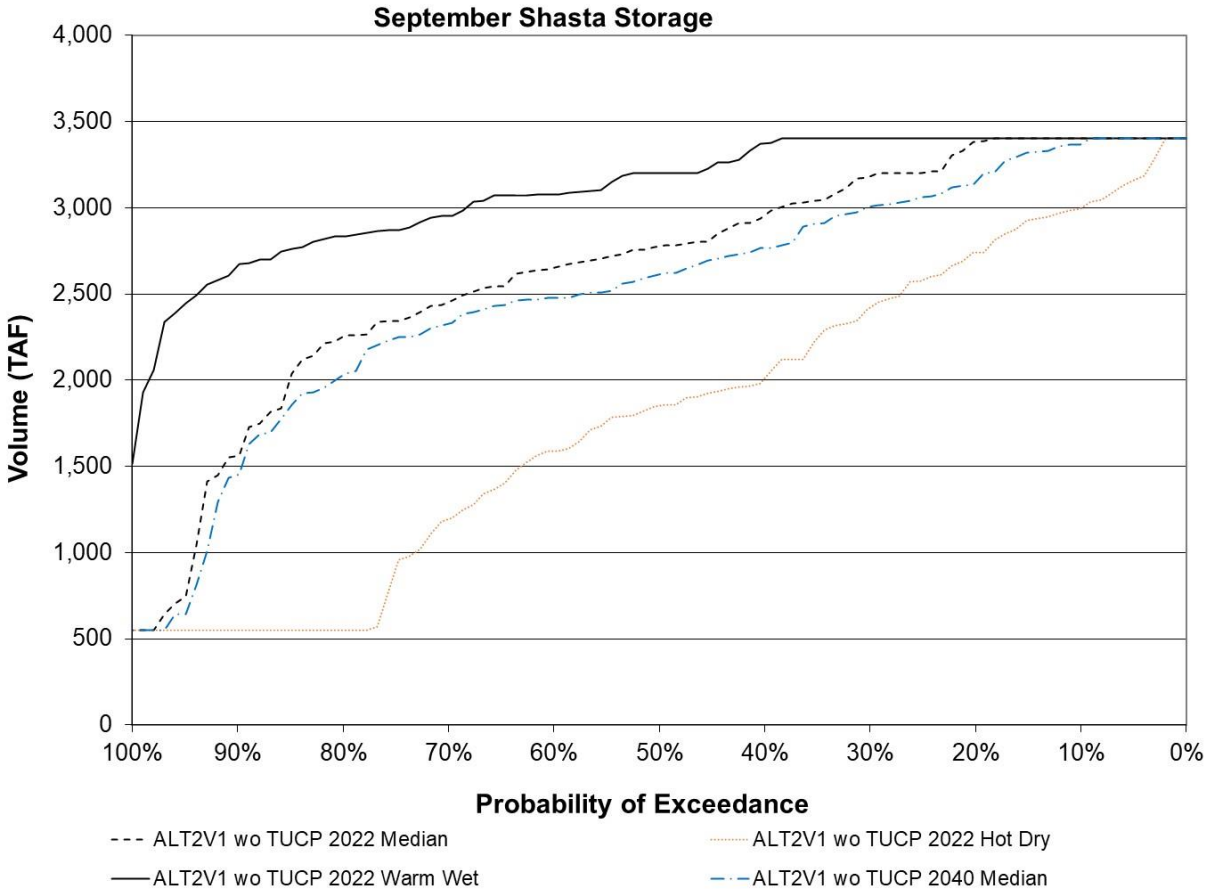

Figure 2. End of September Shasta Storage

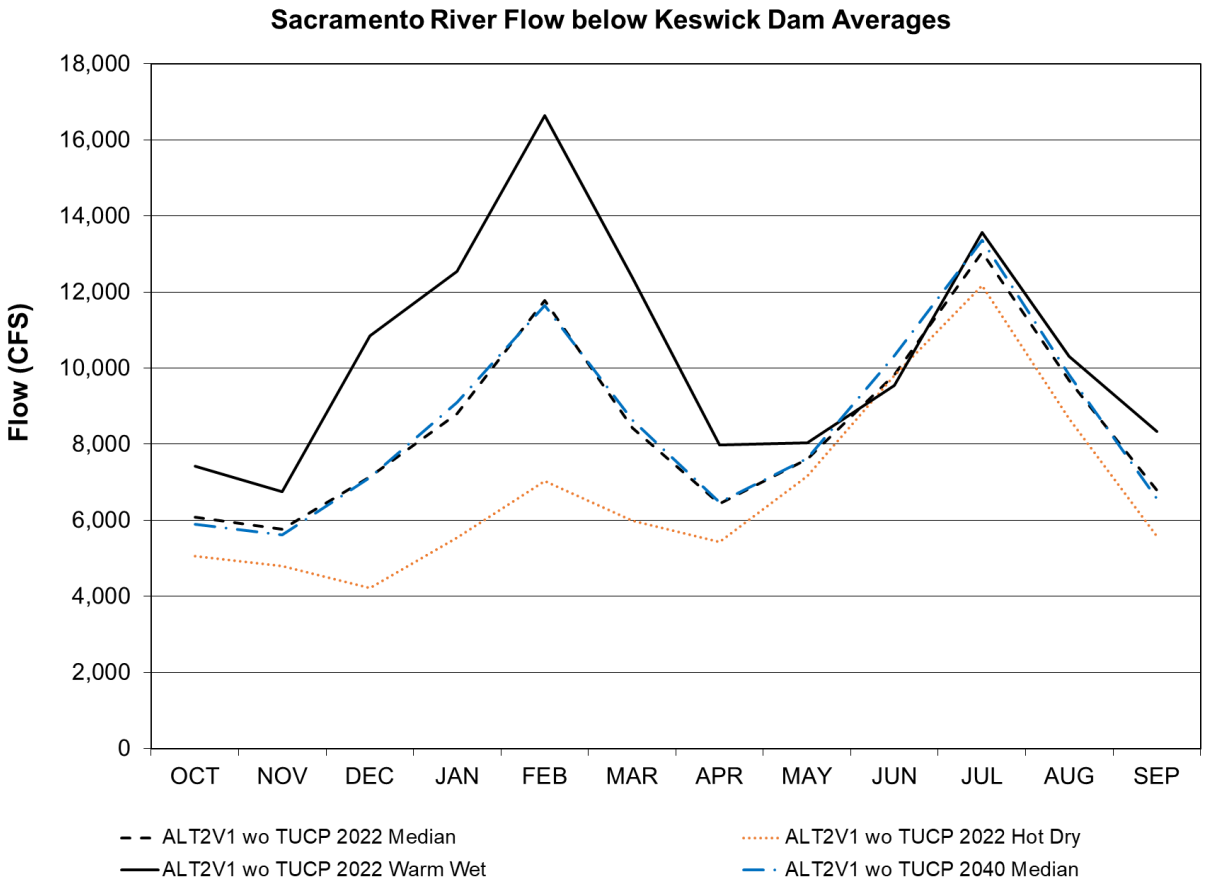

Figure 3. Long-term Average Sacramento River flow below Keswick Dam

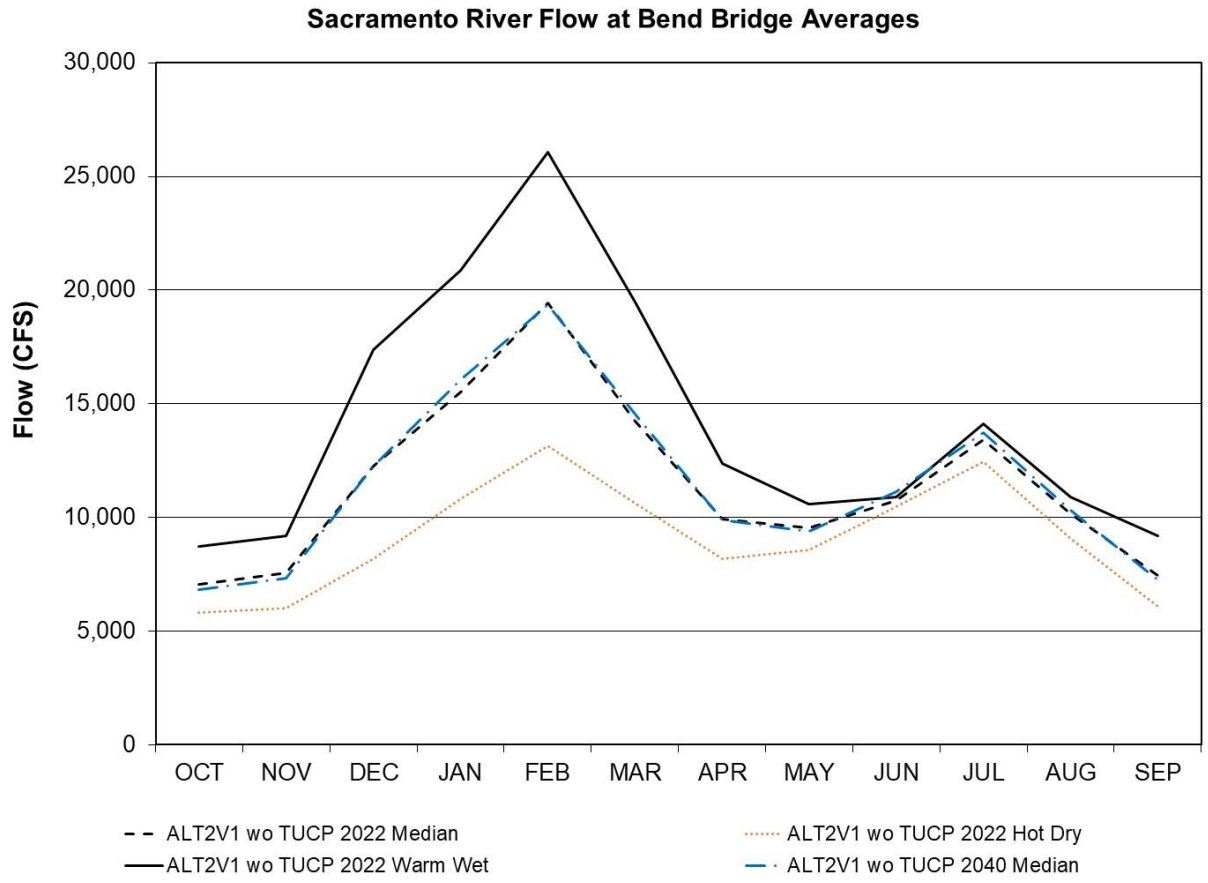

Figure 4. Long-term Average Sacramento River flow at Bend Bridge

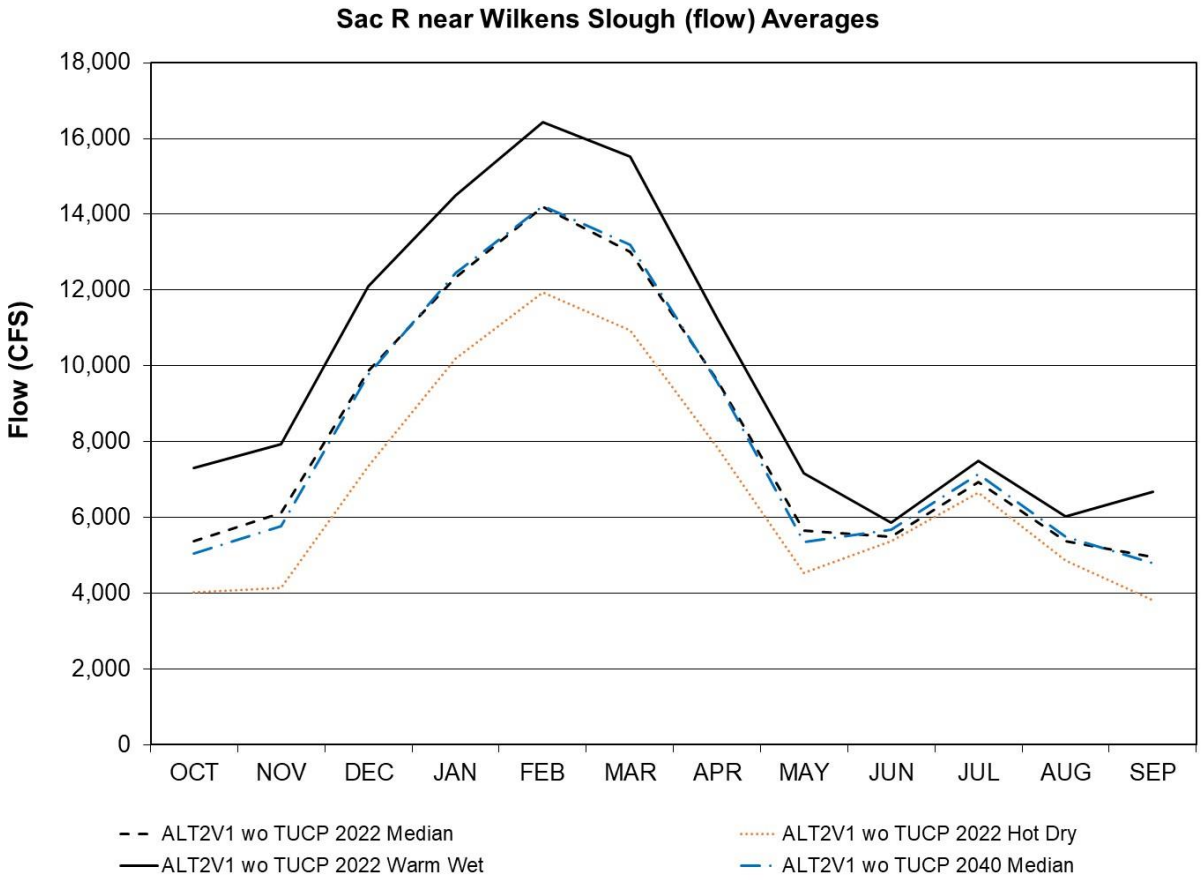

Figure 5. Long-term Average Sacramento River flow near Wilkins Slough

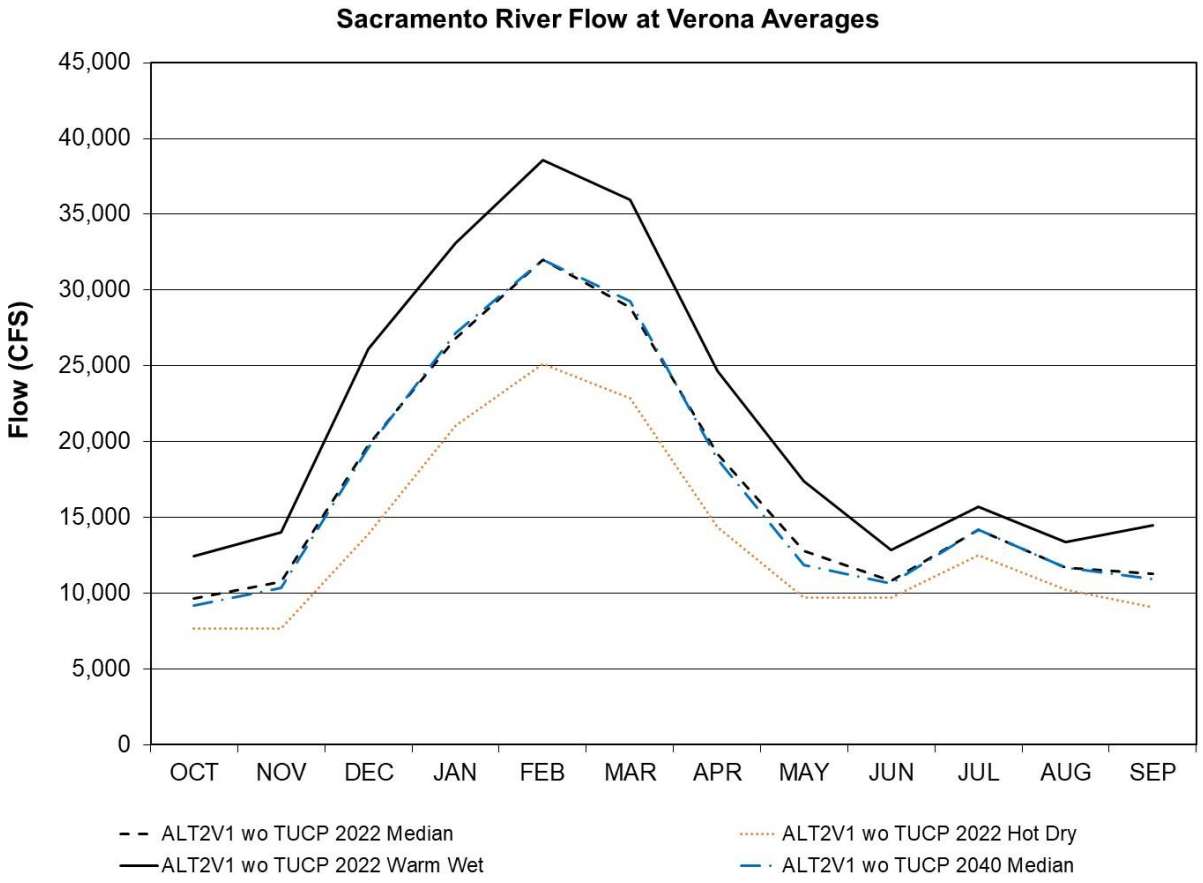

Figure 6. Long-term Average Sacramento River flow at Verona

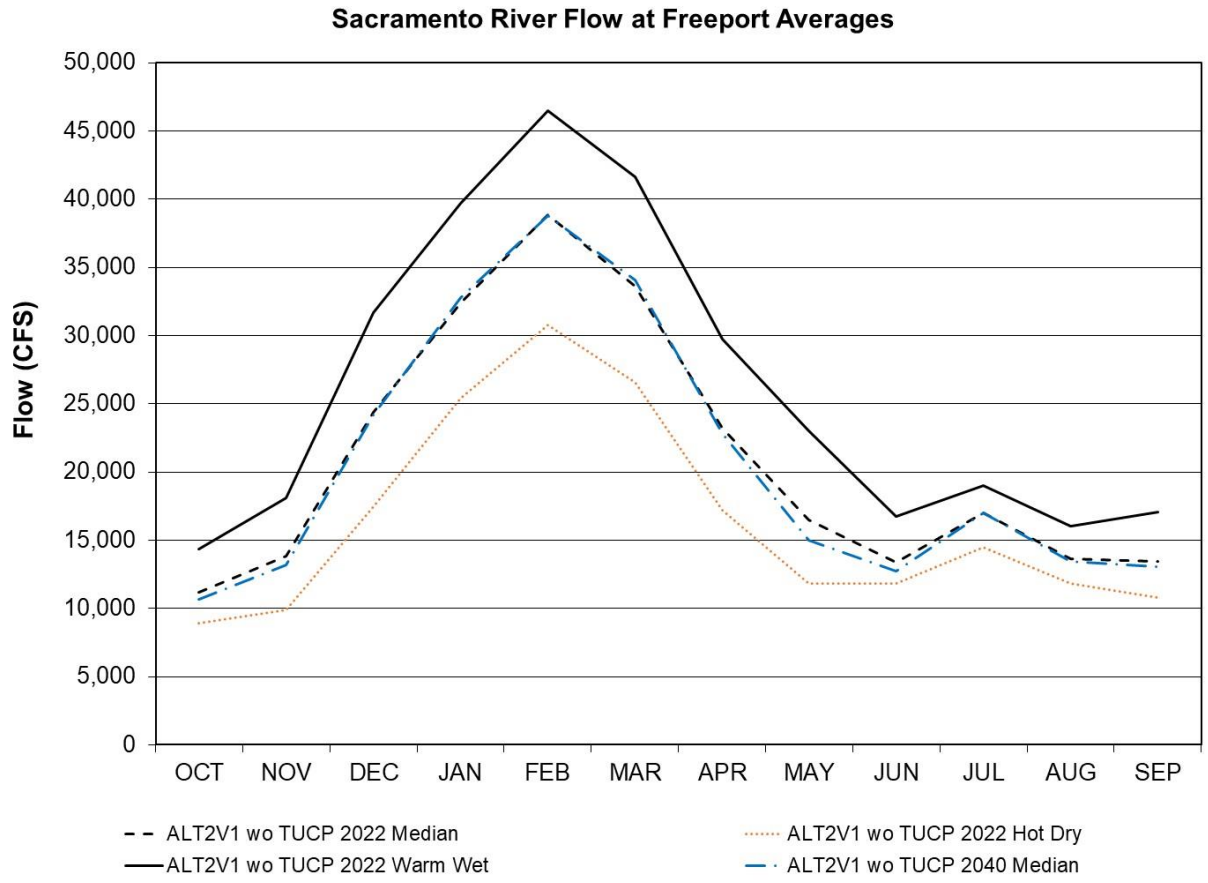

Figure 7. Long-term Average Sacramento River flow at Freeport

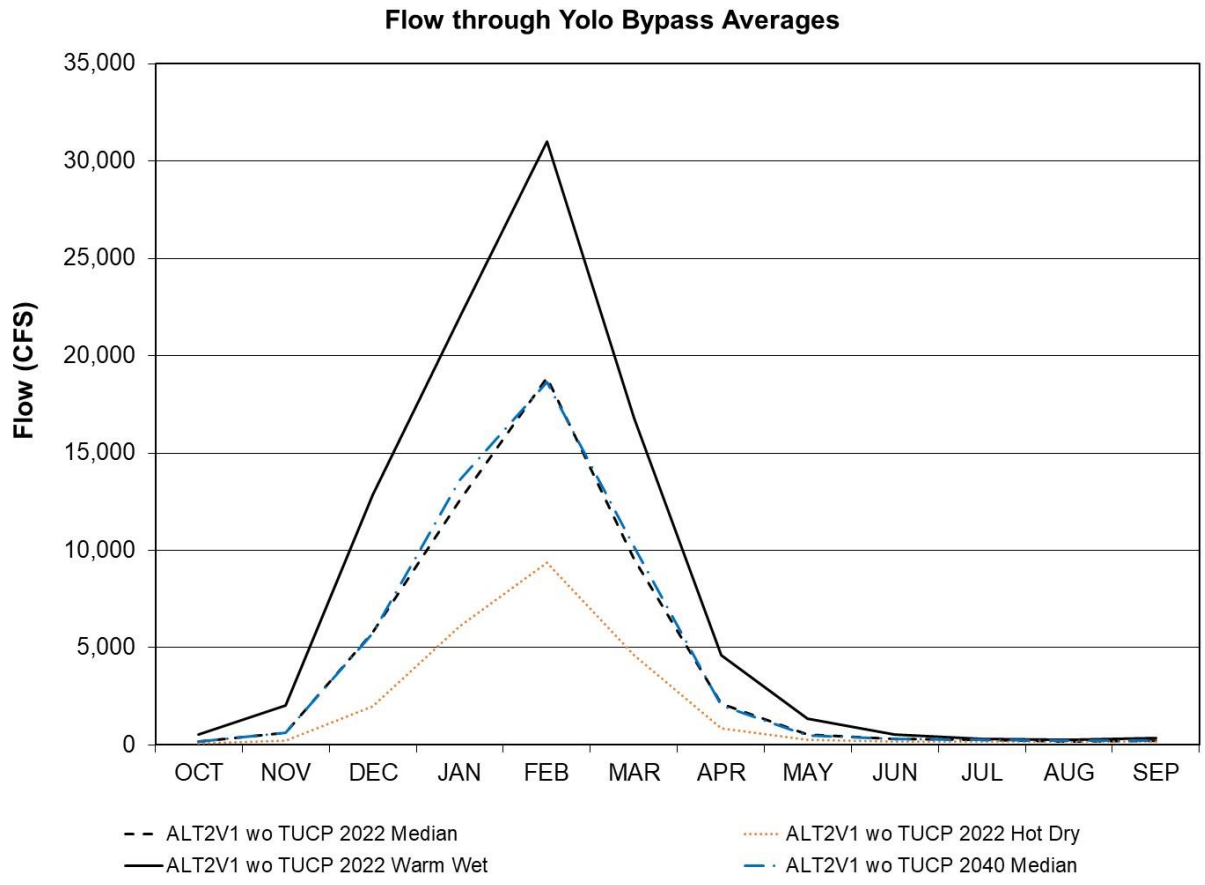

Figure 8. Long-term Average Yolo Bypass Flow

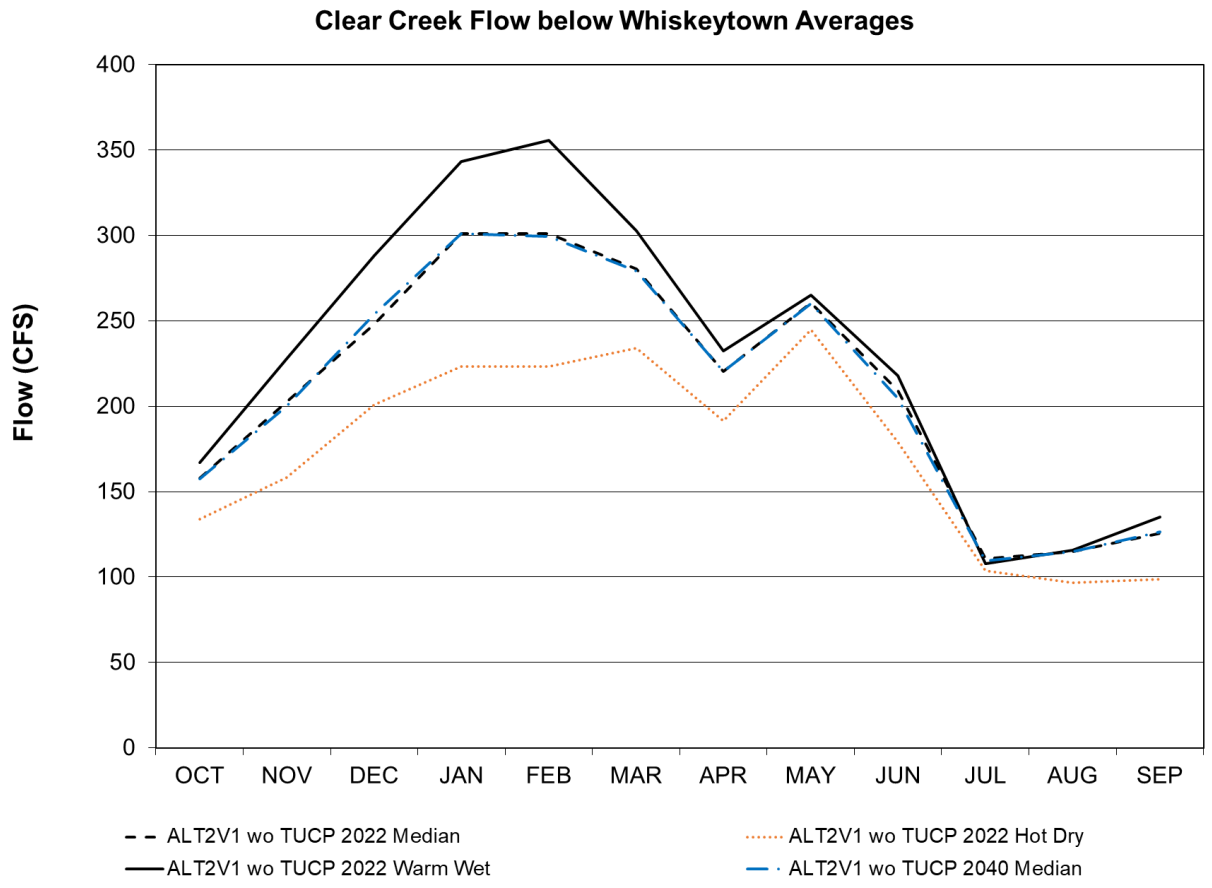

Figure 9. Long-term Average Clear Creek flow below Whiskeytown

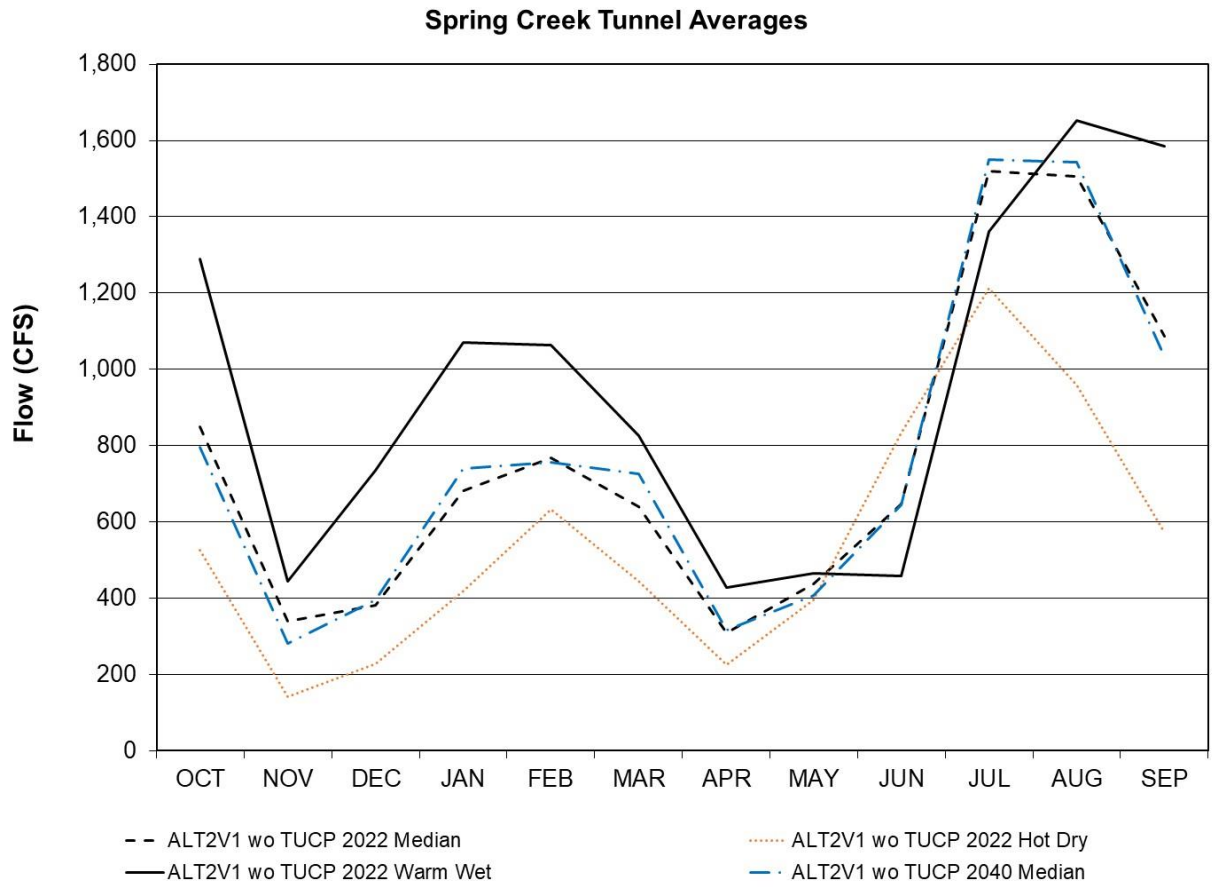

Figure 10. Long-term Average Spring Creek Tunnel Flow

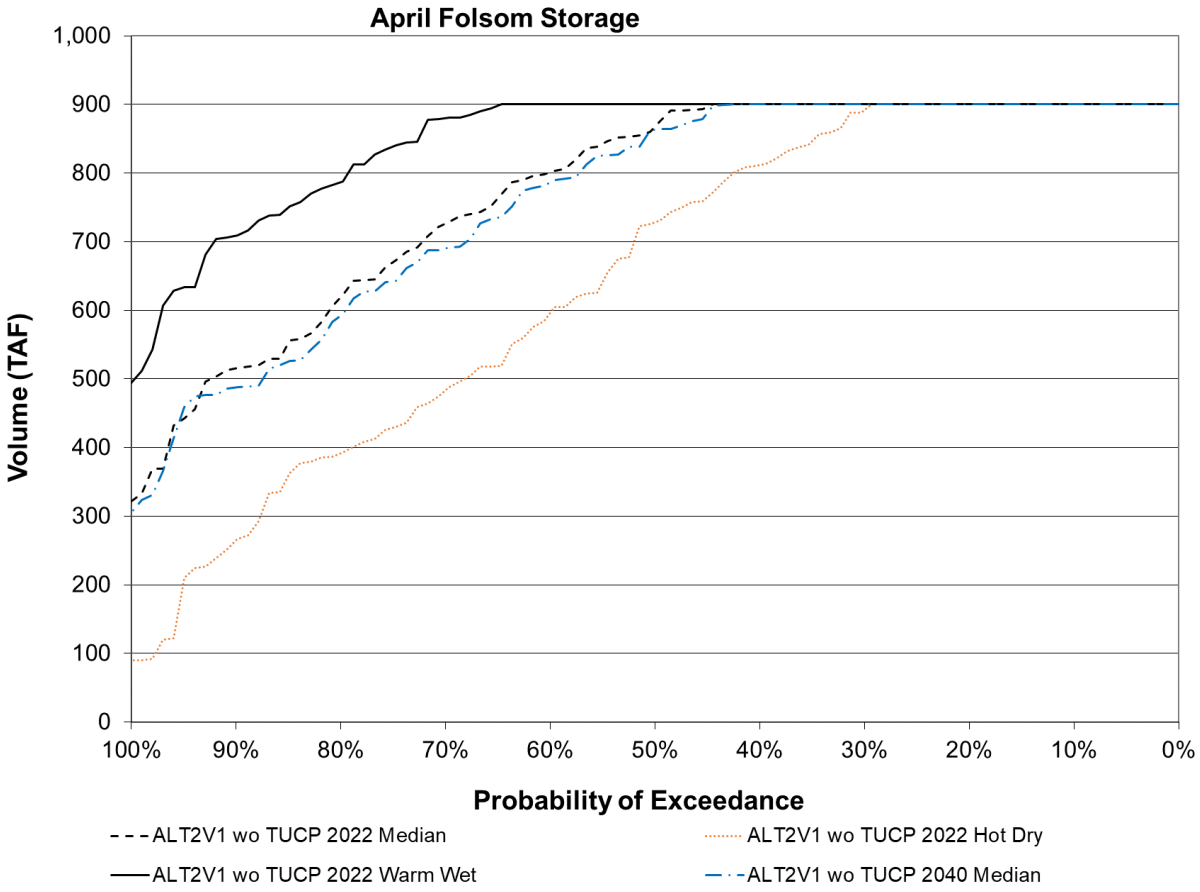

Figure 11. End of April Folsom Storage

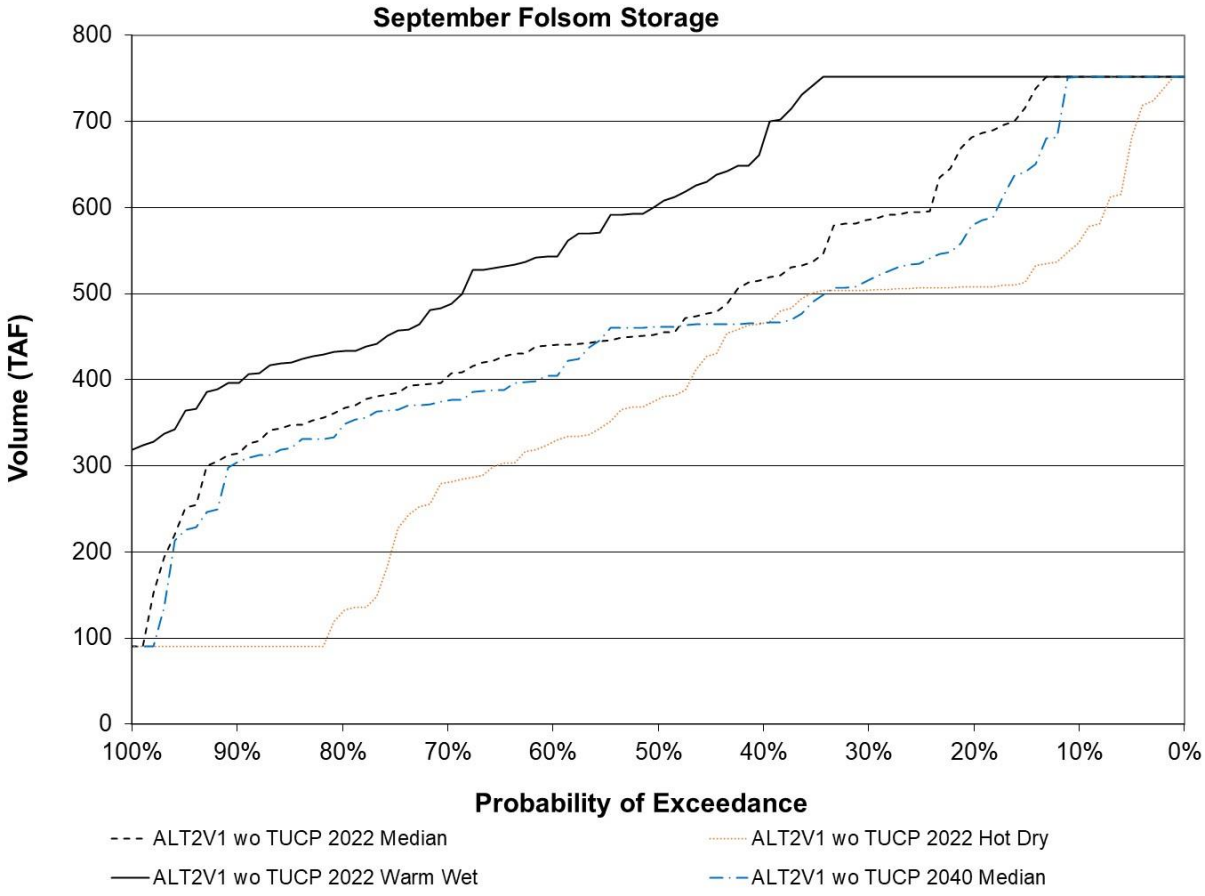

Figure 12. End of September Folsom Storage

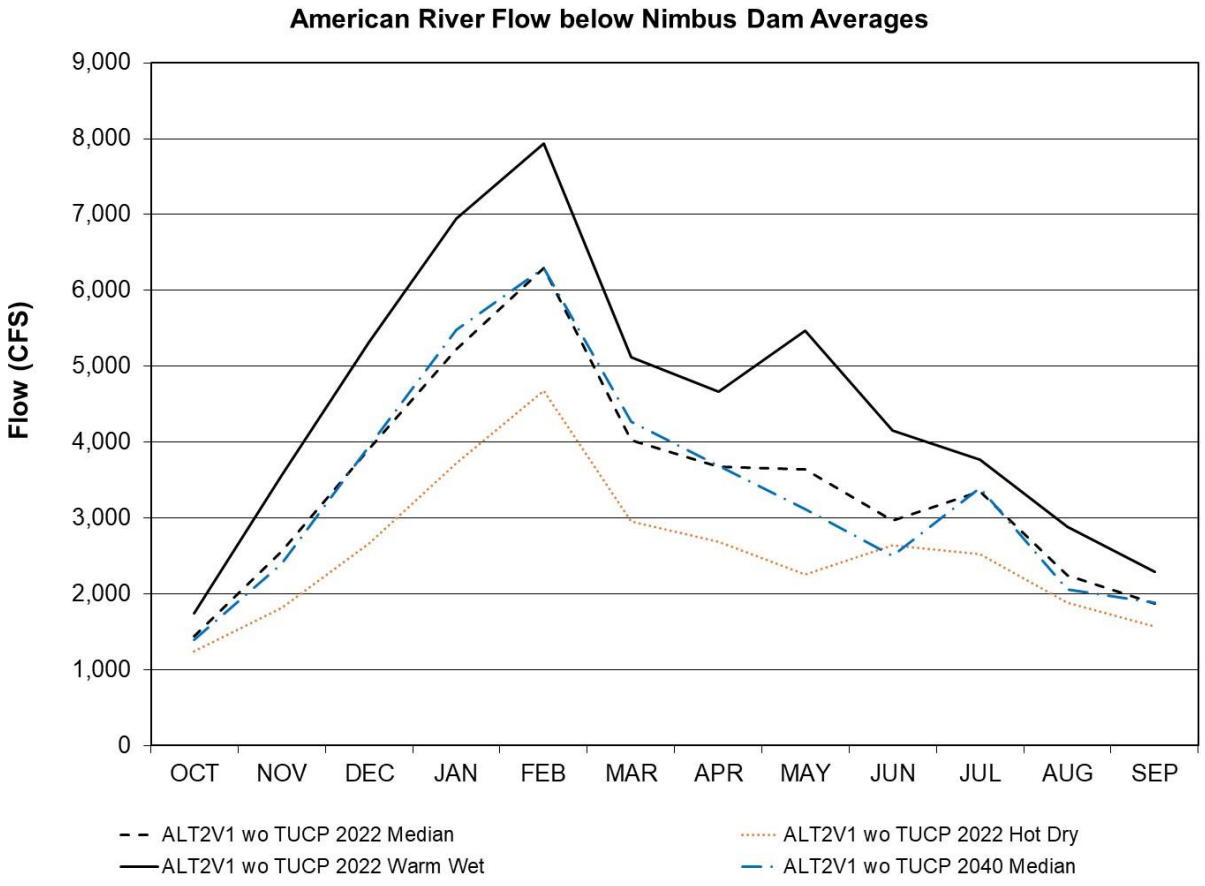

Figure 13. Long-term Average American River flow below Nimbus Dam

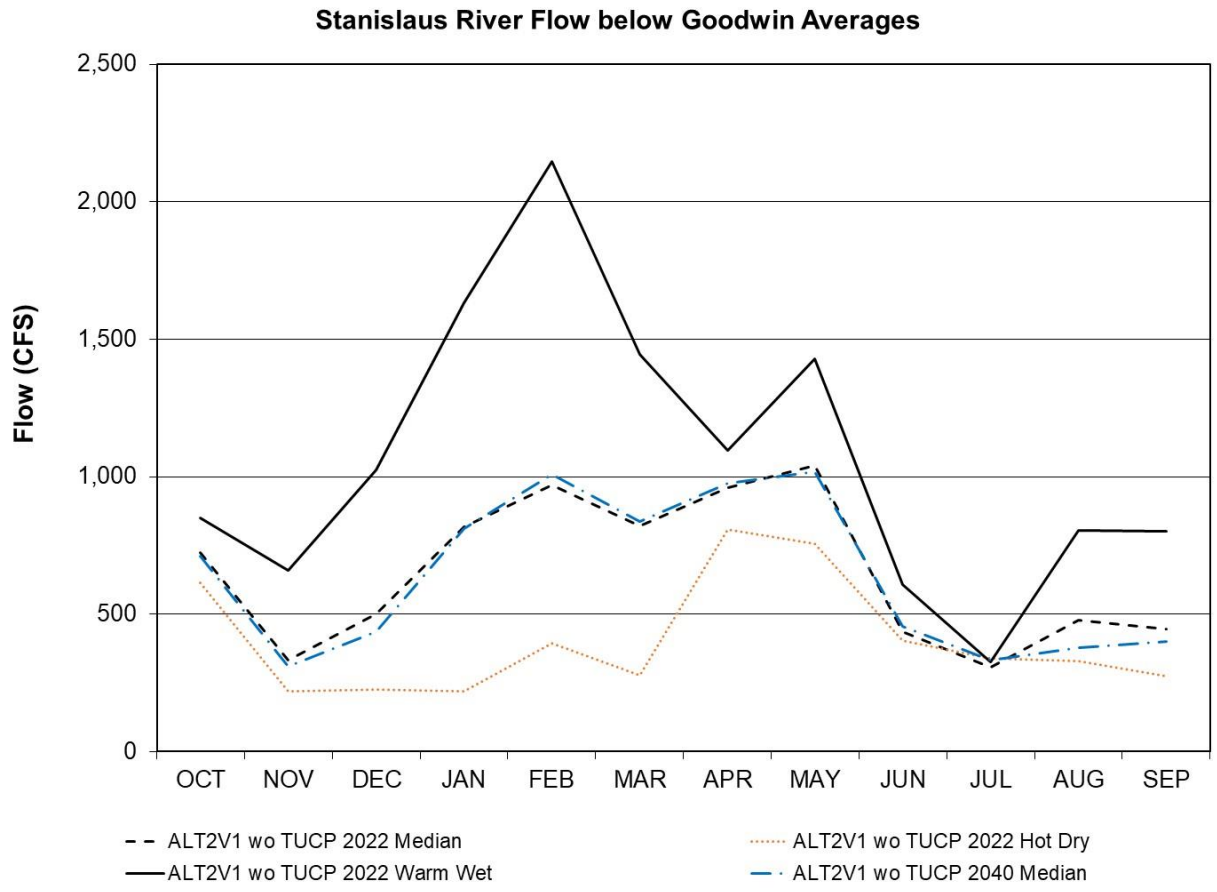

Figure 14. Long-term Average Stanislaus River flow below Goodwin

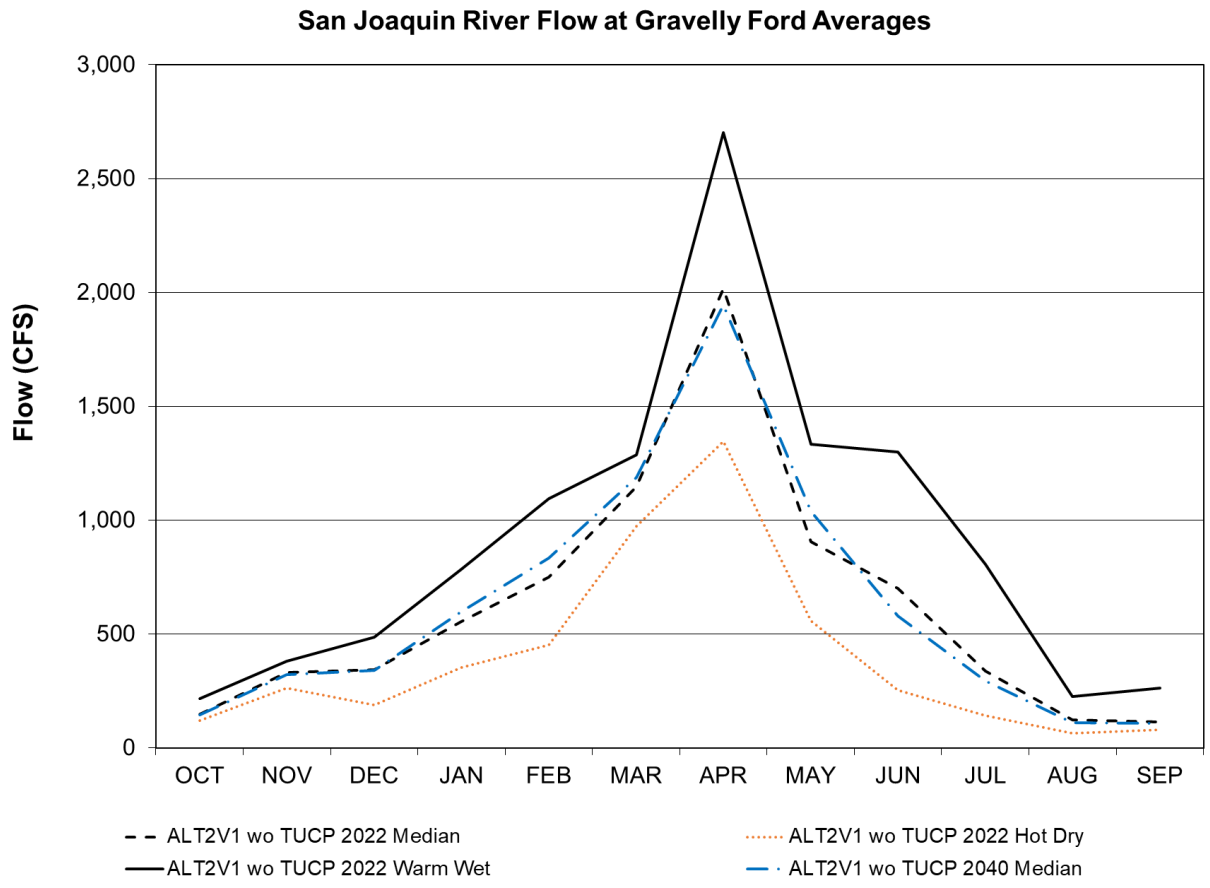

Figure 15. Long-term Average San Joaquin River flow at Gravelly Ford

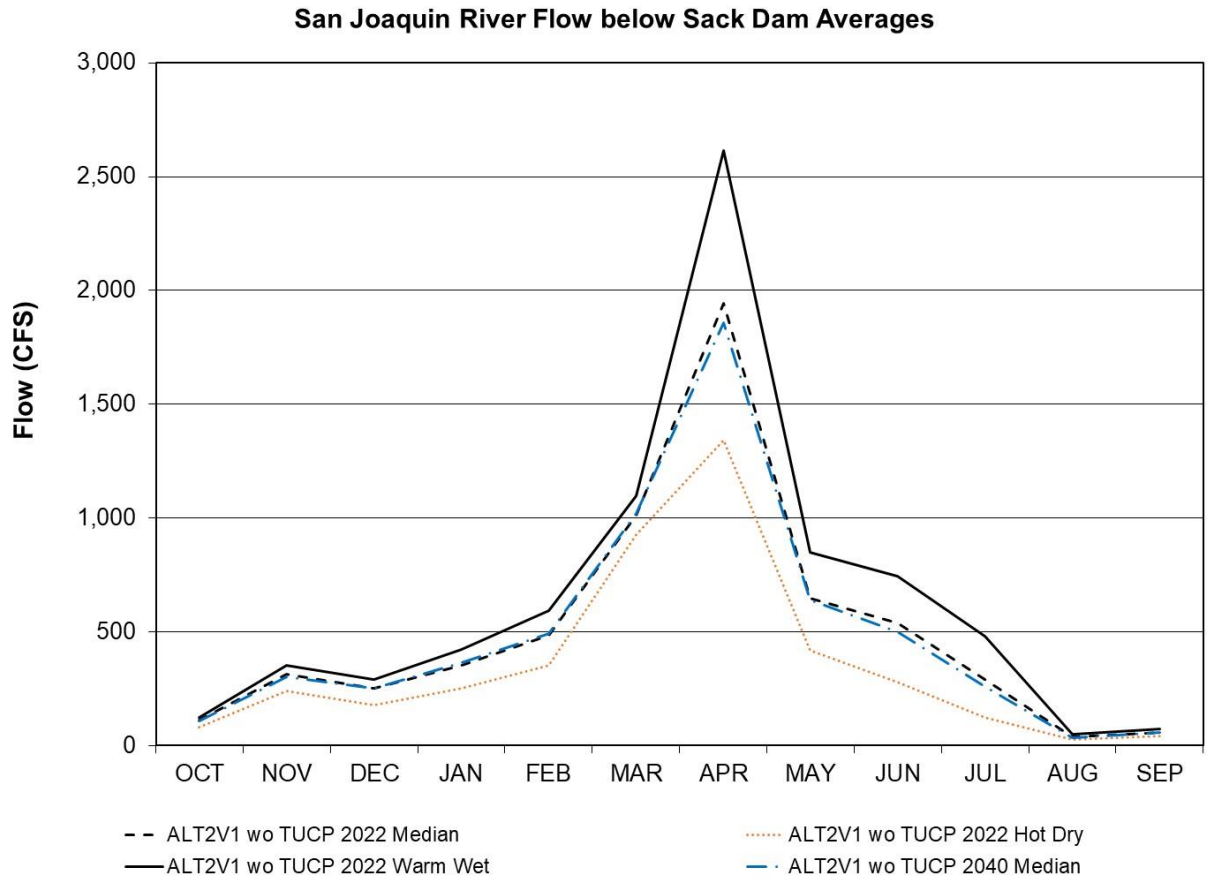

Figure 16. Long-term Average San Joaquin River flow below Sack Dam

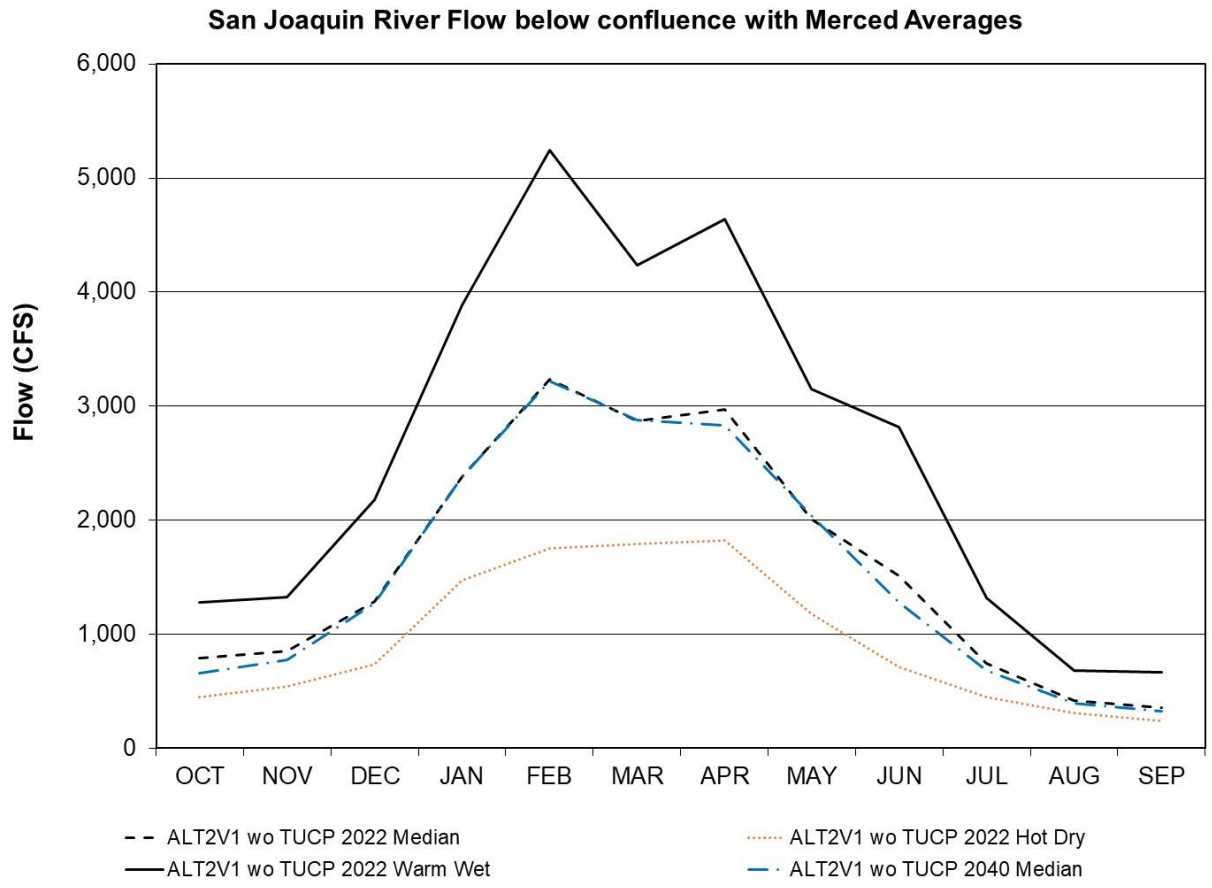

Figure 17. Long-term Average San Joaquin River flow below Confluence with Merced River

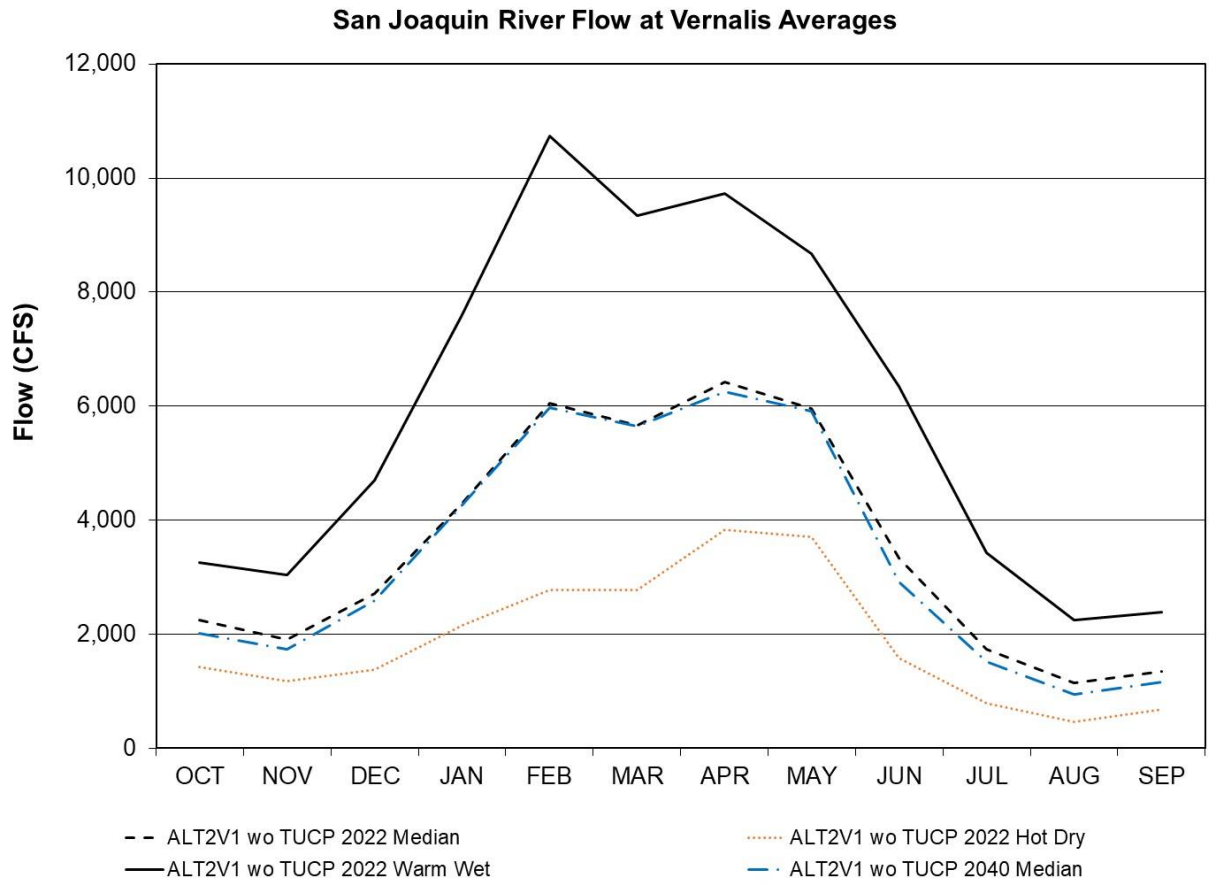

Figure 18. Long-term Average San Joaquin River flow at Vernalis

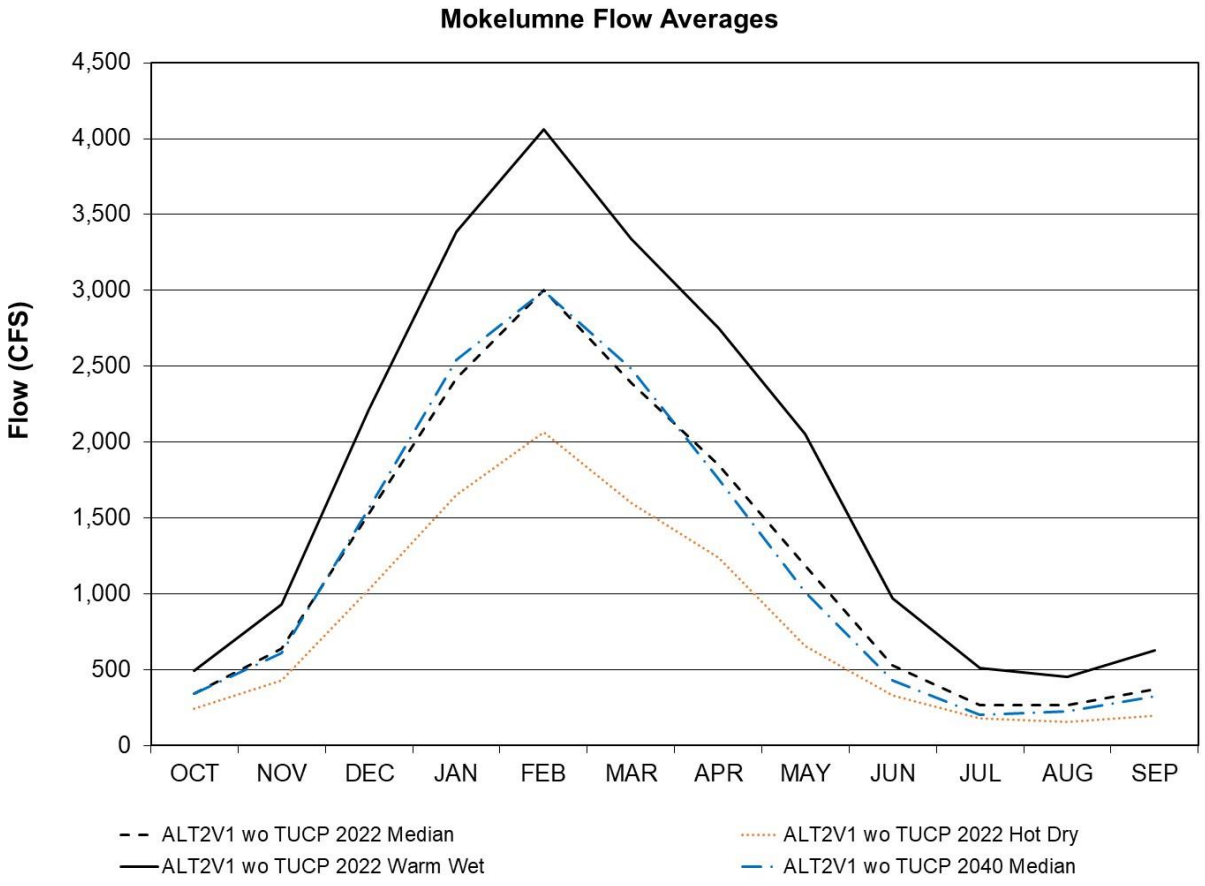

Figure 19. Long-term Average Mokelumne River Flow

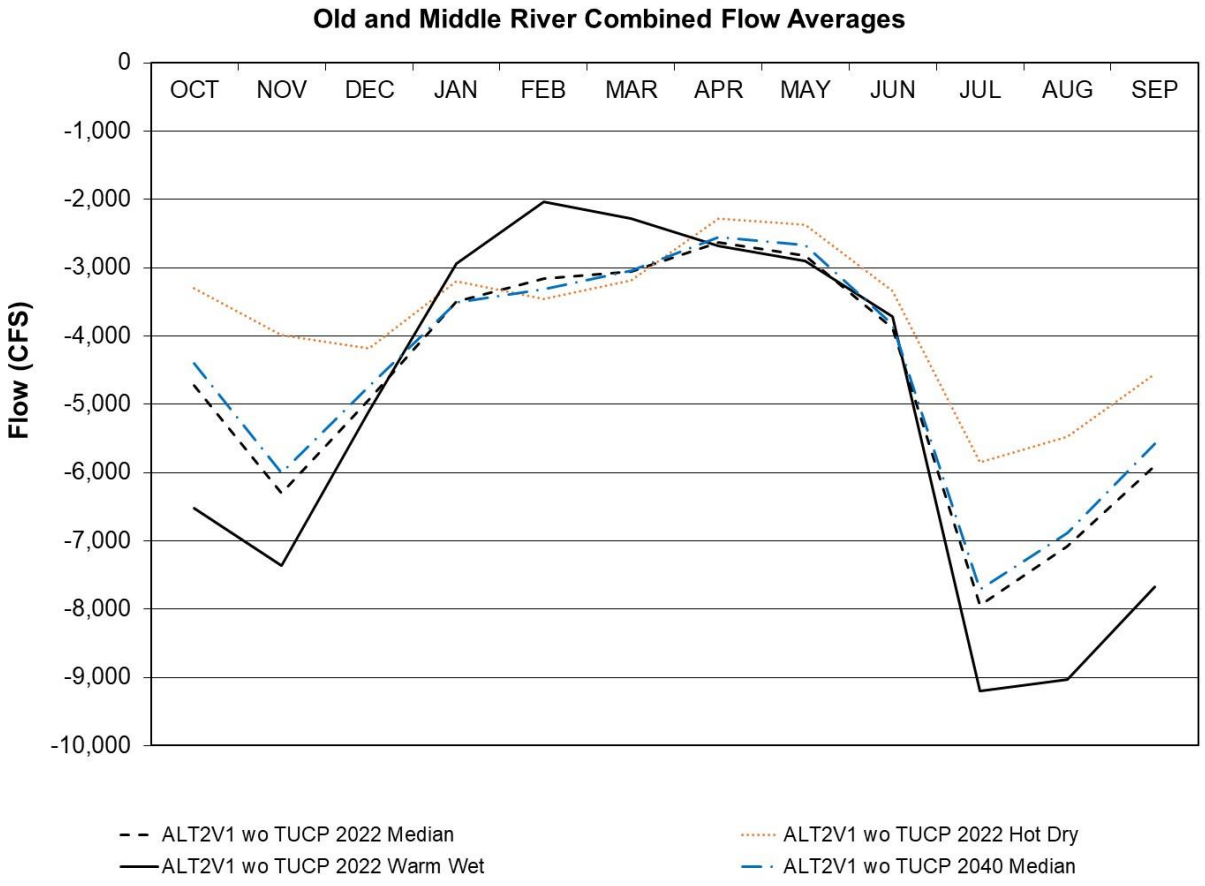

Figure 20. Long-term Average Old and Middle River Combined Flow

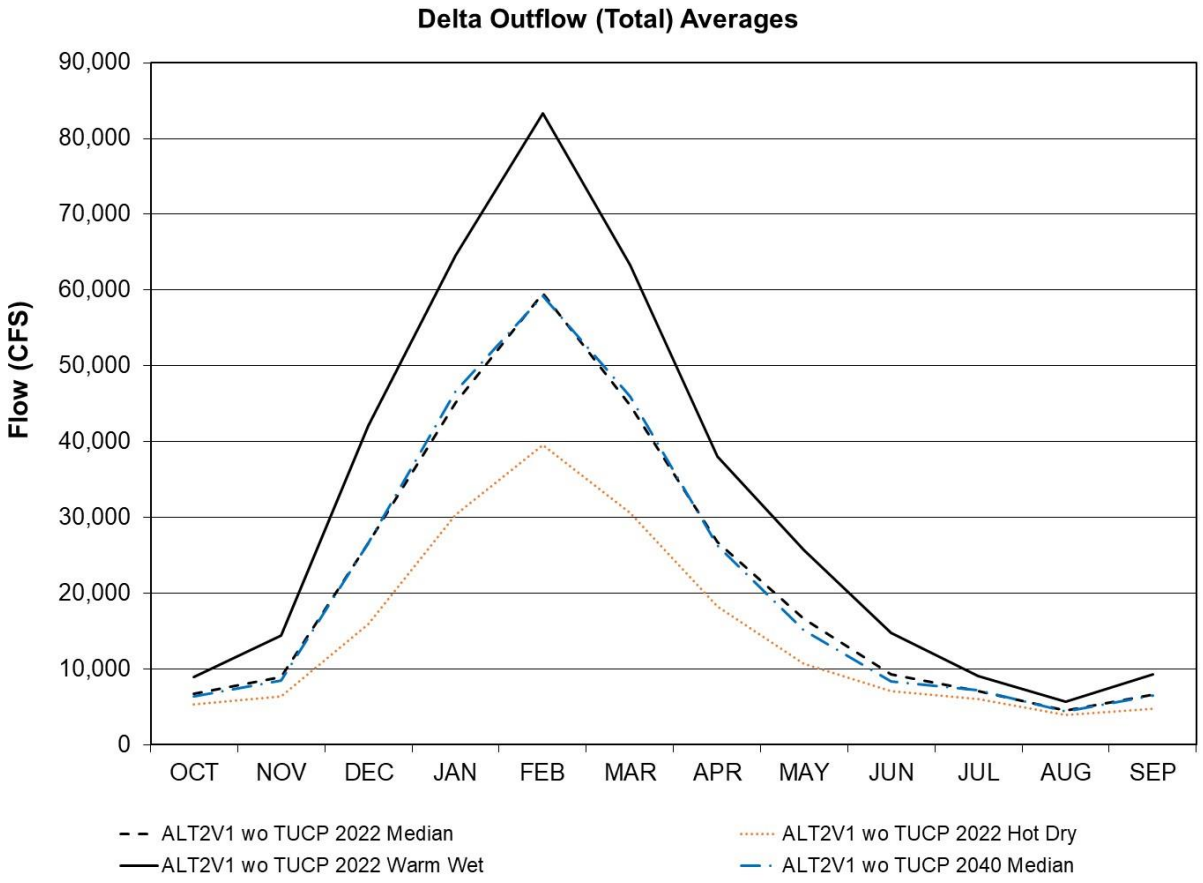

Figure 21. Long-term Average Delta Outflow

F.2-3.2.2 HEC5Q

F.2-3.2.2.1 Sacramento

Figures 22 through 27 summarize the temperature outcomes in the Sacramento River under the climate sensitivities using the Alternative 2 version 1 (2v1) without Temporary Urgency Change Petitions (TUCPs) logic. Temperature dependent mortality (TDM) was calculated using the standard LTO parameterization.

The Alternative 2v1 without TUCPs TDM estimate shown in Figure 22 demonstrates substantial climate variability. Under the 2022 Median climate scenario, TDM exceeds 60% in approximately 10% of the simulated years. Under the 2022 Warm Wet climate scenario which is cooler and wetter than the 2022 Median climate scenario, TDM exceeds 60% in approximately 3% of the simulated years. Conversely, the 2022 Hot Dry climate scenario which is warmer and drier than the 2022 Median scenario has large TDM values occur more frequently with 60% TDM occurring in approximately 40% of the simulated years. The 2040 Median scenario performs similarly to the 2022 Median scenario, albeit with an approximately 10% upward exceedance shift surrounding the 20% exceedance threshold.

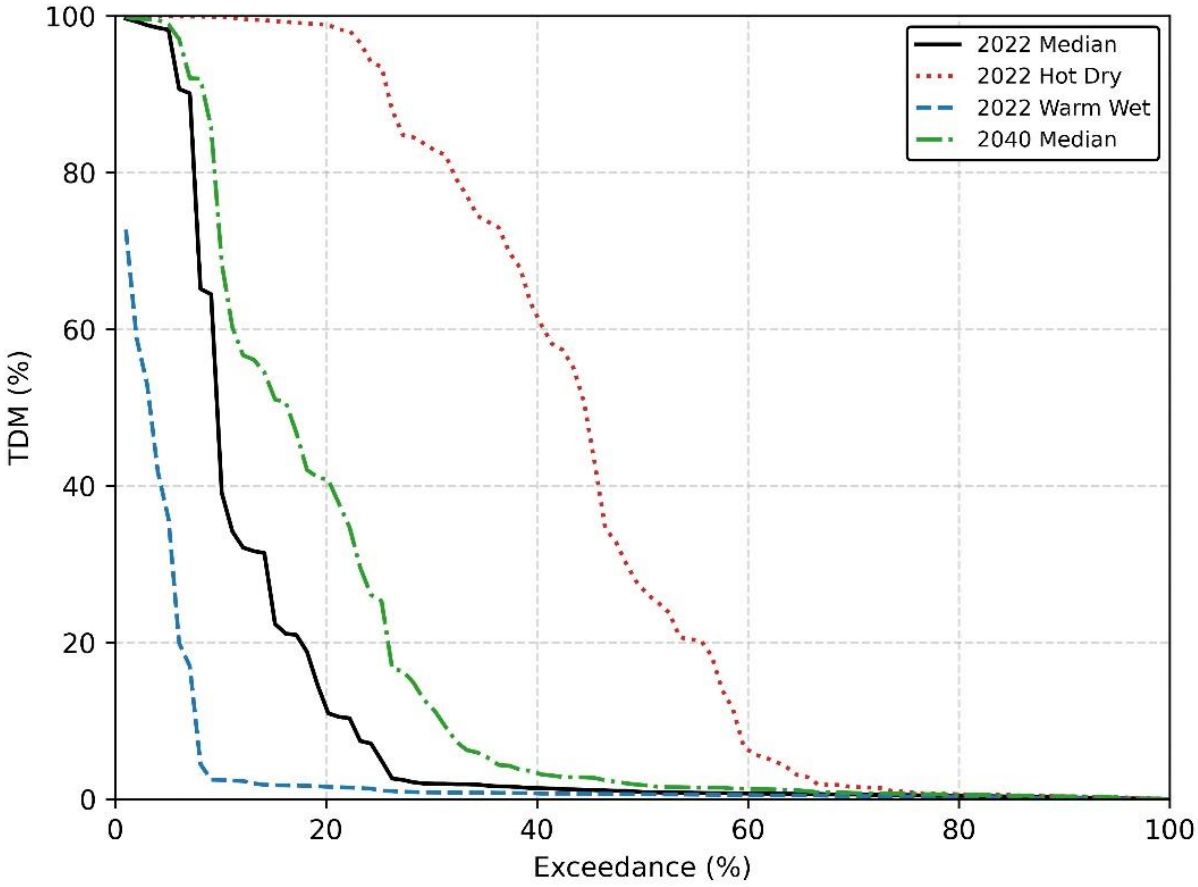

Figure 22: Martin model TDM exceedance plot for Alternative 2v1 without TUCPs under various climate assumptions for water years 1922 through 2021

The Alternative 2v1 without TUCPs TDM values are driven by the Sacramento River temperatures from Clear Creek down to Red Bluff. Figures 23 and 24 show the average and maximum May through end of October temperatures in the Sacramento River below Clear Creek with Figure 25 and 26 providing the same information for Red Bluff.

The scaling of TDM follows temperature outcomes with the 2022 Hot Dry scenario having the largest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest temperatures of the scenarios. While the scenarios have a clear incremental increase in average temperature, temperatures above the 70% exceedance threshold are largely similar. An analogous trend is visible in Figure 27 with the volume of water less than 52 degrees Fahrenheit (°F) at the end of April. More cold water correlates with lower TDMs across the climate scenarios. However, despite having generally similar cold-water volumes, the 2040 Median condition exhibits worse TDM outcomes than the 2022 Median, likely due to the roughly degree higher average temperatures under the 2040 Median scenario. The higher average temperatures under the 2040 Median scenario are likely due in part to the greater in-stream and reservoir warming.

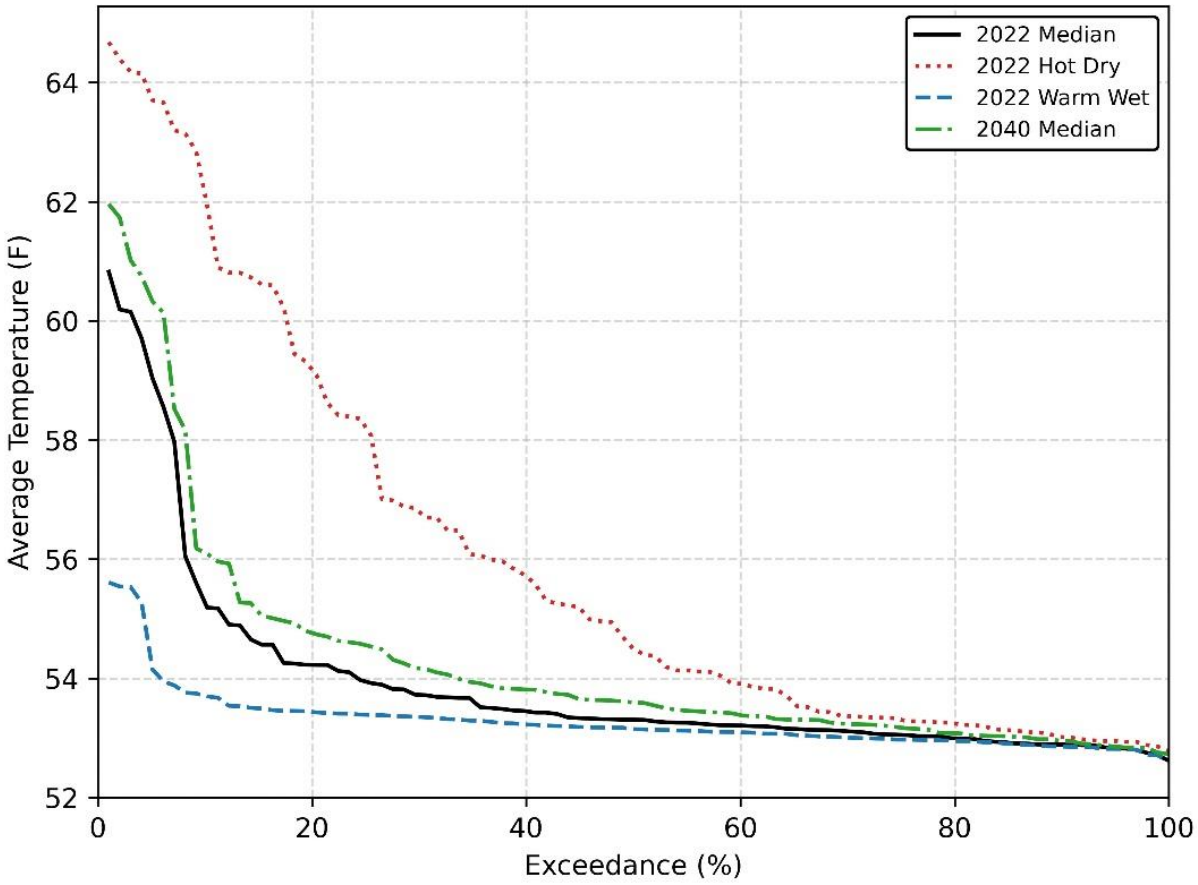

Figure 23: Average May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2020

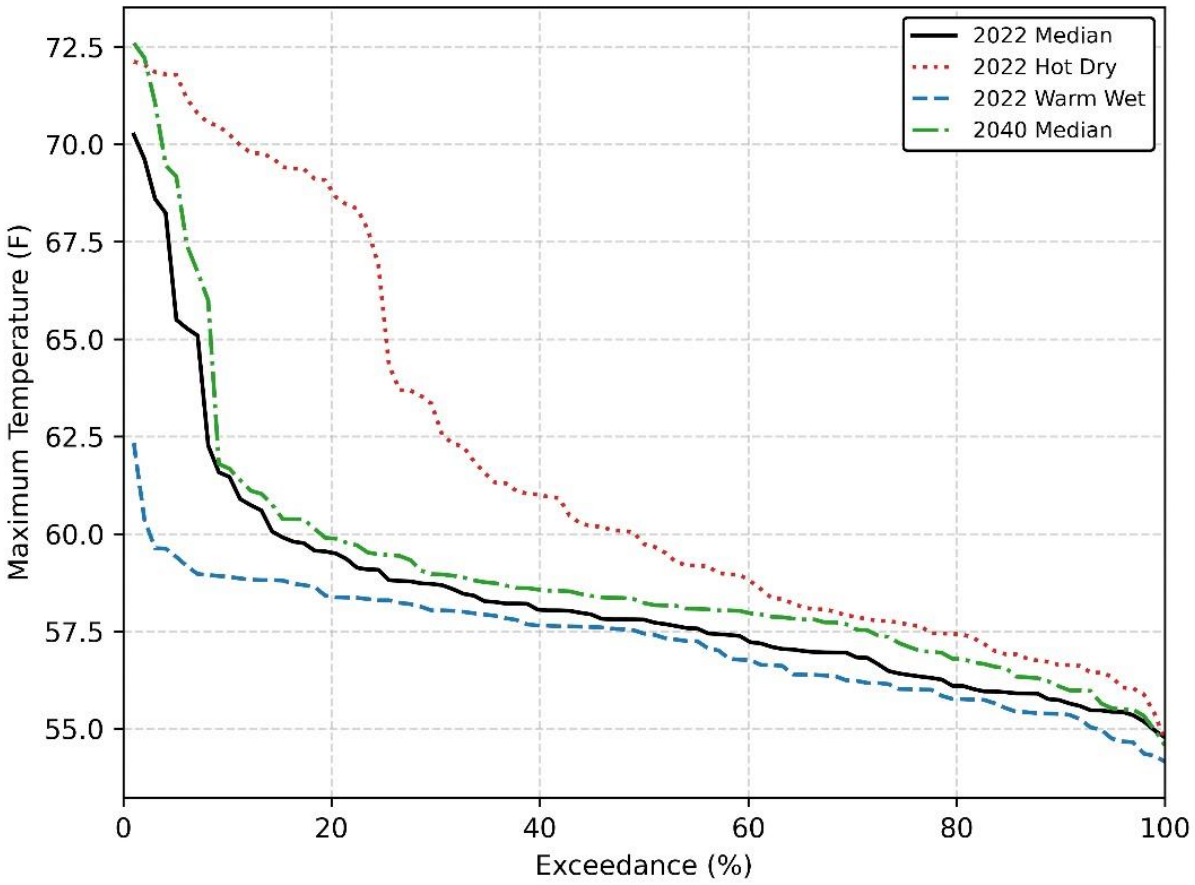

Figure 24: Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2020

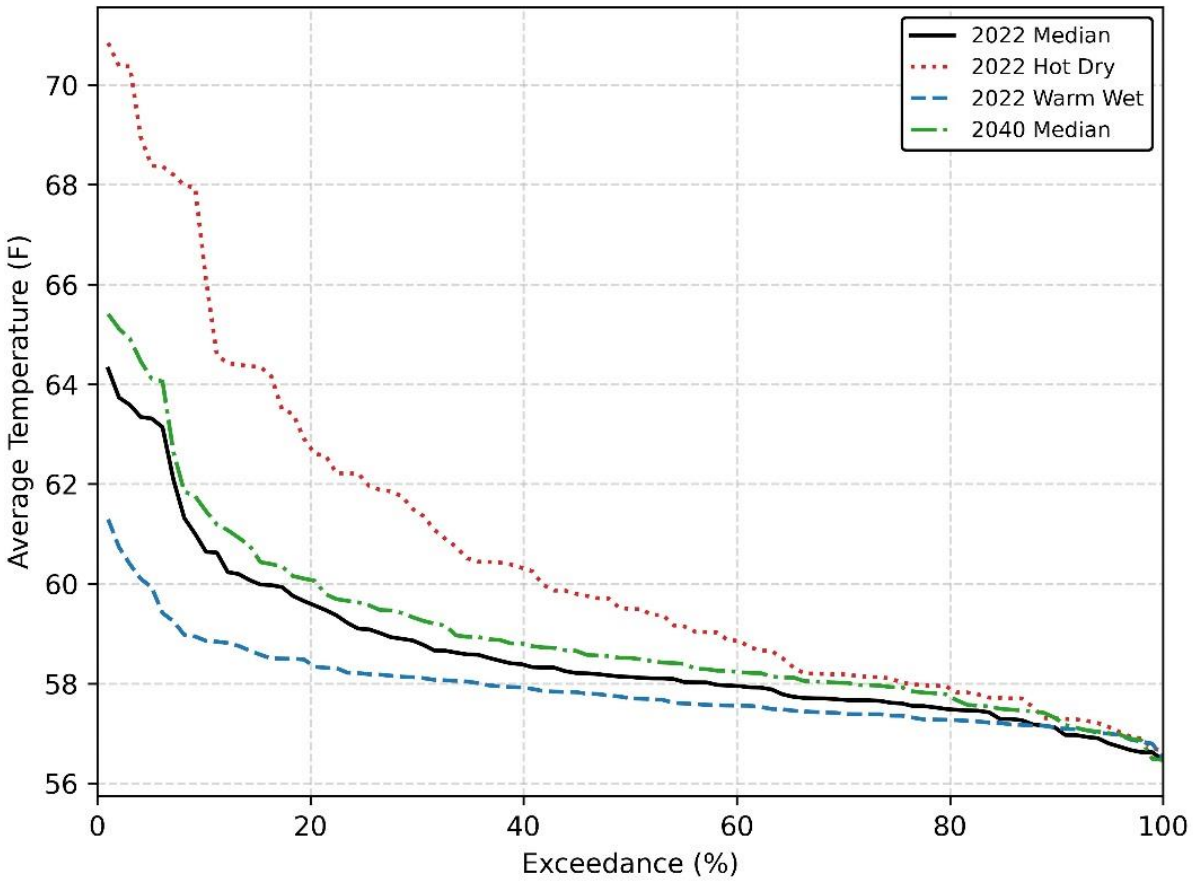

Figure 25: Average May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2020

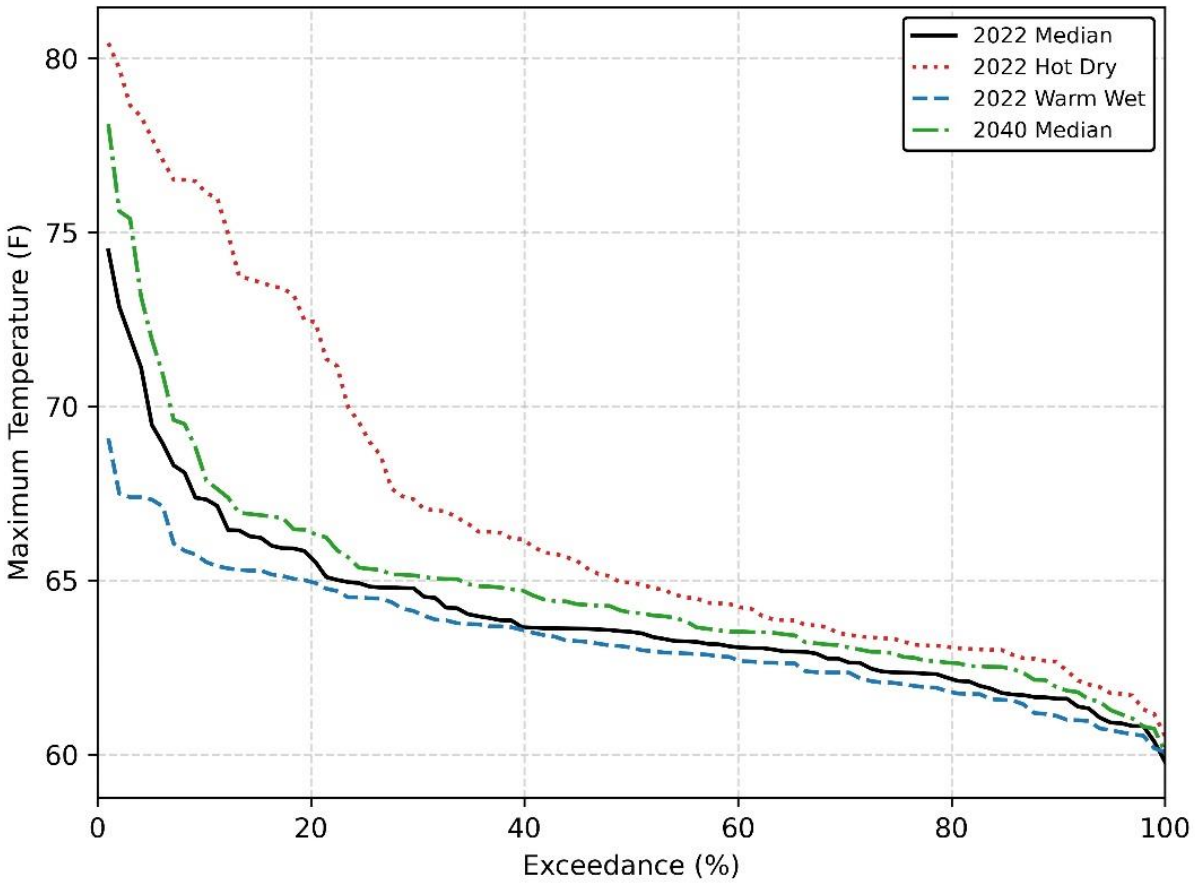

Figure 26: Maximum May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2020

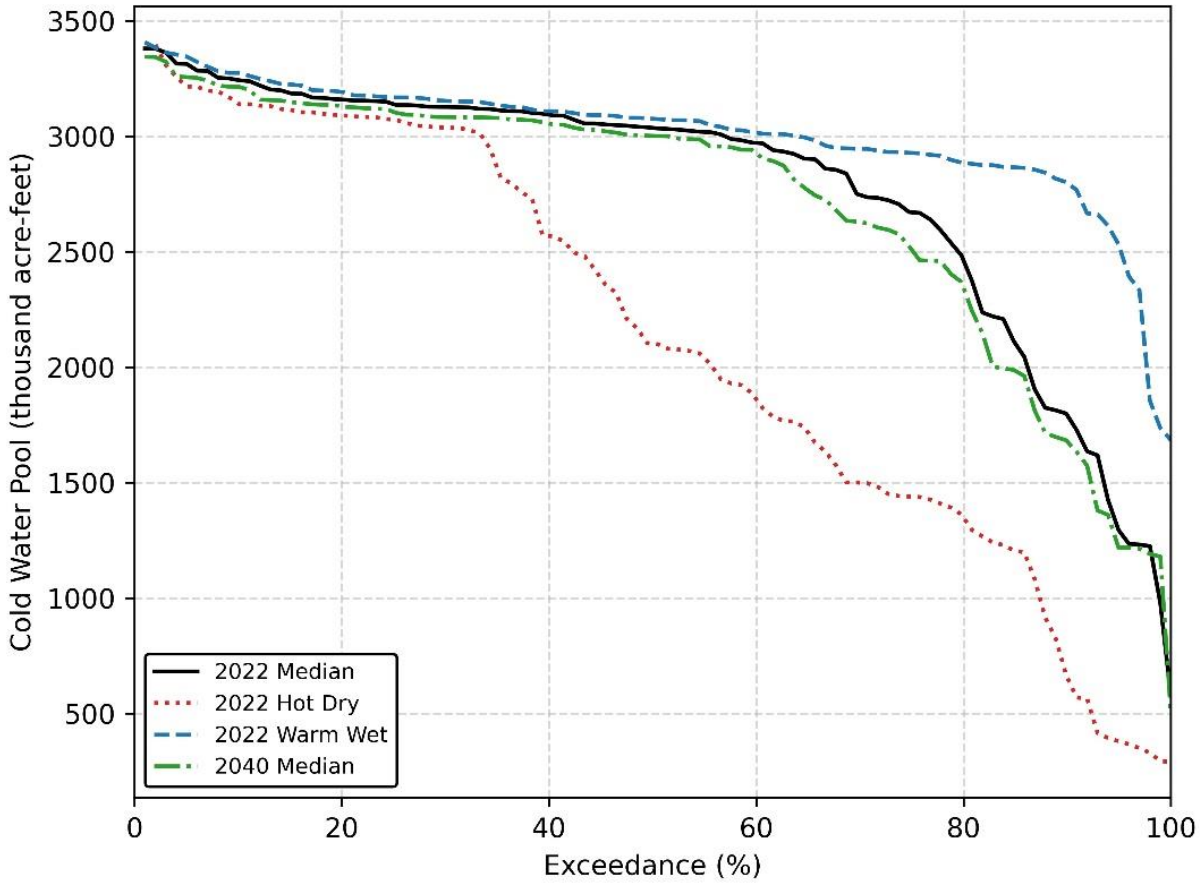

Figure 27: Volume of water at the end of April less than 52°F in Shasta Lake for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2021

F.2-3.2.2.2 American

Figures 28 through 30 evaluate the temperature outcomes in the American River under the climate sensitivities using the Alternative 2v1 without TUCPs logic. The 2022 Hot Dry scenario has the highest average and maximum temperatures at low exceedances. At high exceedances, both the 2022 Hot Dry and 2040 Median scenarios have the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. Figure 30 shows the volume of water less than 52 °F at the end of April in Folsom Lake. The 2022 Hot Dry scenario has the lowest volumes of cold-water and the 2022 Warm Wet scenario has the highest volumes of cold-water. Despite the 2022 Median and 2040 Median having similar volumes of cold-water, the 2040 scenario exhibits higher average and maximum temperatures likely due in part to the greater in-stream and reservoir warming.

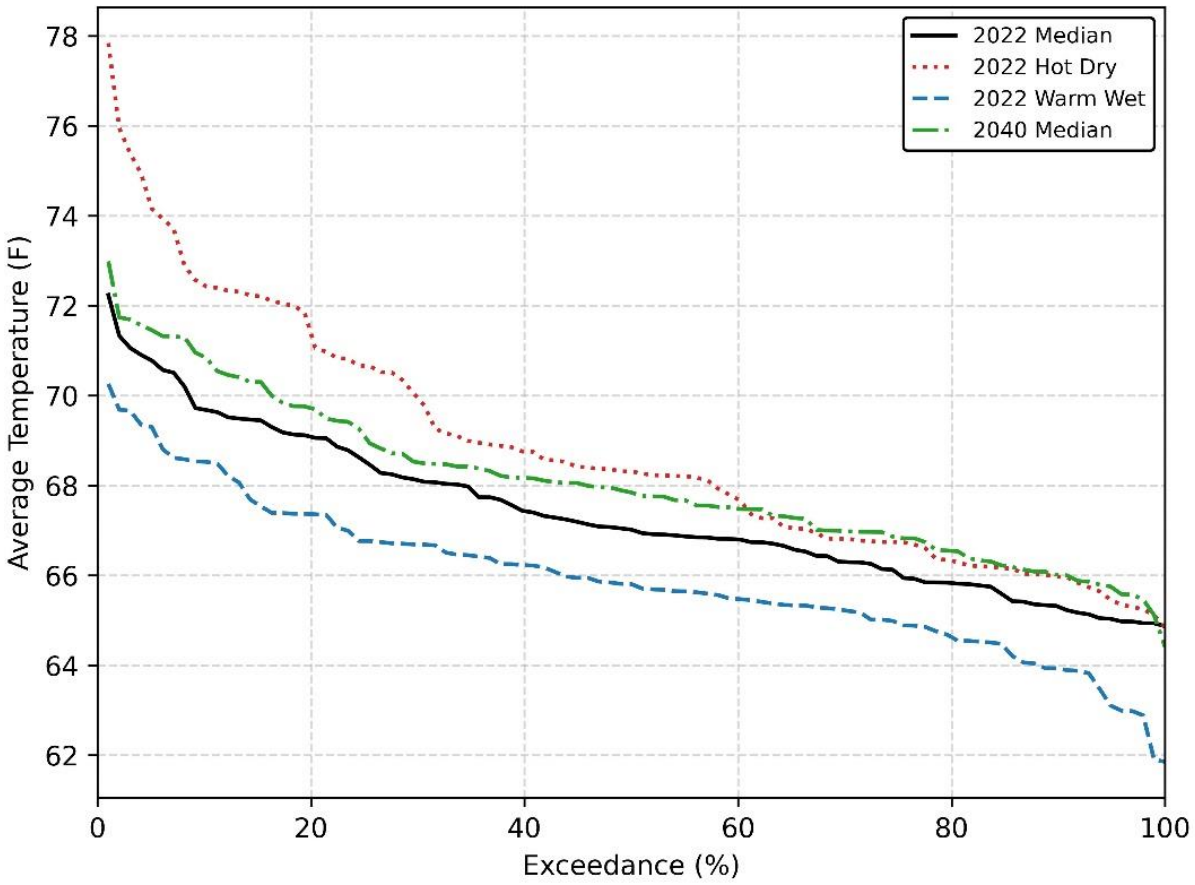

Figure 28: Average May through end of October temperatures on the American River at Watt Avenue for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2020

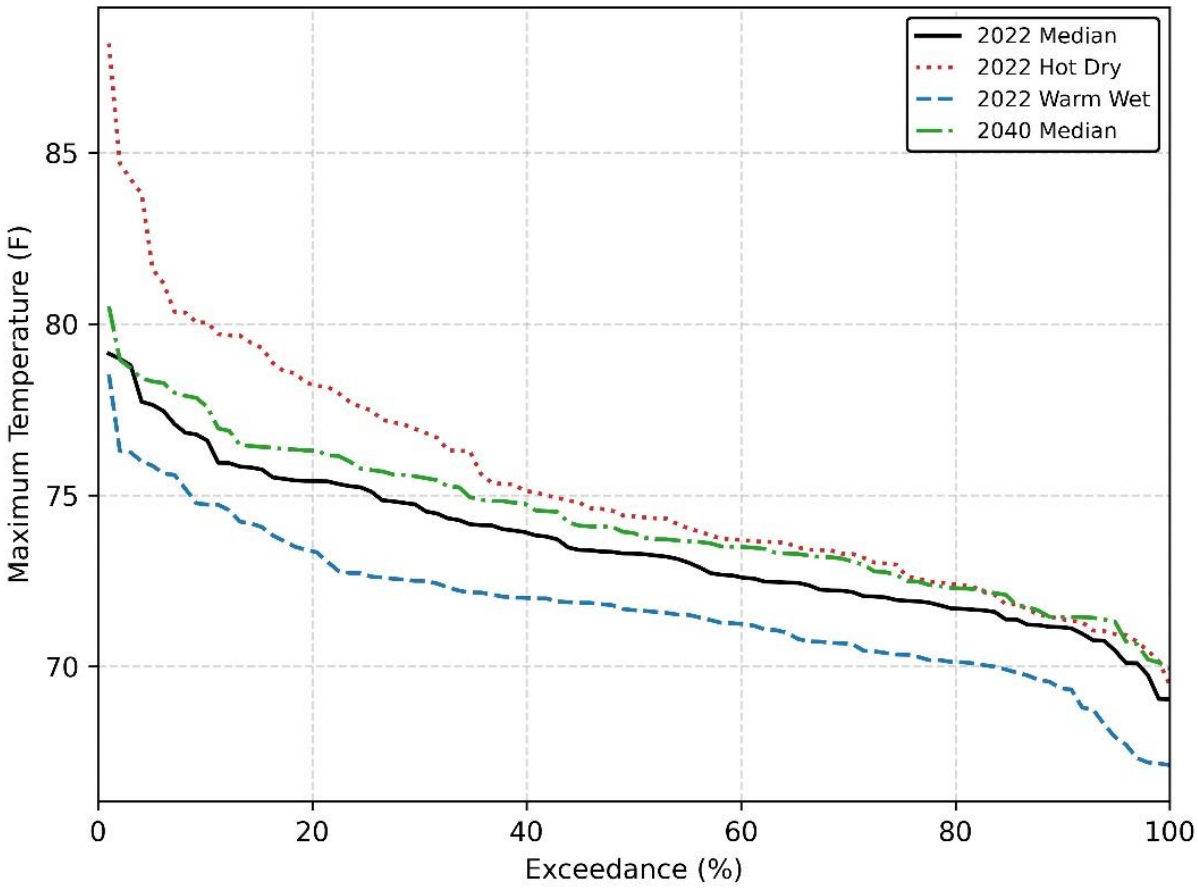

Figure 29: Maximum May through end of October temperatures on the American River at Watt Avenue for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2020

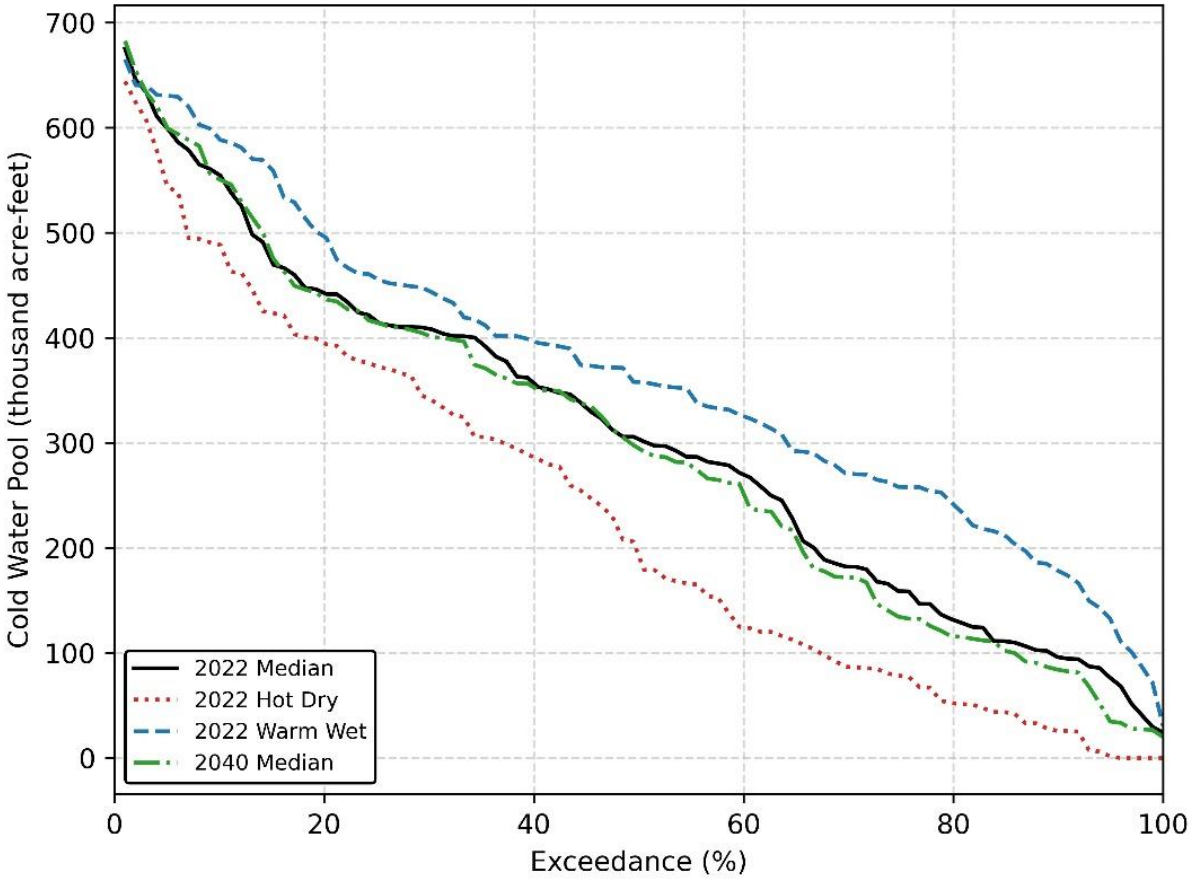

Figure 30: Volume of water at the end of April less than 52 °F in Folsom Lake for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2021

F.2-3.2.2.3 Stanislaus

Figures 31 and 32 evaluate the temperature outcomes in the Stanislaus River under the climate sensitivities using the Alternative 2v1 without TUCPs logic. The 2022 Hot Dry scenario has the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures. The 2040 Median temperatures are slightly higher than the 2022 Median due to instream warming.

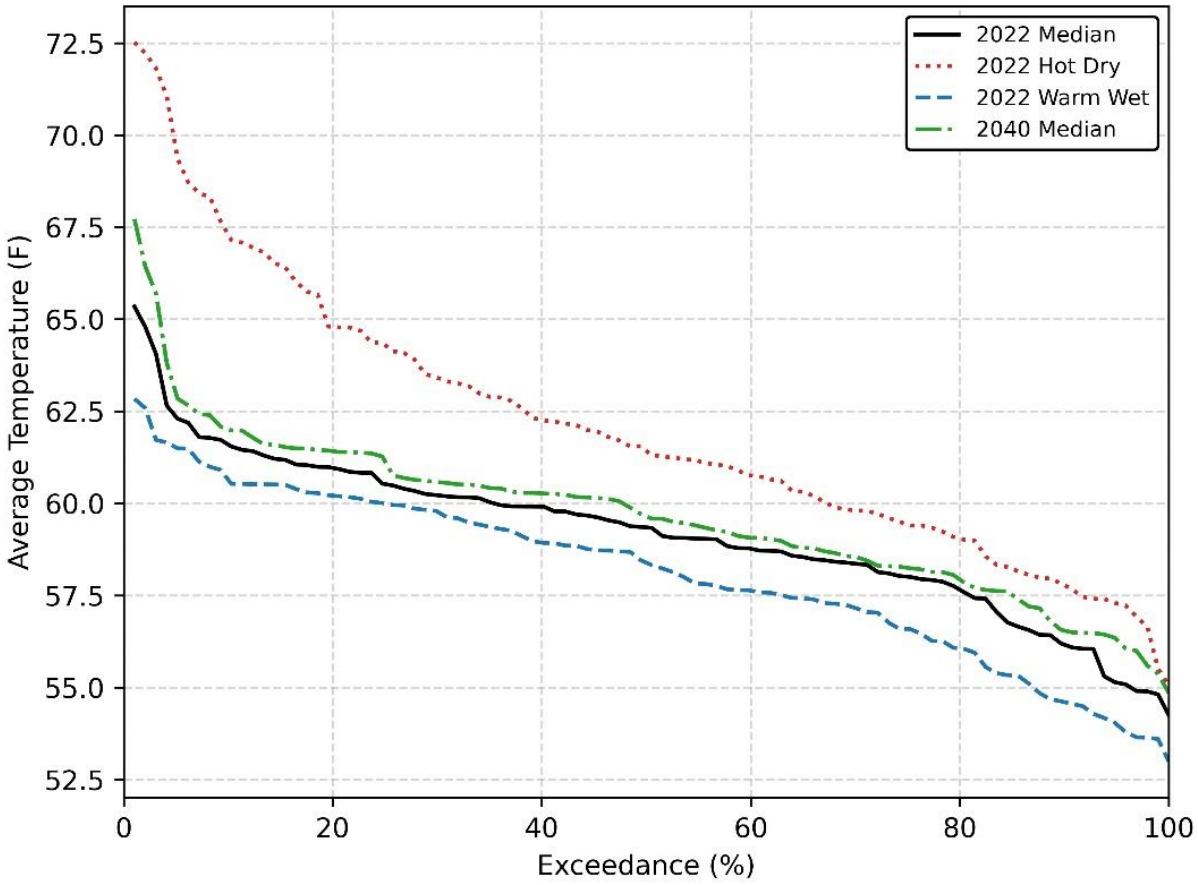

Figure 31: Average May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2019

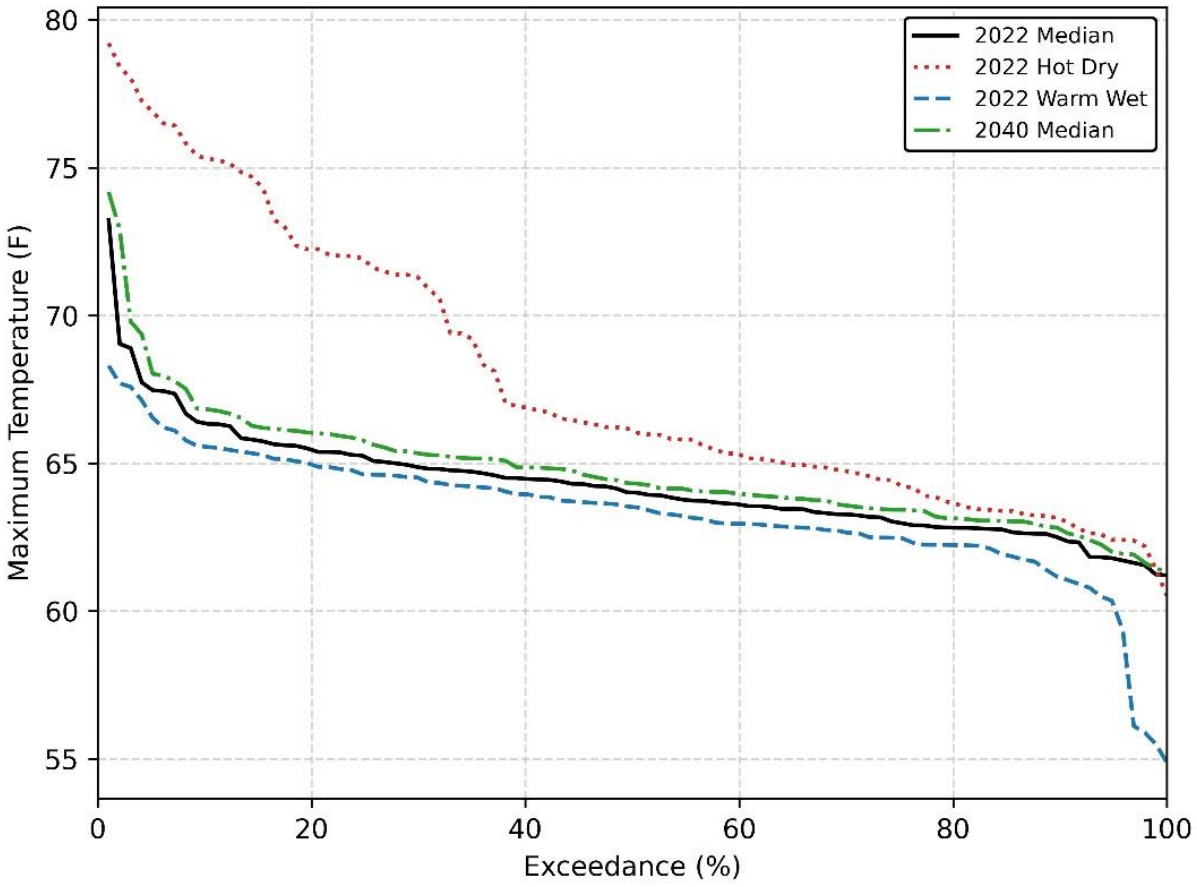

Figure 32: Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 2v1 without TUCPs under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Appendix F.2-4 Climate Sensitivity Analysis, Alternative 2 v1 with TUCP

F.2-4.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative 2 without Voluntary Agreement and with TUCPs (Alt 2v1 w TUCP) under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-4.2 Climate Change Comparison

F.2-4.2.1 CalSim 3

Figure F.2-4-1 through Figure F.2-4-21 show CalSim 3 simulation results for Alternative 2v1 w TUCP. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 2v1 w TUCP were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough
- Sacramento River at Verona

- Sacramento River at Freeport
- Flow though Yolo Bypass
- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-4-1) and end of September (Figure F.2-4-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 10% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows, long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of reservoir management season, the differences are less notable. Summer months are commonly when river flows are due primarily to releases from storage instead of runoff events. Flows under 2040 Median climate are similar to flows under 2022 Median climate.

Clear Creek below Whiskeytown (Figure F.2-4-9) flow changes are similar to the changes observed in the Sacramento River watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in fall and winter months. For Spring Creek inflow to Keswick Reservoir (Figure F.2-4-10), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-4-11) and end of September (Figure F.2-4-12 Folsom storage is higher under 2022 Warm and Wet and lower

under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-4-13), changes to flow are similar to the changes in the Sacramento watershed. In all months, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May and June due to lower Folsom inflows in spring months. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. As compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in January of 2040 Median conditions due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-4-14), changes are similar to the changes in the Sacramento watershed. Flows across all climate conditions are most in June and July, months when releases consist of stored water. Otherwise, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows.

For long-term monthly average San Joaquin River flows, changes to flow are similar to the changes in the Sacramento watershed. San Joaquin River at Gravelly Ford (Figure F.2-4-15) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam (Figure F.2-4-16) are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced (Figure F.2-4-17).

For long-term monthly average flows in the Delta (Figure F.2-4-18 through Figure F.2-4-21), changes are generally similar to the changes in the Sacramento watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows. Flows across all climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure F.2-4-20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

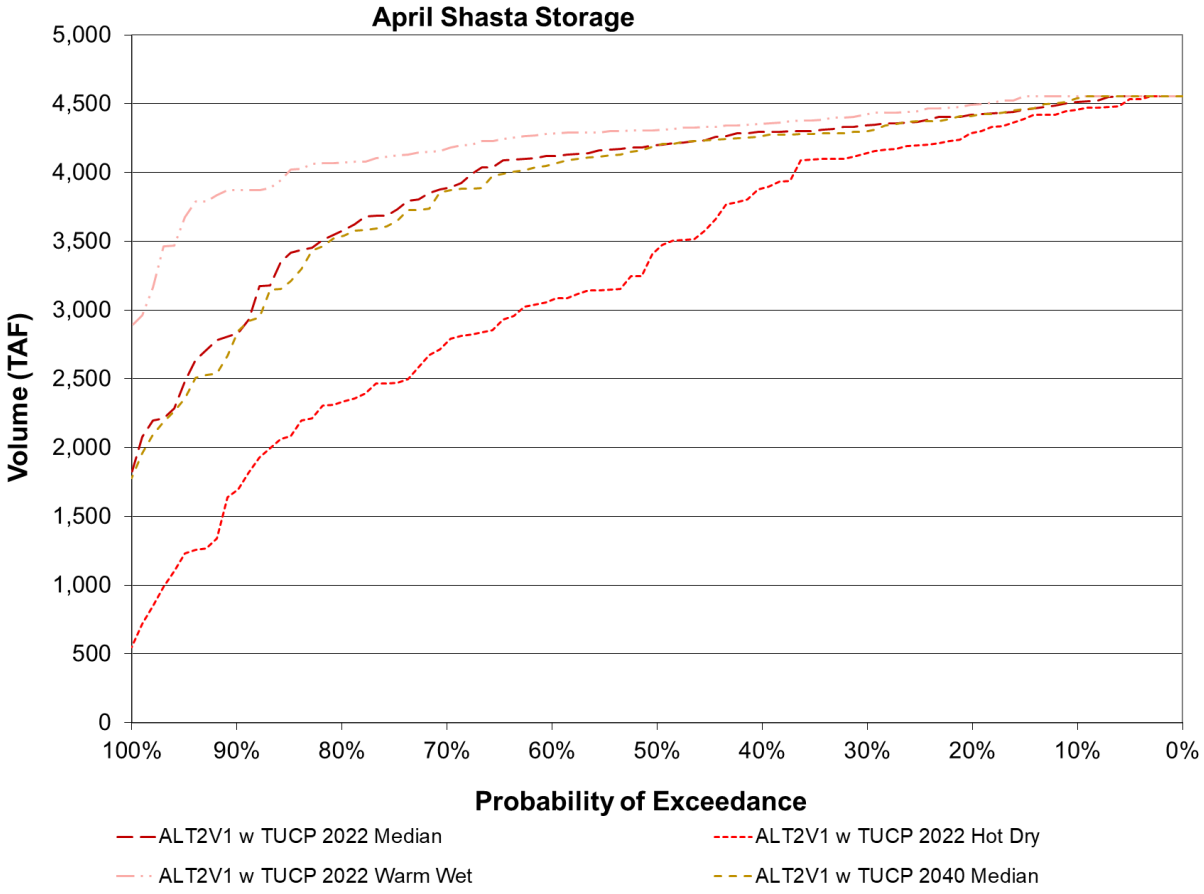

Figure F.2-4-1. End of April Shasta Storage

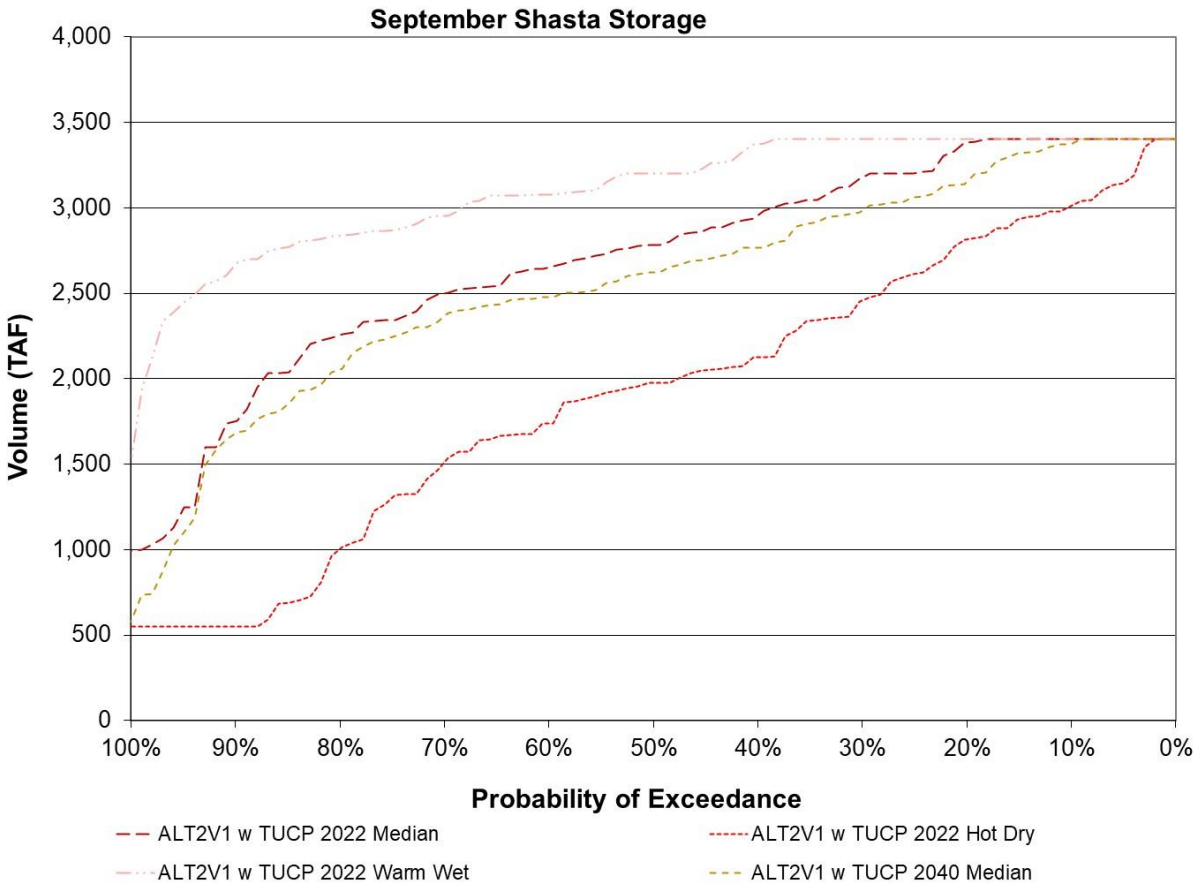

Figure F.2-4-2. End of September Shasta Storage

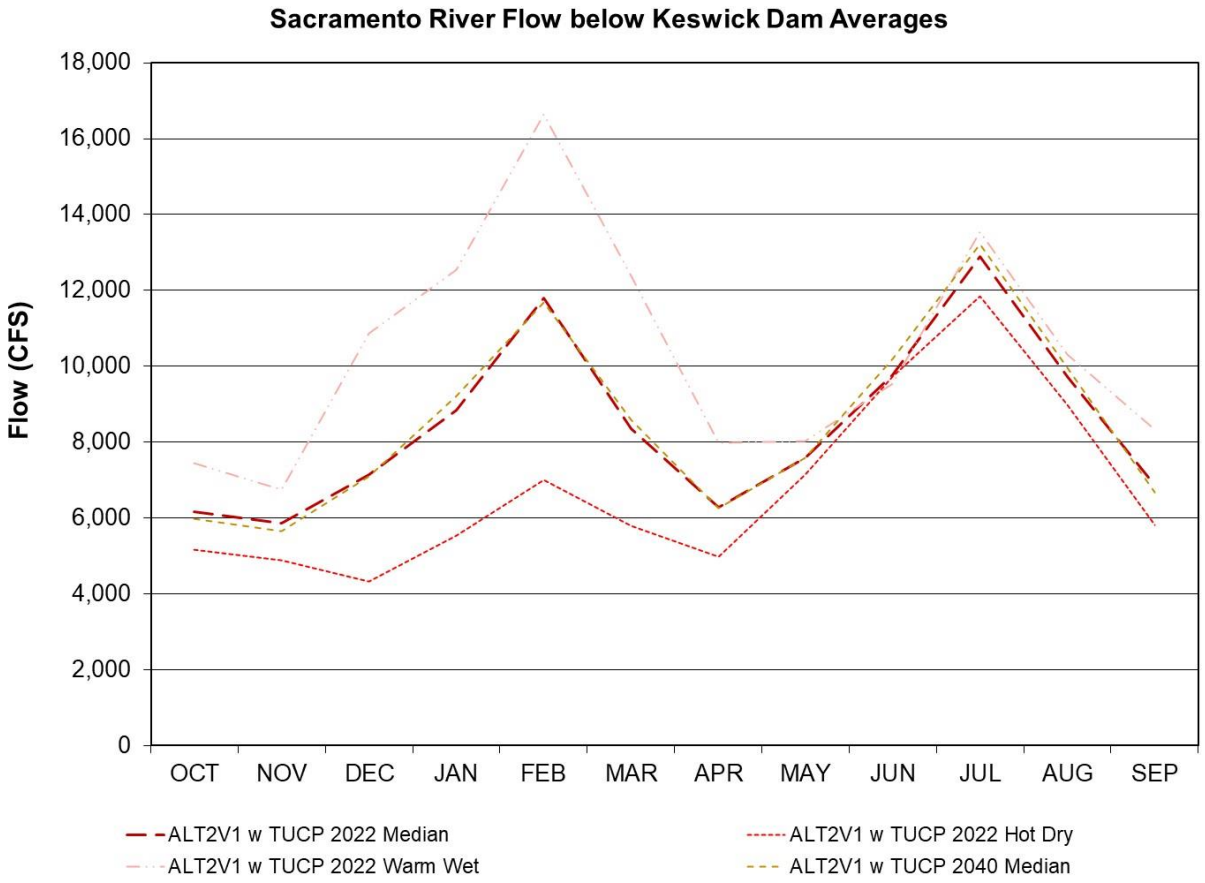

Figure F.2-4-3. Long-term Average Sacramento River flow below Keswick Dam

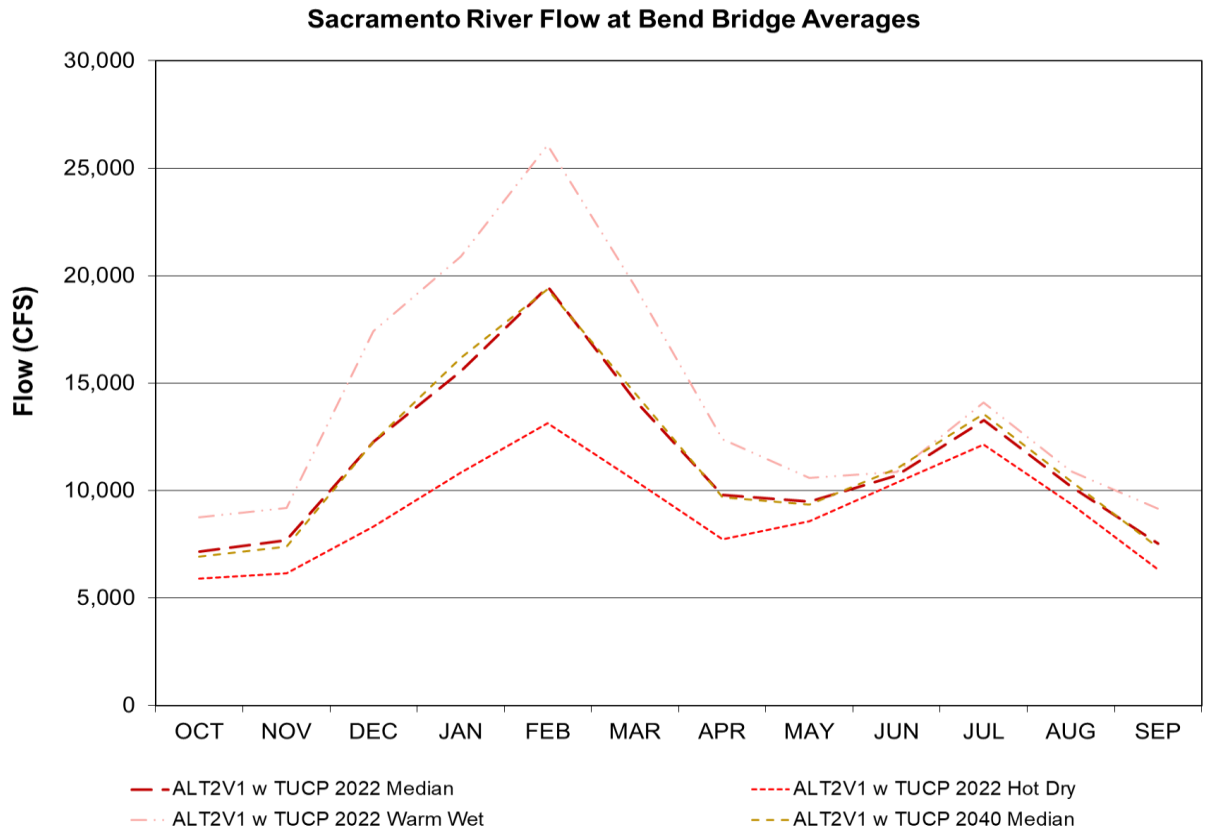

Figure F.2-4-4. Long-term Average Sacramento River flow at Bend Bridge

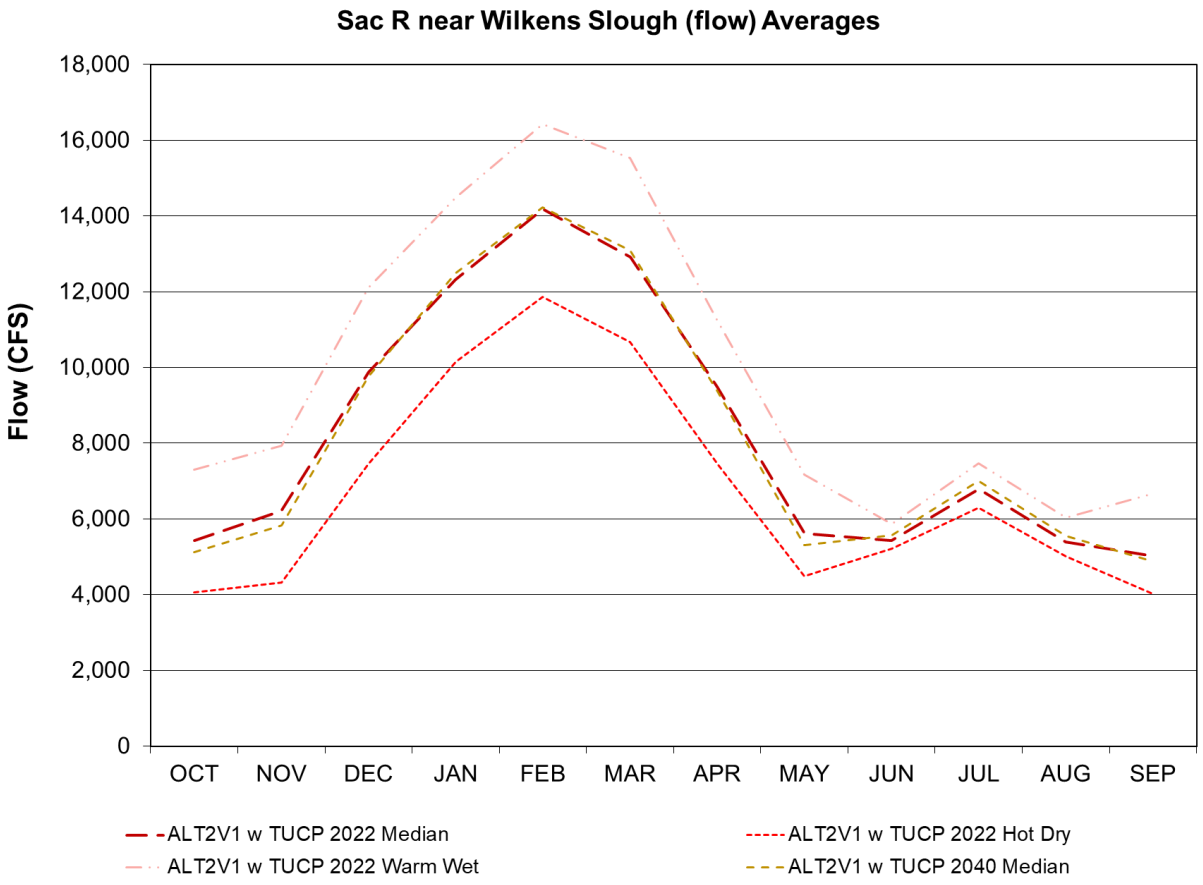

Figure F.2-4-5. Long-term Average Sacramento River flow near Wilkins Slough

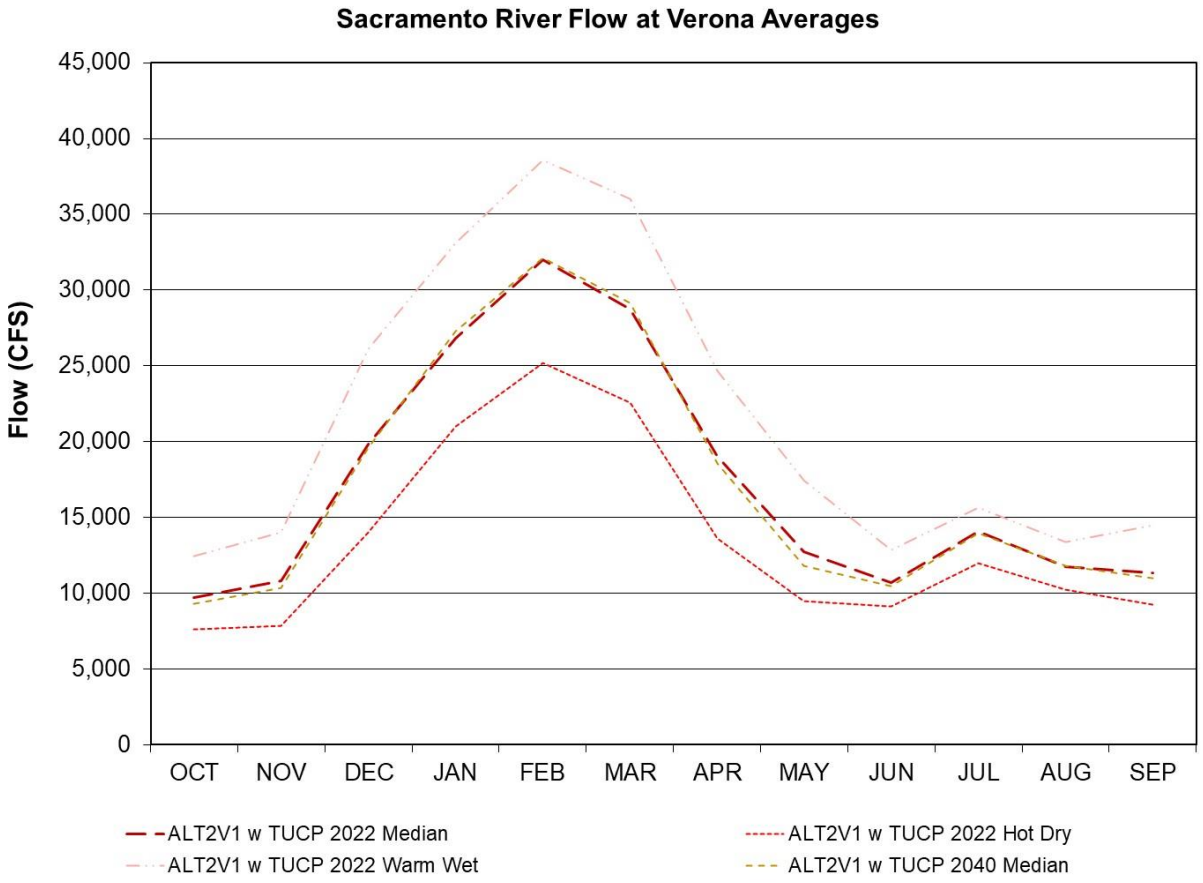

Figure F.2-4-6. Long-term Average Sacramento River flow at Verona

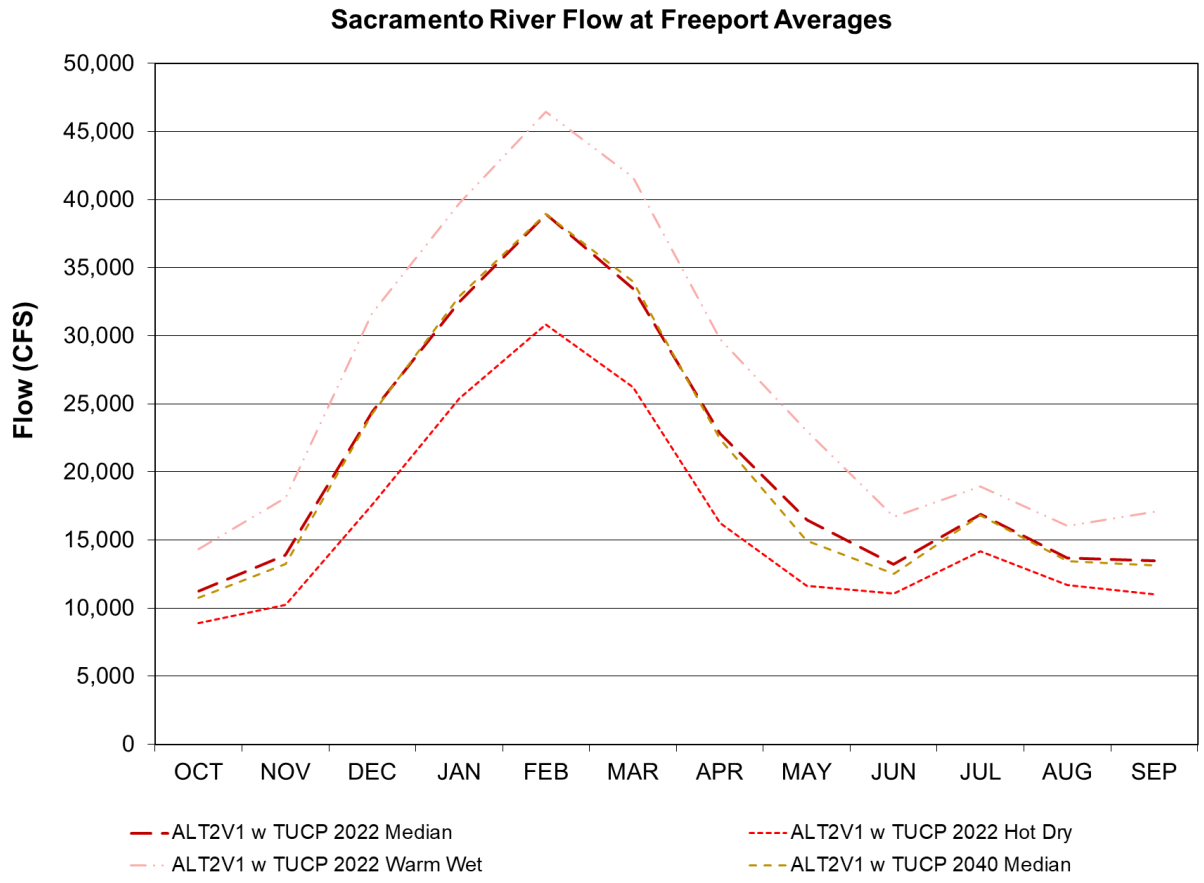

Figure F.2-4-7. Long-term Average Sacramento River flow at Freeport

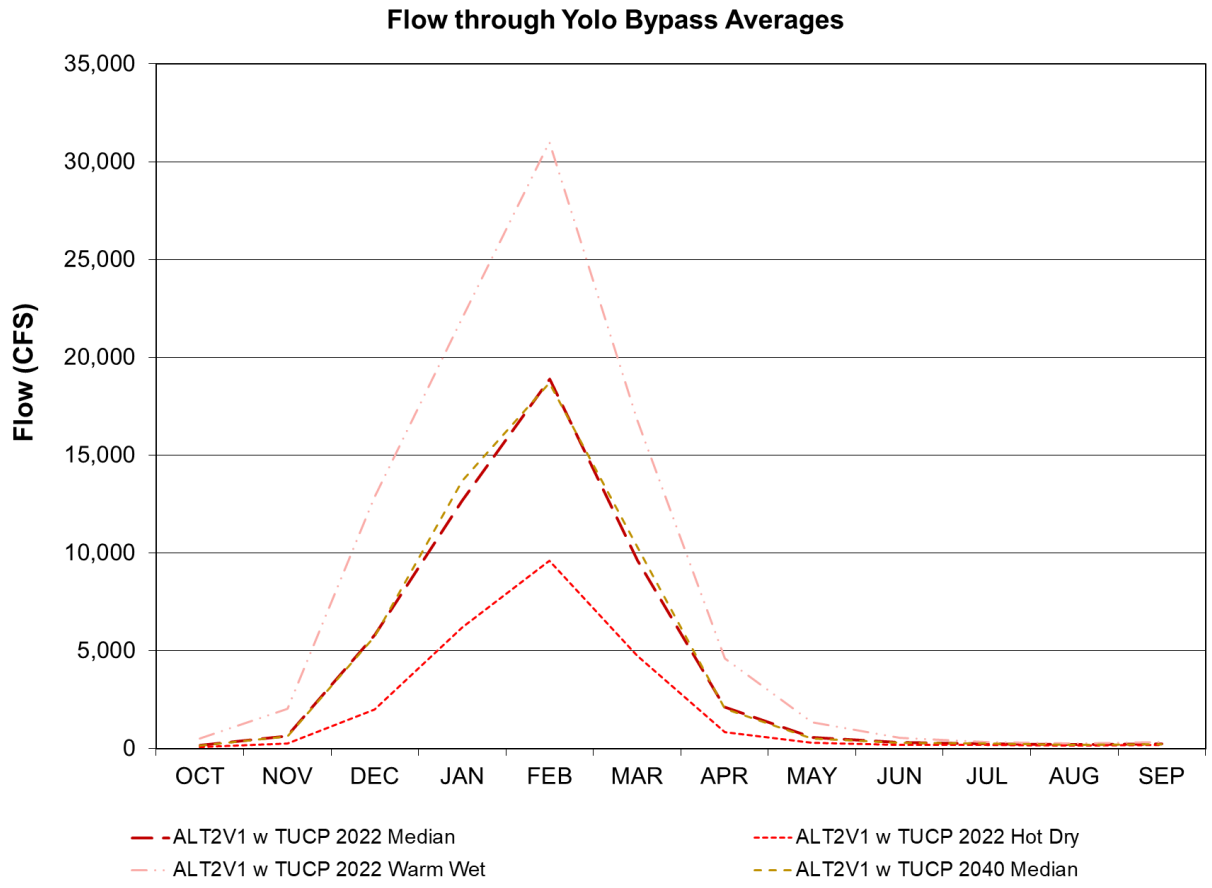

Figure F.2-4-8. Long-term Average Yolo Bypass Flow

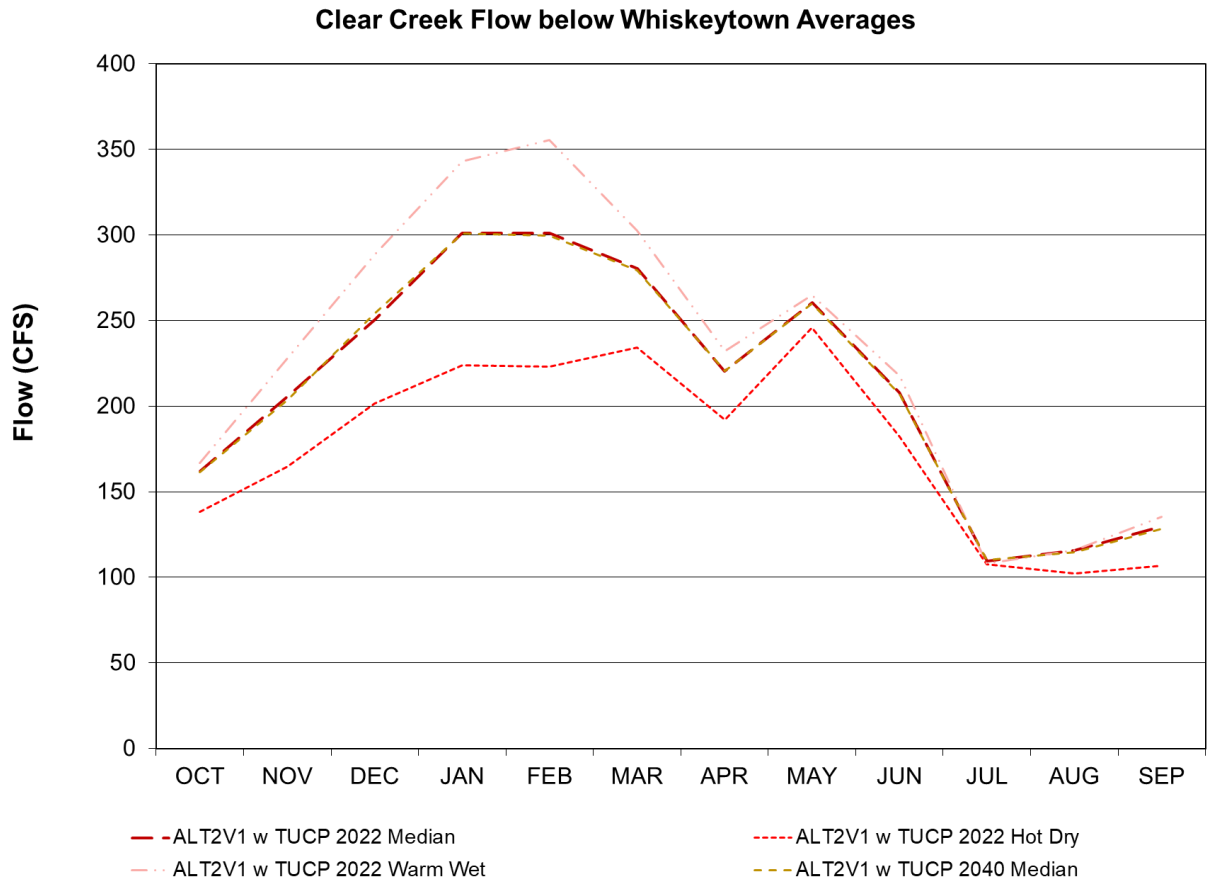

Figure F.2-4-9. Long-term Average Clear Creek flow below Whiskeytown

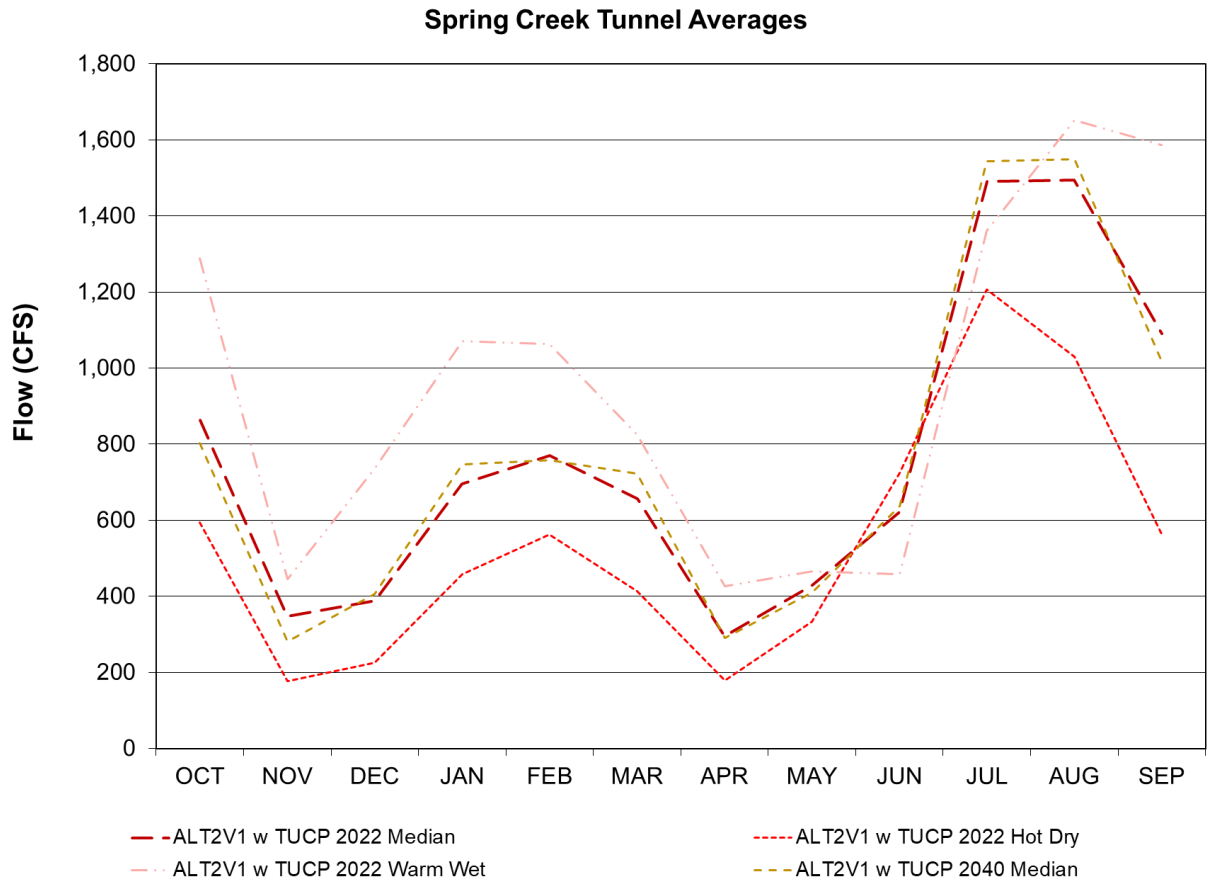

Figure F.2-4-10. Long-term Average Spring Creek Tunnel Flow

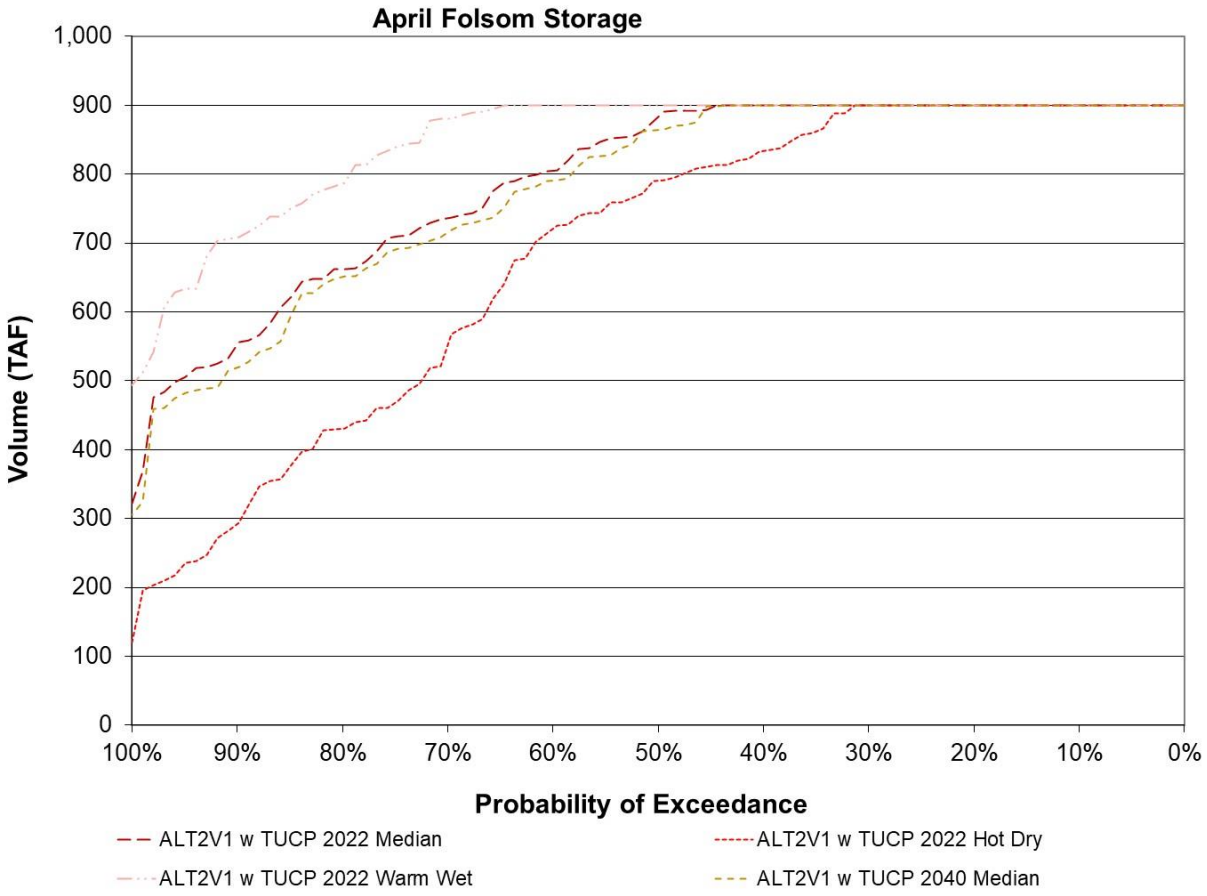

Figure F.2-4-11. End of April Folsom Storage

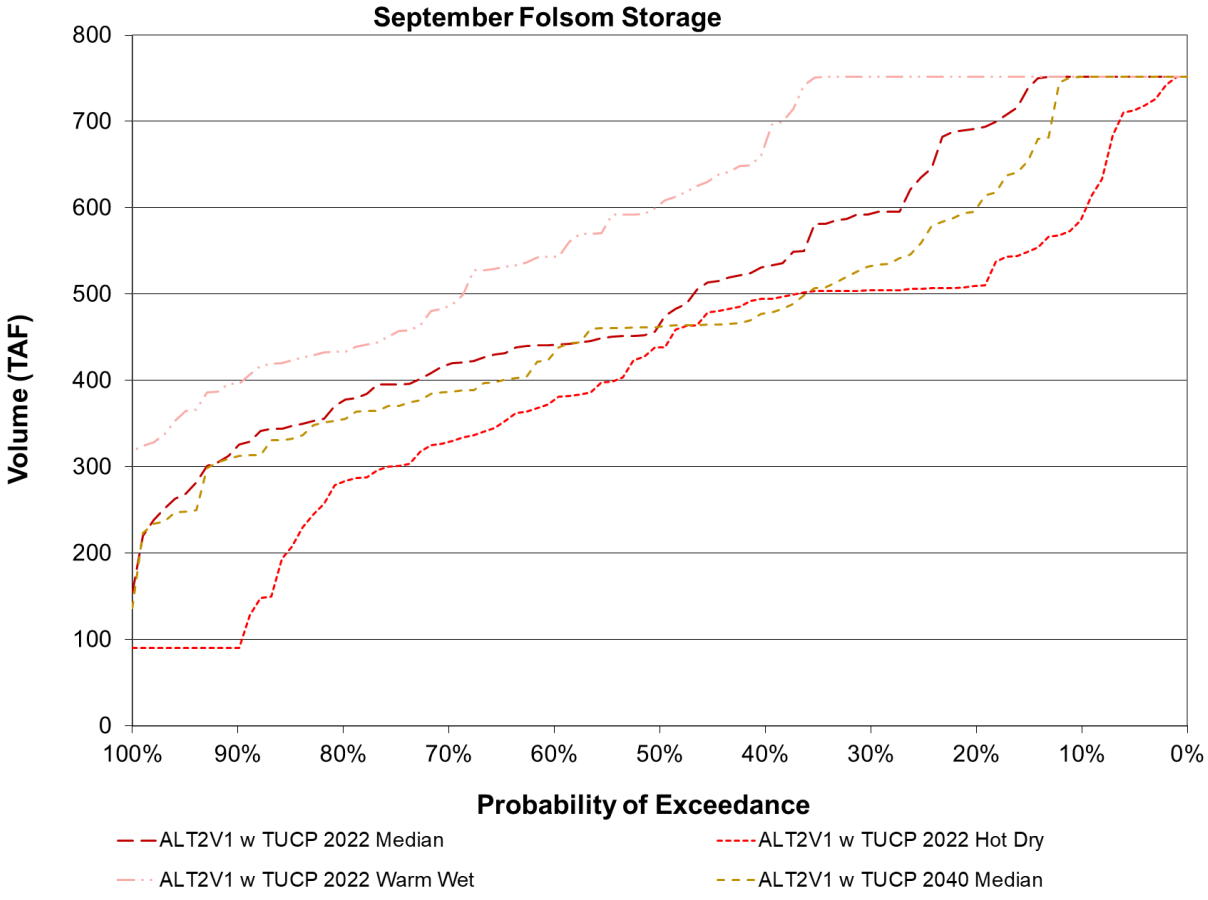

Figure F.2-4-12. End of September Folsom Storage

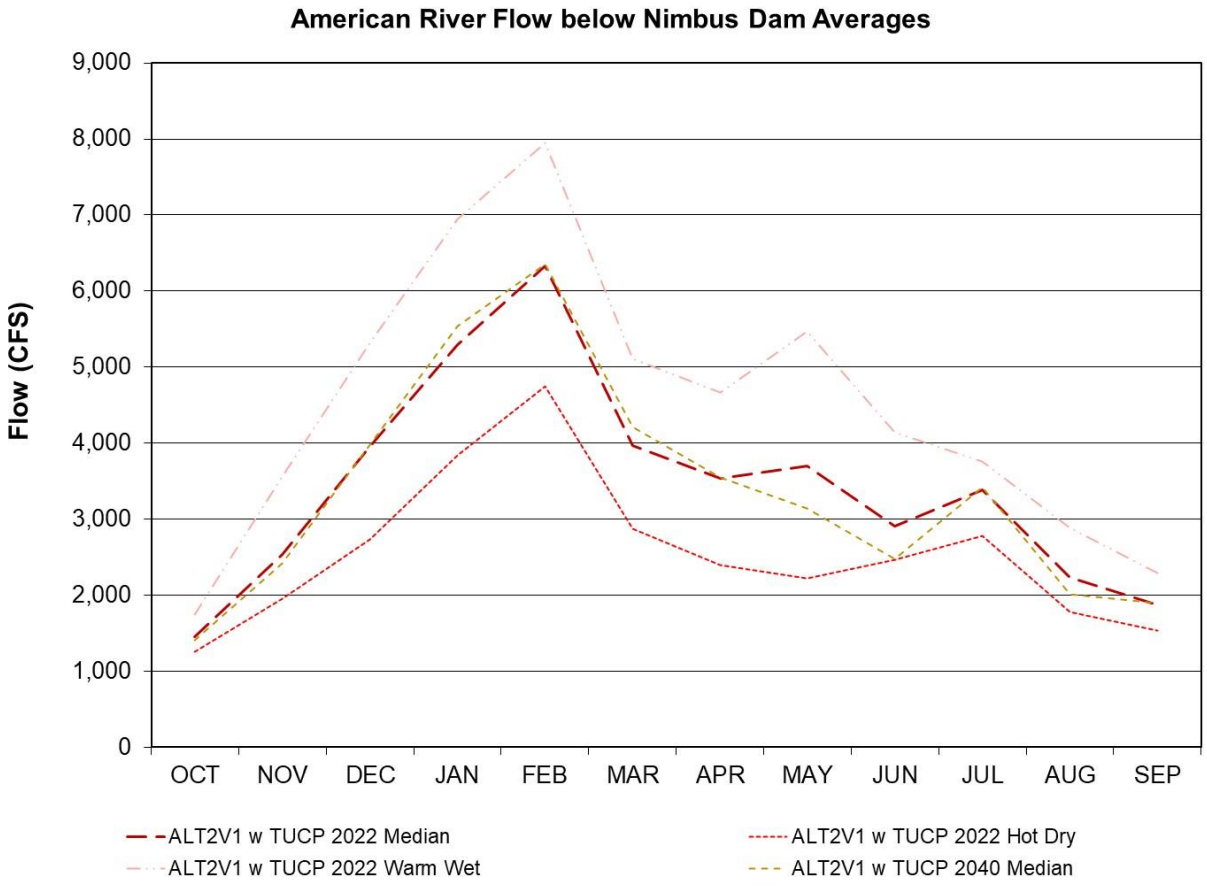

Figure F.2-4-13. Long-term Average American River flow below Nimbus Dam

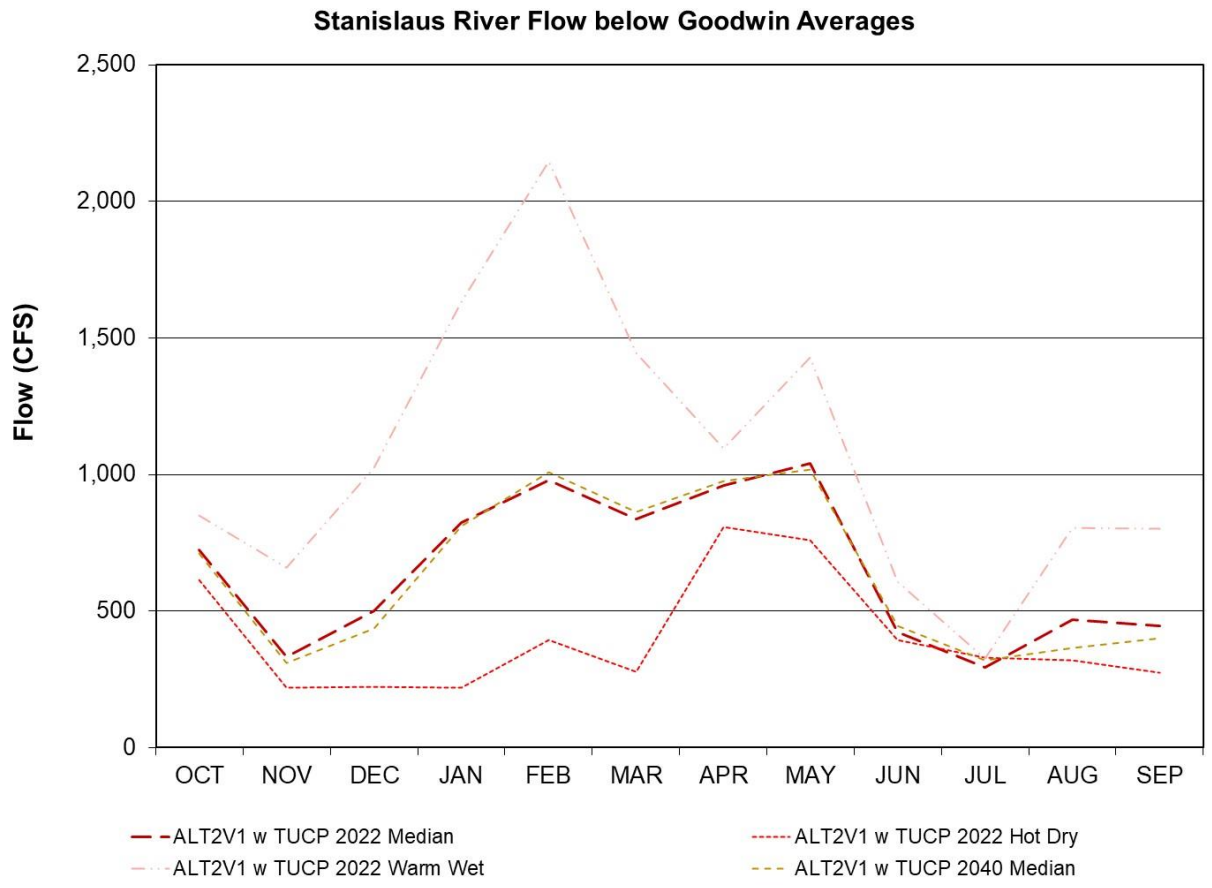

Figure F.2-4-14. Long-term Average Stanislaus River flow below Goodwin

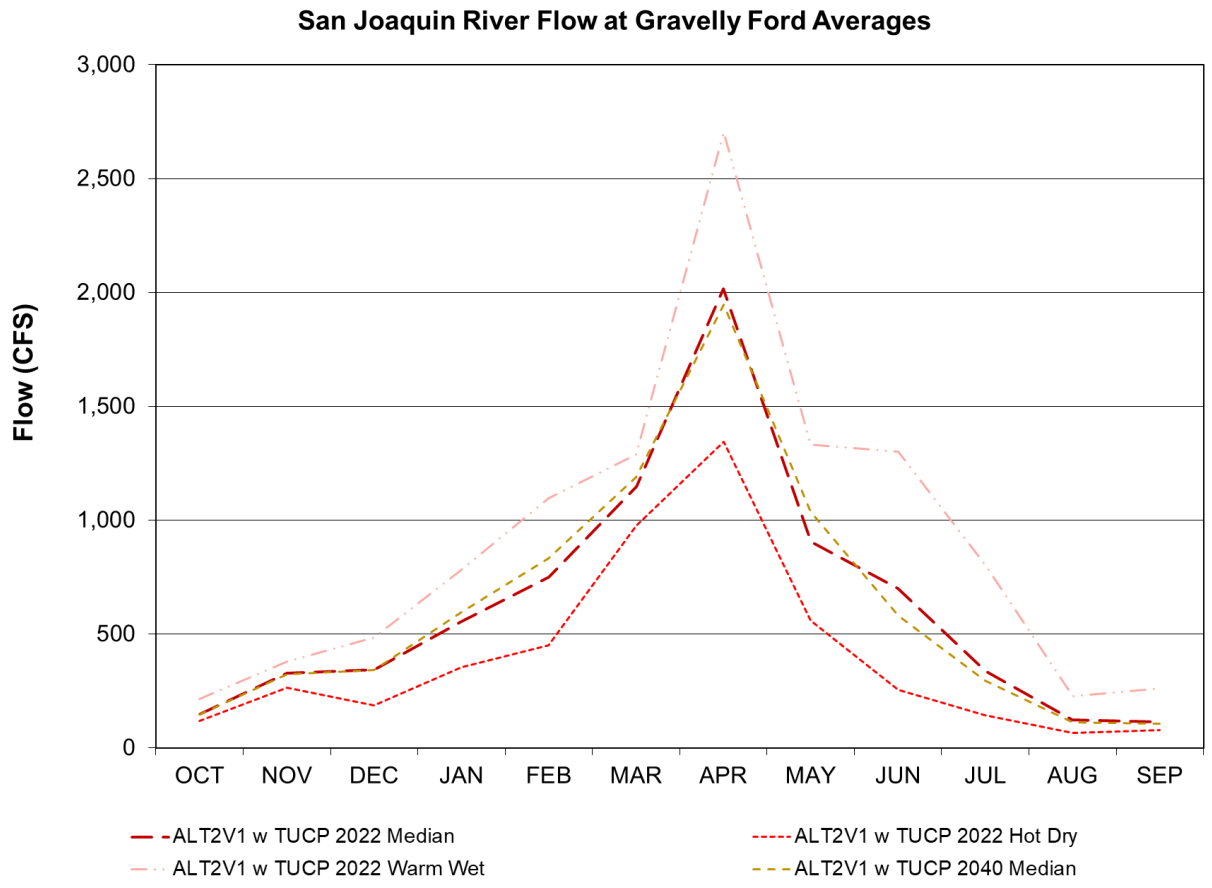

Figure F.2-4-15. Long-term Average San Joaquin River flow at Gravelly Ford

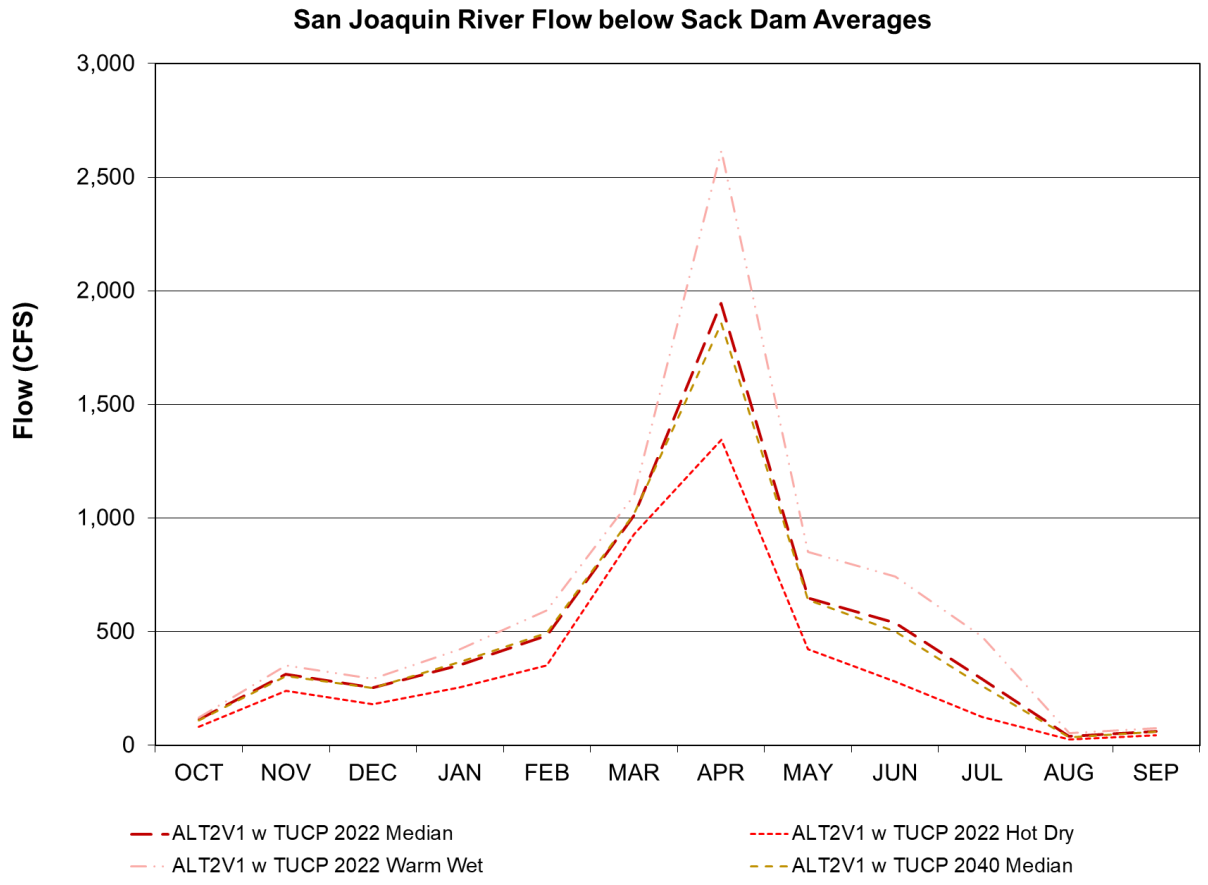

Figure F.2-4-16. Long-term Average San Joaquin River flow below Sack Dam

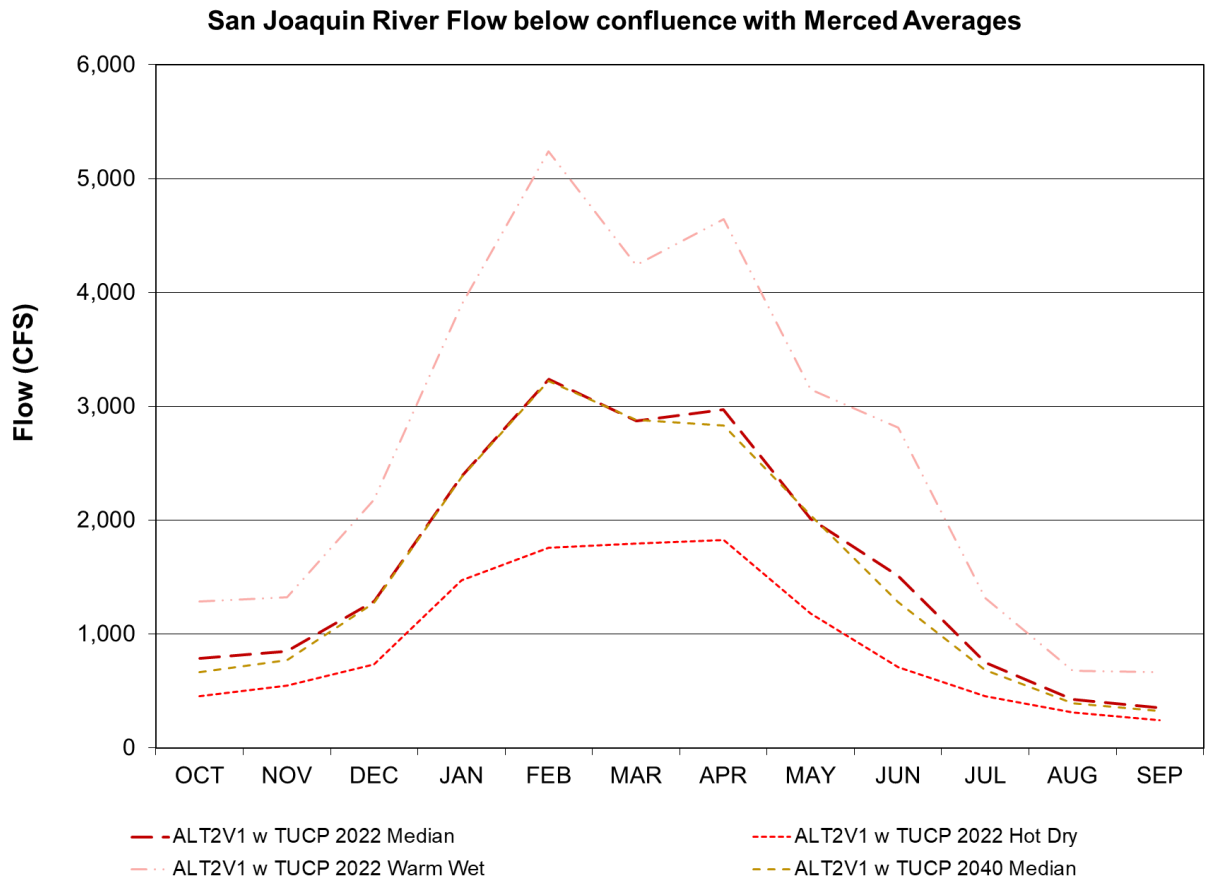

Figure F.2-4-17. Long-term Average San Joaquin River flow below Confluence with Merced River

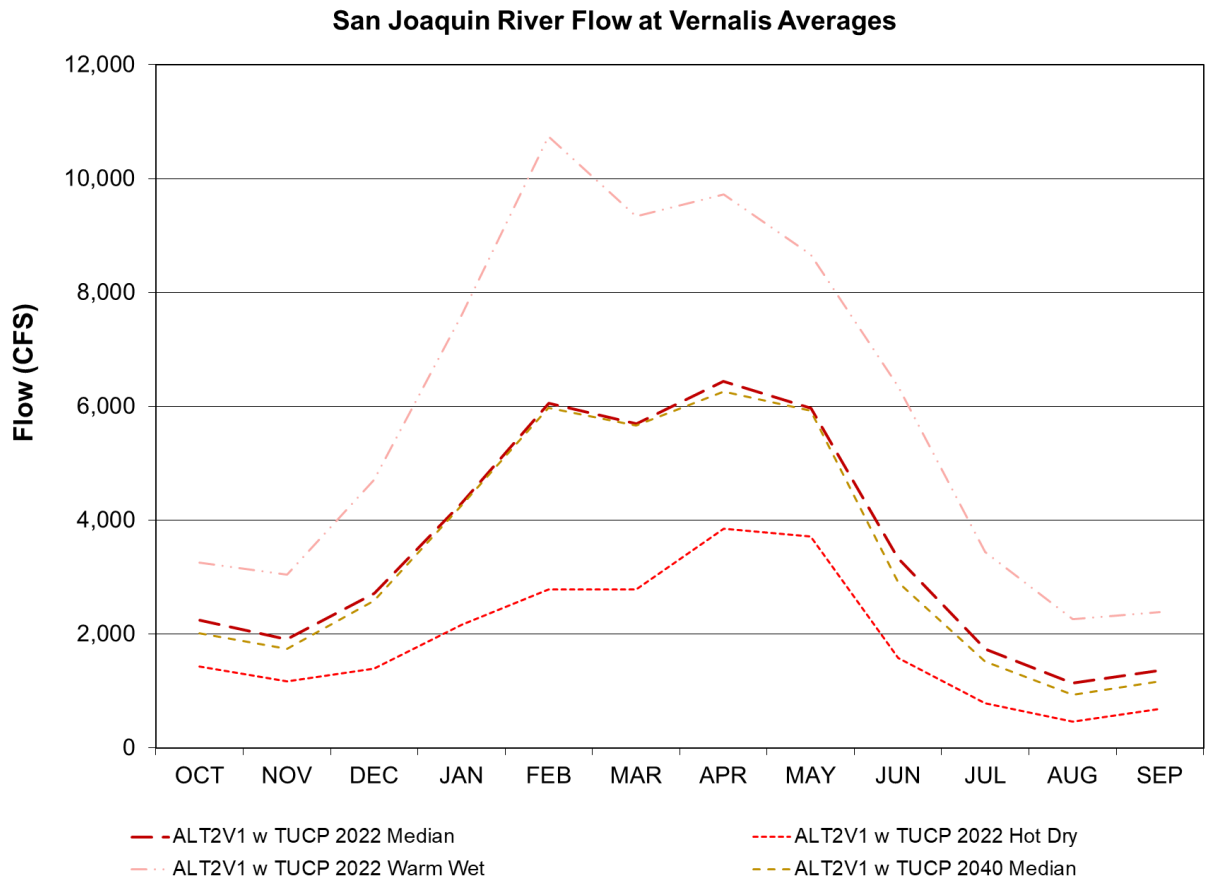

Figure F.2-4-18. Long-term Average San Joaquin River flow at Vernalis

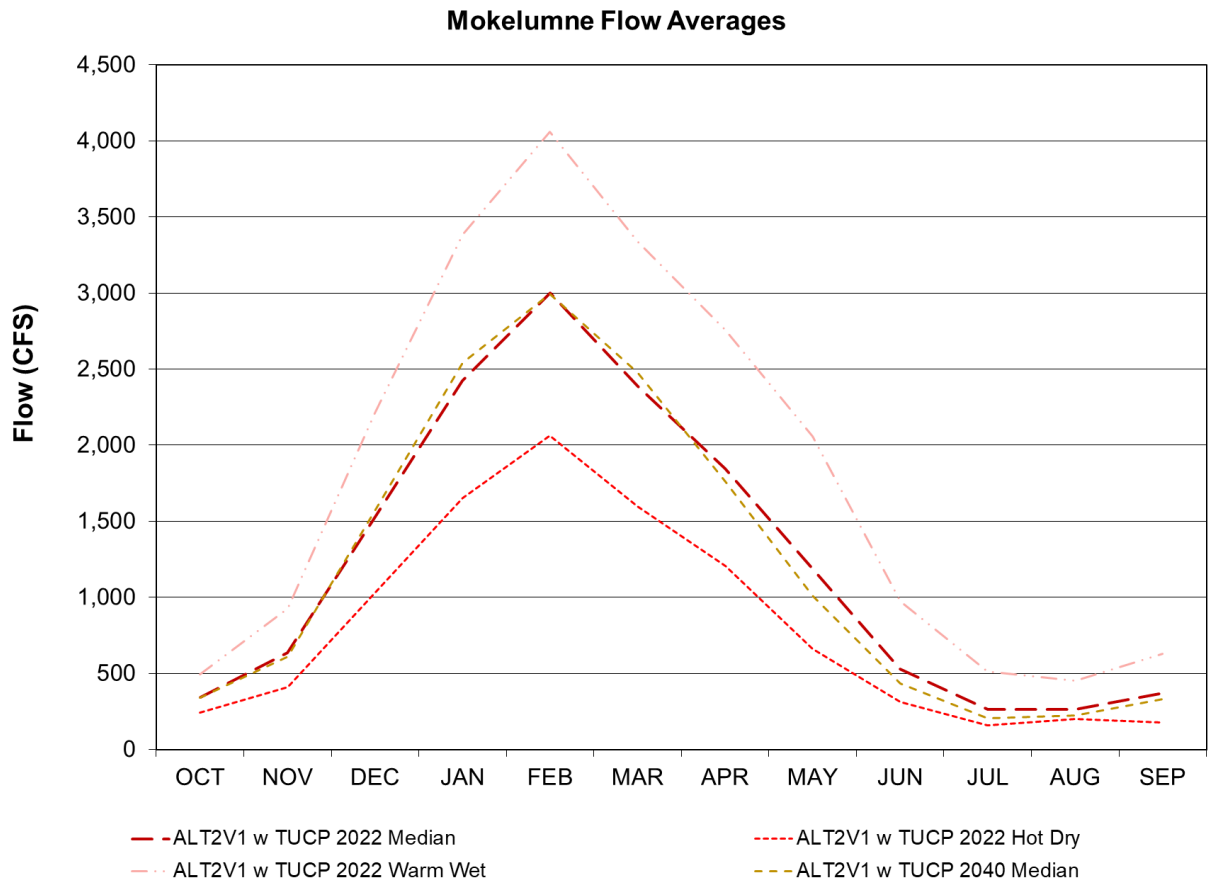

Figure F.2-4-19. Long-term Average Mokelumne River Flow

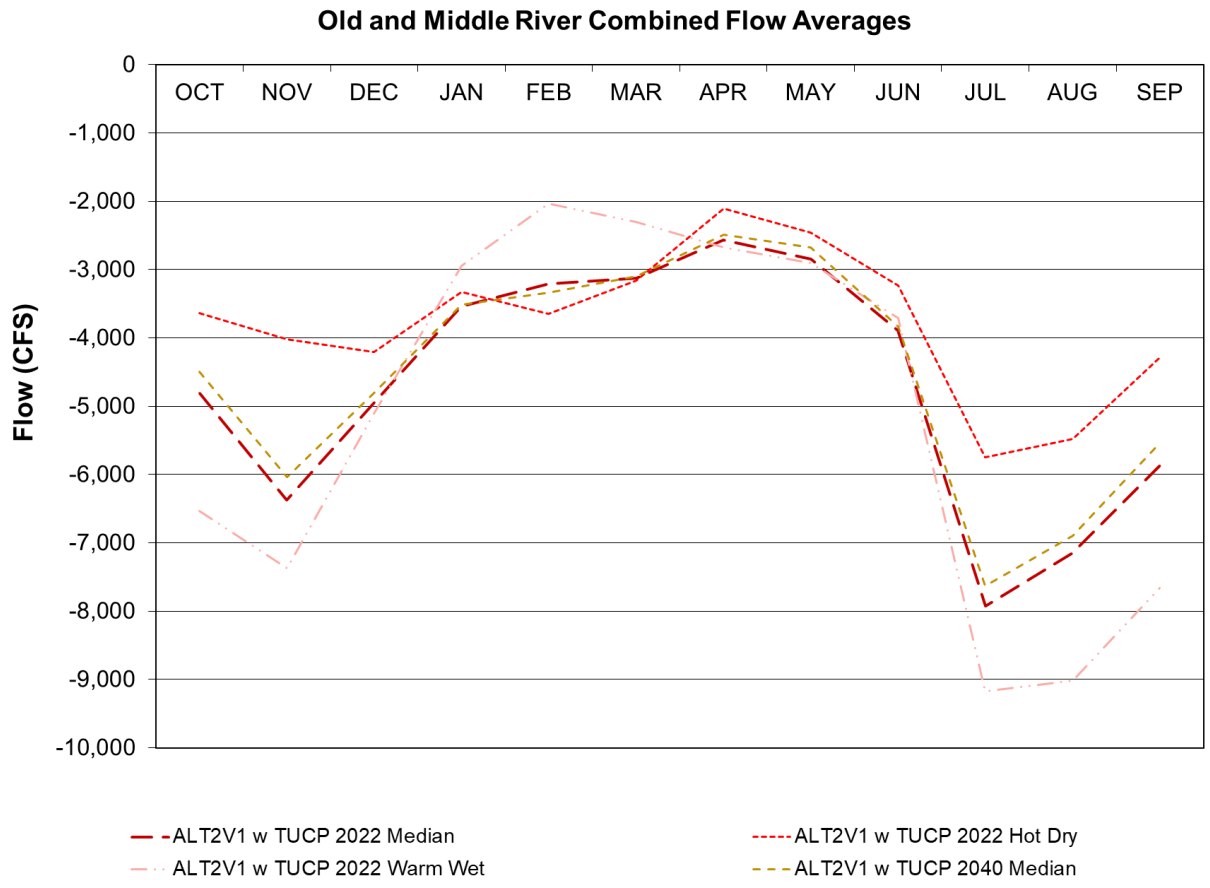

Figure F.2-4-20. Long-term Average Old and Middle River Combined Flow

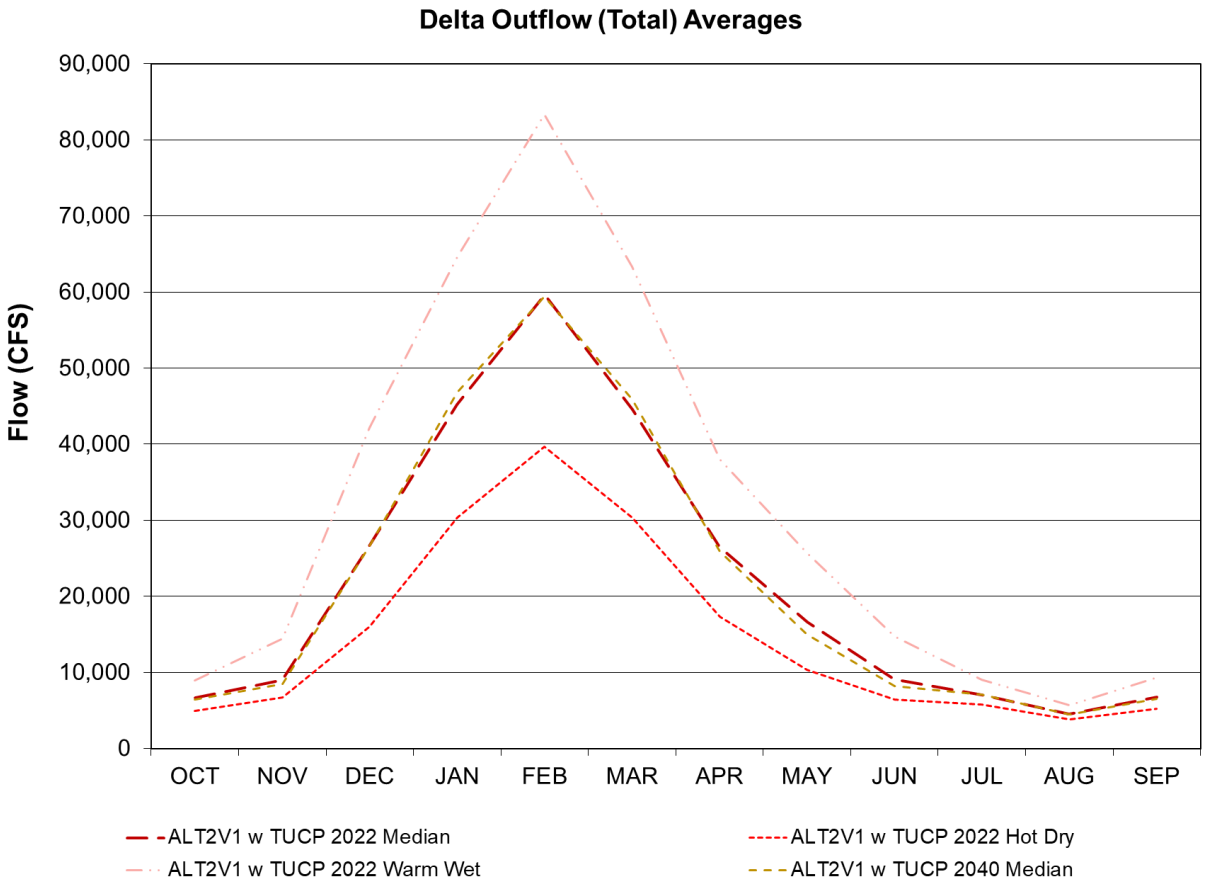

Figure F.2-4-21. Long-term Average Delta Outflow

F.2-4.2.2 HEC5Q

F.2-4.2.2.1 Sacramento

Figure F.2-4-22 through Figure F.2-4-27 summarize the temperature outcomes in the Sacramento River under the climate sensitivities using the Alternative 2v1 with TUCPs logic. TDM was calculated using the standard LTO parameterization.

The Alternative 2v1 with TUCPs TDM estimate shown in Figure F.2-4-22 demonstrates substantial climate variability. Under the 2022 Median climate scenario, TDM using the mixed logic exceeds 60% in approximately 8% of the simulated years. Under the 2022 Warm Wet climate scenario which is cooler and wetter than the 2022 Median climate scenario, the TDM using the mixed logic exceeds 60% in approximately 3% of the simulated years. Conversely, the 2022 Hot Dry climate scenario which is warmer and drier than the 2022 Median scenario has large TDM values occur more frequently with 60% TDM using the mixed logic occurring in approximately 30% of the simulated years. The 2040 Median scenario performs similarly to the 2022 Median scenario, albeit with an approximately 10% upward exceedance shift surrounding the 20% exceedance. When comparing the 2021 temperature tiers logic to the mixed logic, the mean TDM of each climate scenario is reduced under the 2021 temperature tiers.

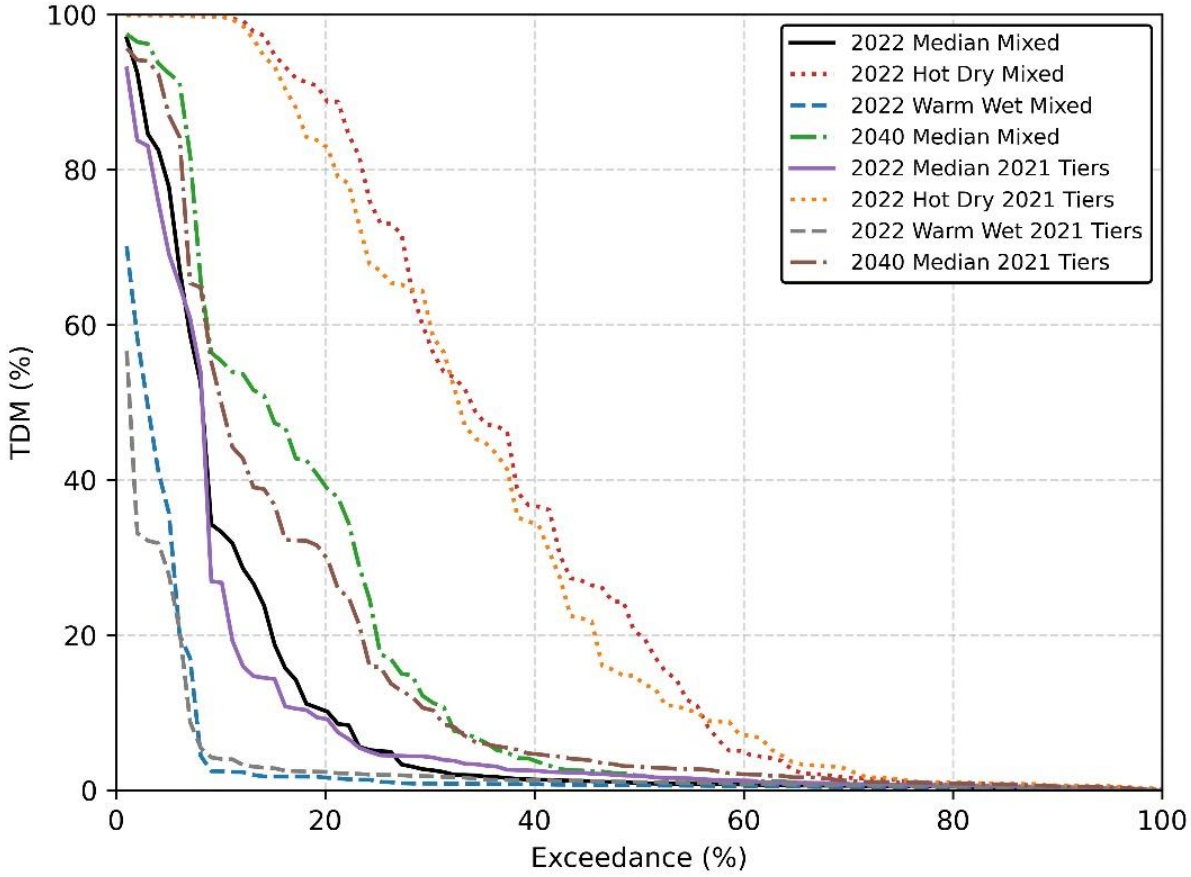

Figure F.2-4-22. Martin model TDM exceedance plot for Alternative 2v1 with TUCPs under various climate assumptions for water years 1922 through 2021

The Alternative 2v1 without TUCPs TDM values are driven by the Sacramento River temperatures from Clear Creek down to Red Bluff. Figure F.2-4-23 and Figure F.2-4-24 show the average and maximum May through end of October temperatures in the Sacramento River below Clear Creek with Figure F.2-4-25 and Figure F.2-4-26 providing the same information for Red Bluff.

The scaling of TDM follows temperature outcomes with the 2022 Hot Dry scenario having the largest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest temperatures of the scenarios. While the scenarios have a clear incremental increase in average temperature, temperatures above the 70% exceedance threshold are largely similar. The average temperatures of the climate scenarios using the 2021 temperature tiers logic have higher average and maximum temperatures than the climate scenarios using the mixed logic centering on 50% exceedance. This is due to the extended shoulder period in the 2021 temperature targets which allows for better temperature performance later in the temperature management season at the expense of early season temperatures. The better performance of the 2021 temperature tiers logic later in the temperature management season results in lower TDM.

An analogous trend between the climate scenarios is visible in Figure F.2-4-27 with the volume of water less than 52 degrees Fahrenheit (°F) at the end of April. More cold water correlates with lower TDMs across the climate scenarios. However, despite having generally similar cold-water volumes, the 2040 Median condition exhibits worse TDM outcomes than the 2022 Median, likely due to the roughly degree higher average temperatures under the 2040 Median scenario. The higher average temperatures under the 2040 Median scenario are likely due in part to the greater in-stream and reservoir warming.

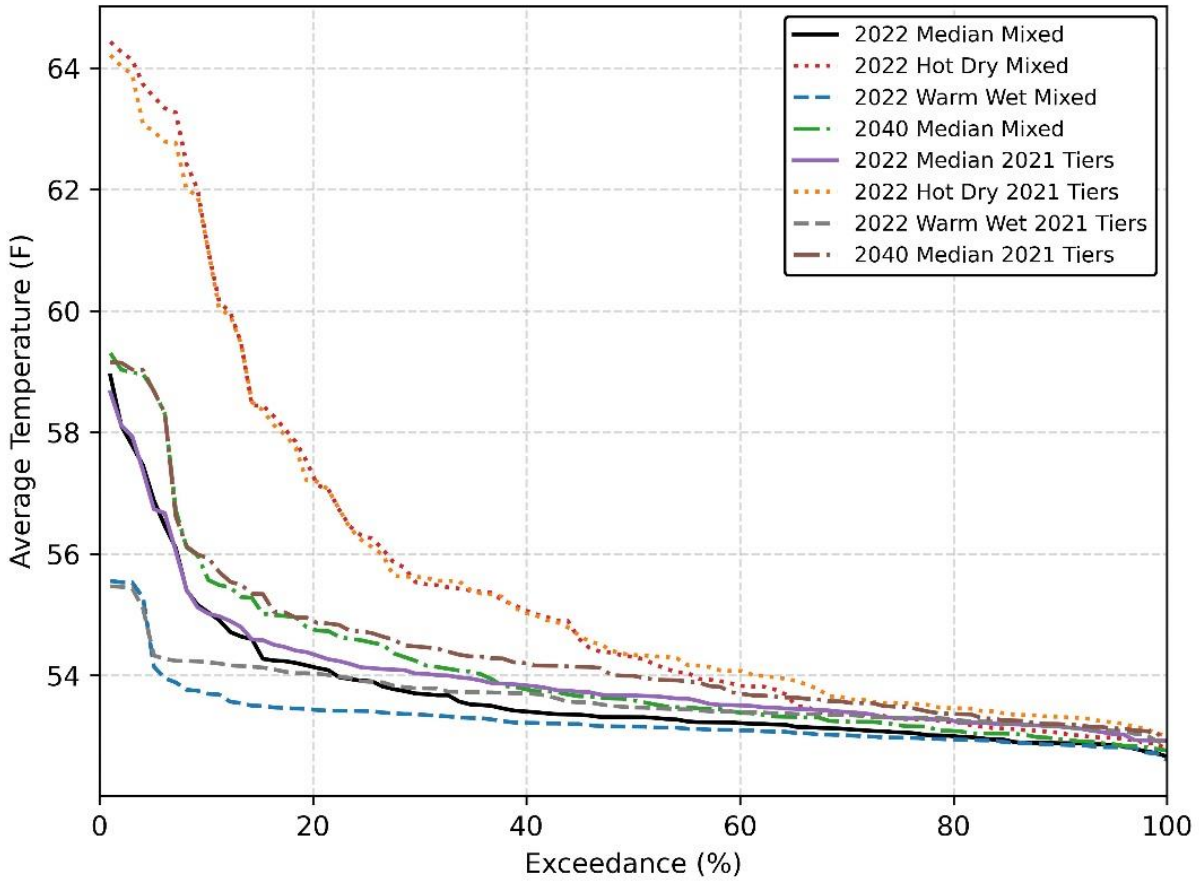

Figure F.2-4-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2020

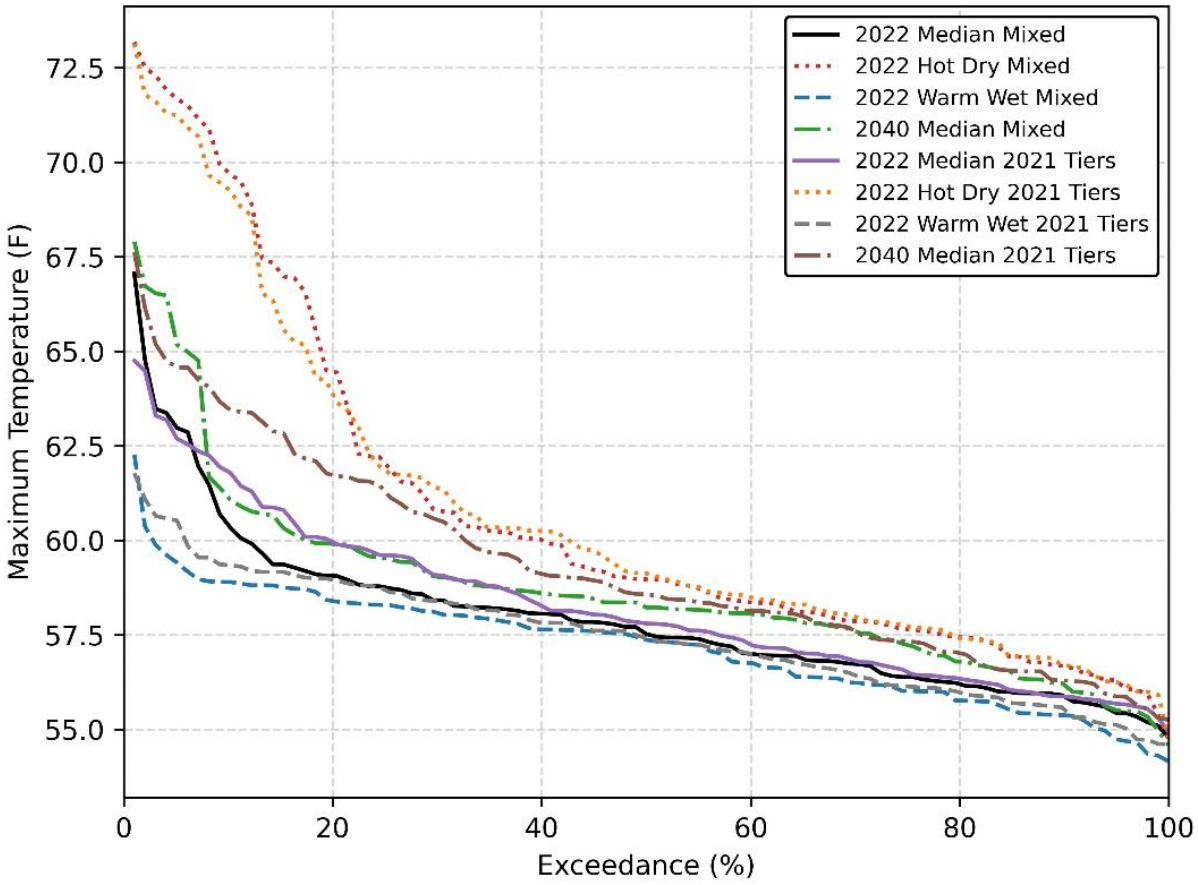

Figure F.2-4-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2020

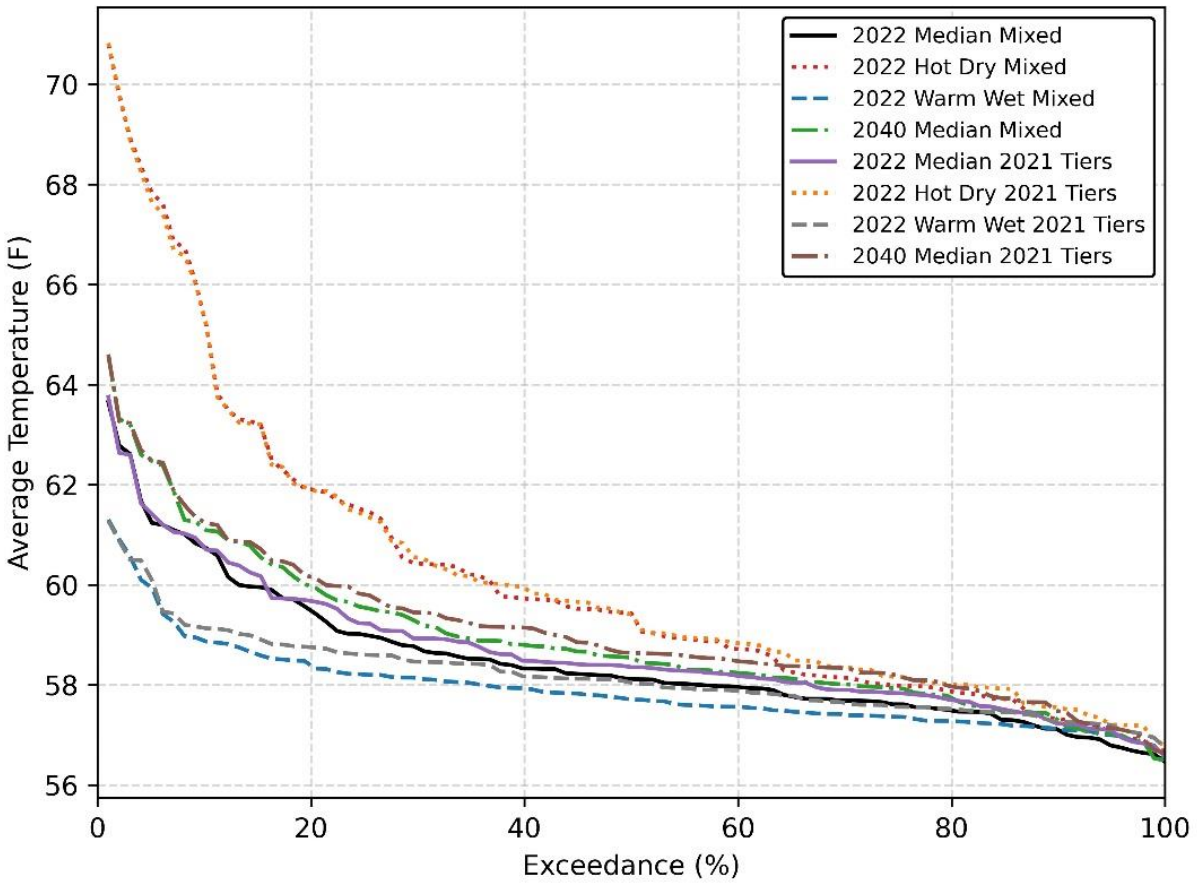

Figure F.2-4-25. Average May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2020

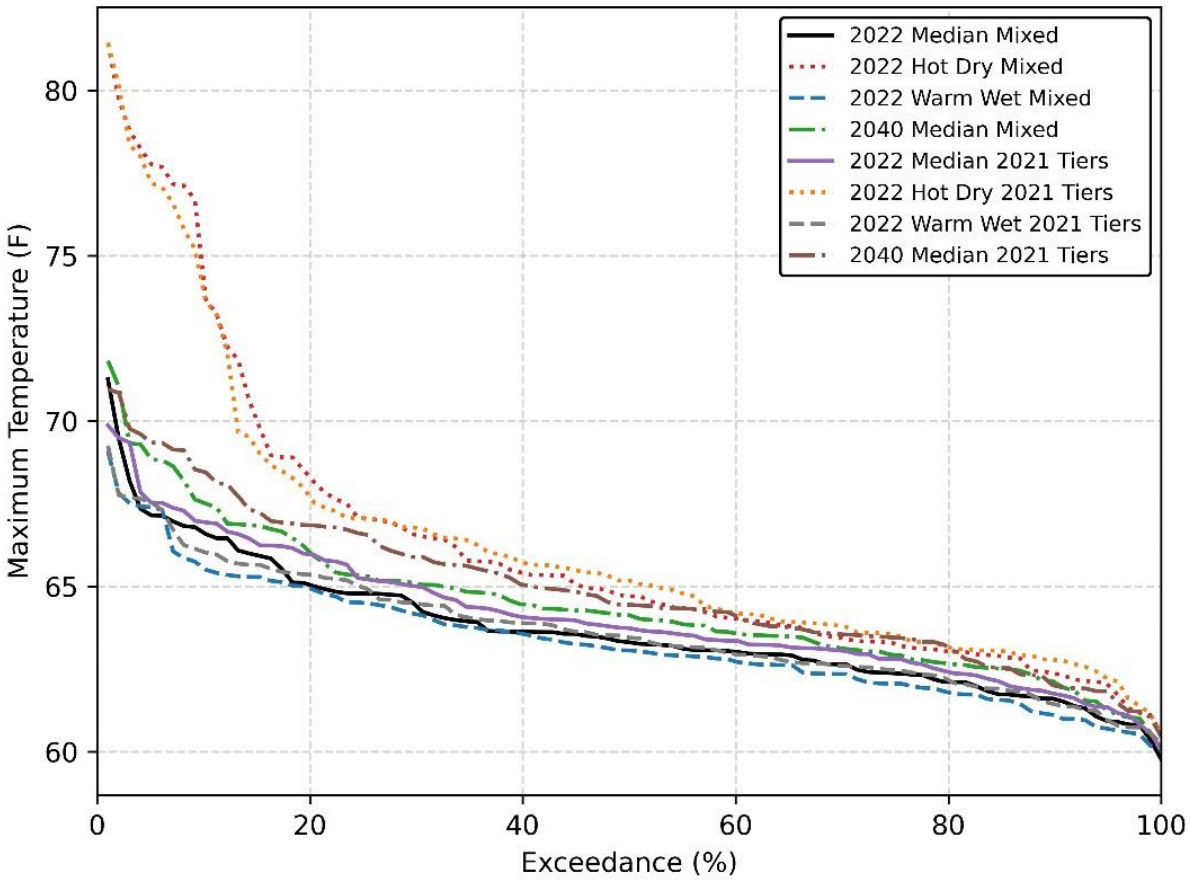

Figure F.2-4-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2020

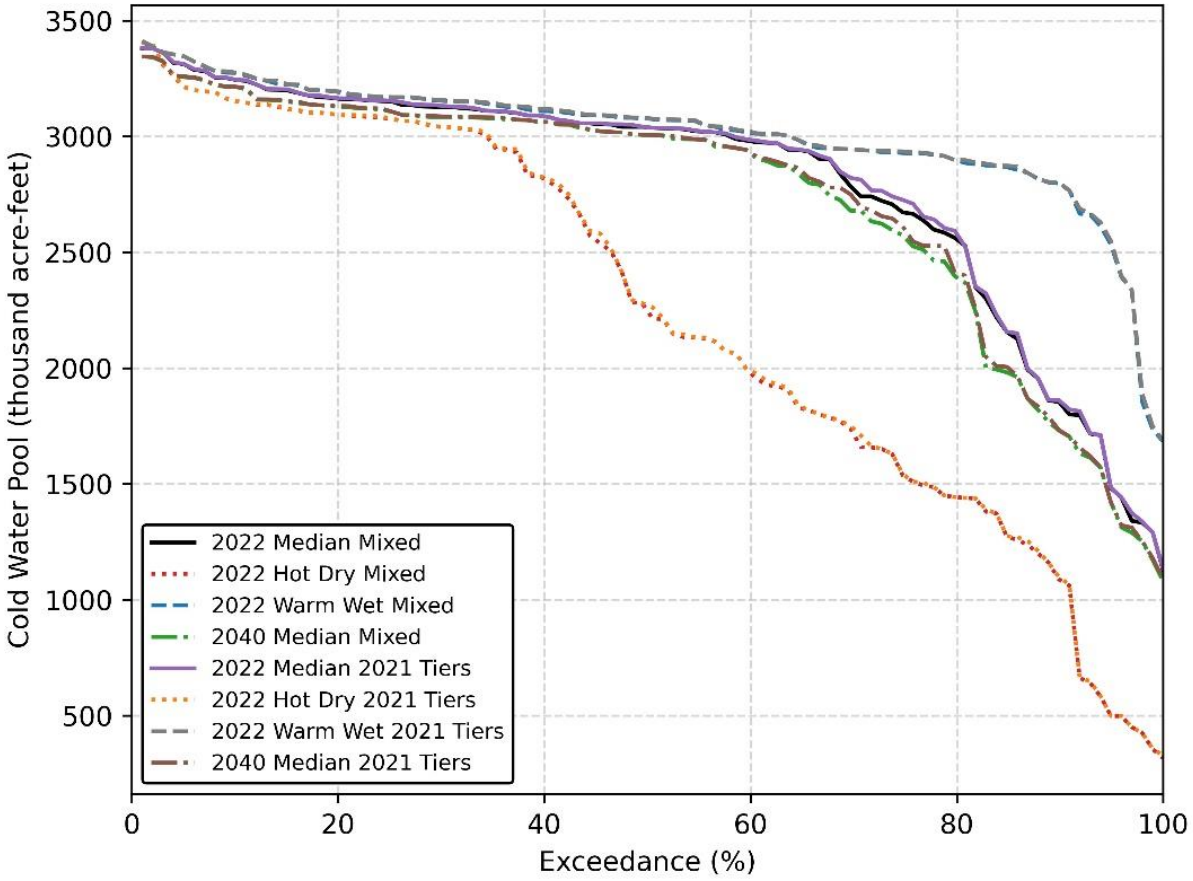

Figure F.2-4-27. Volume of water at the end of April less than 52°F in Shasta Lake for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2021

F.2-4.2.2.2 American

Figure F.2-4-28 through Figure F.2-4-30 evaluate the temperature outcomes in the American River under the climate sensitivities using the Alternative 2v1 with TUCPs logic. The 2022 Hot Dry scenario has the hottest average and maximum temperatures at low exceedances. At high exceedances, the 2040 Median scenario has the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. Figure F.2-4-30 shows the volume of water less than 52 °F at the end of April in Folsom Lake. The 2022 Hot Dry scenario has the lowest volumes of cold-water and the 2022 Warm Wet scenario has the highest volumes of cold-water. Despite the 2022 Median and 2040 Median having similar volumes of cold-water, the 2040 scenario exhibits higher average and maximum temperatures likely due in part to the greater in-stream and reservoir warming.

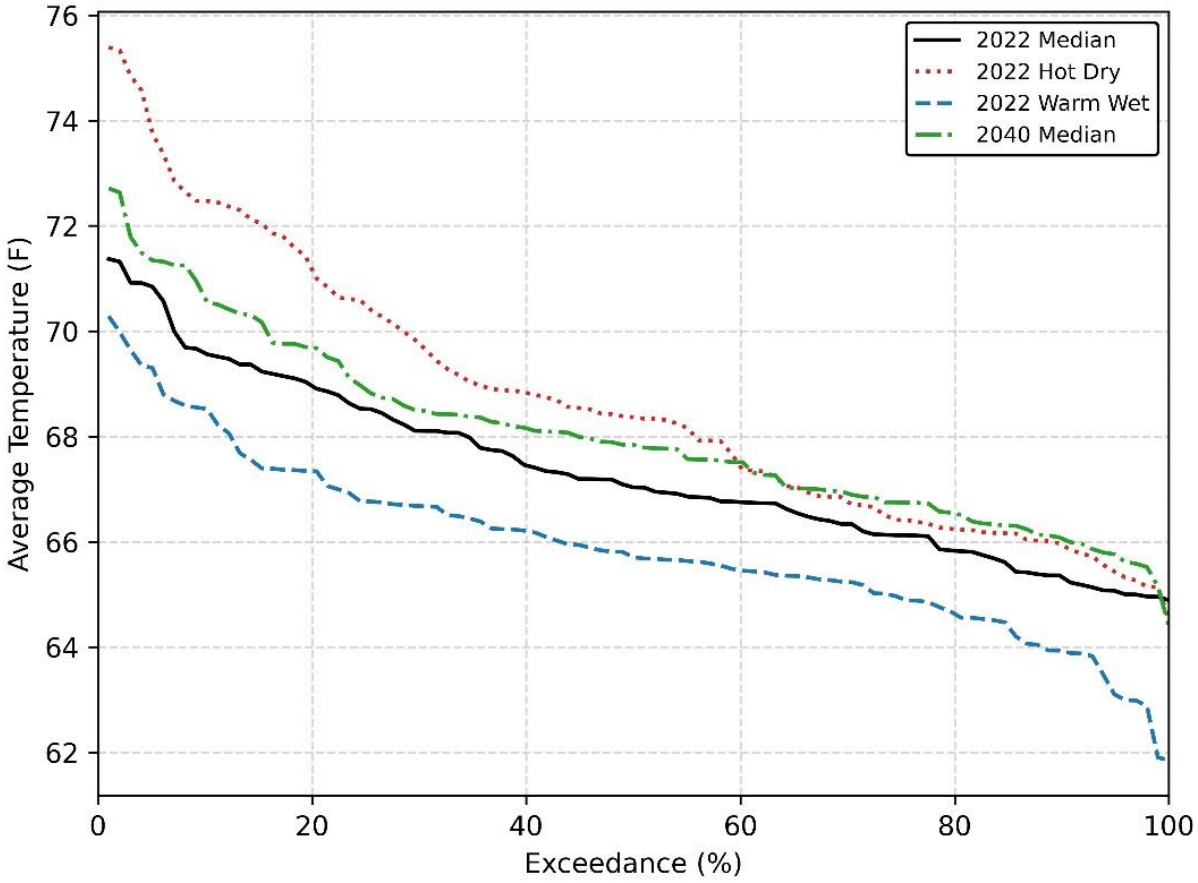

Figure F.2-4-28. Average May through end of October temperatures on the American River at Watt Avenue for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2020

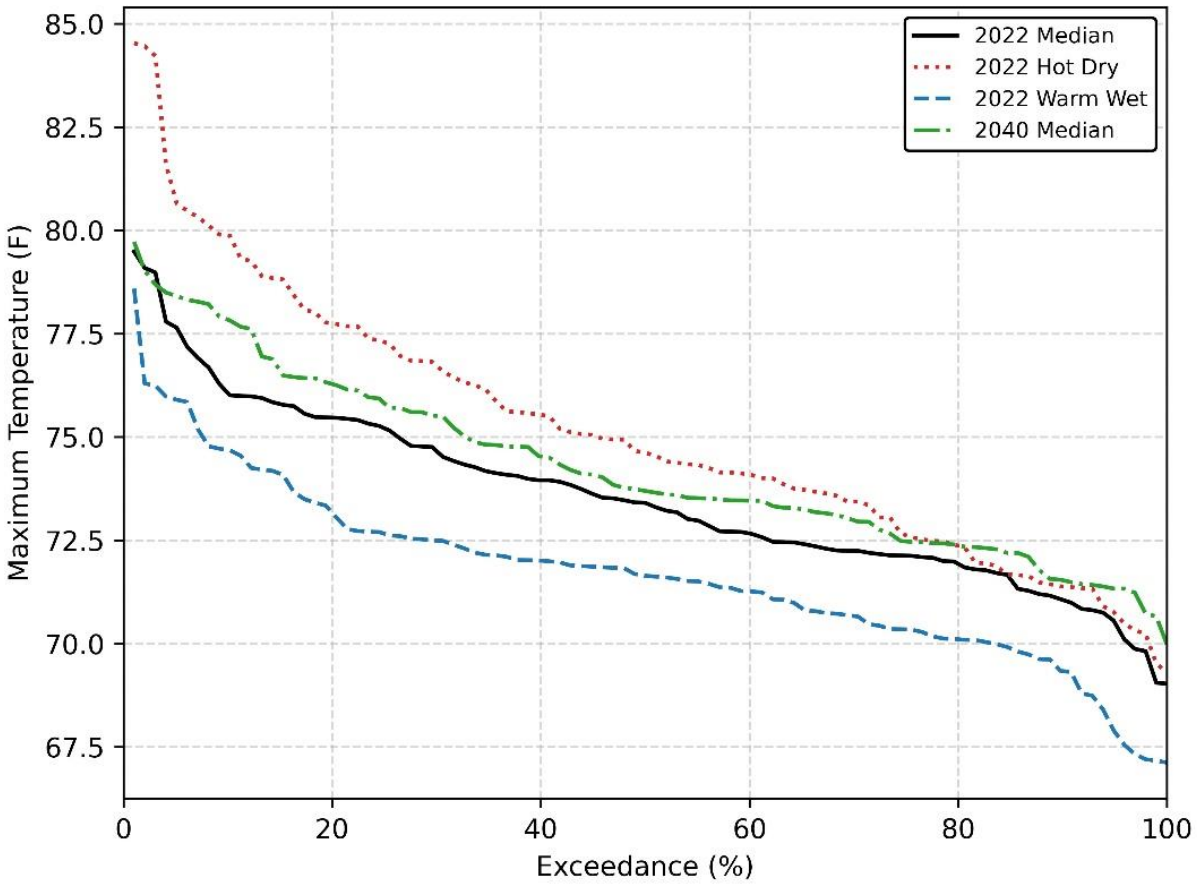

Figure F.2-4-29. Maximum May through end of October temperatures on the American River at Watt Avenue for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2020

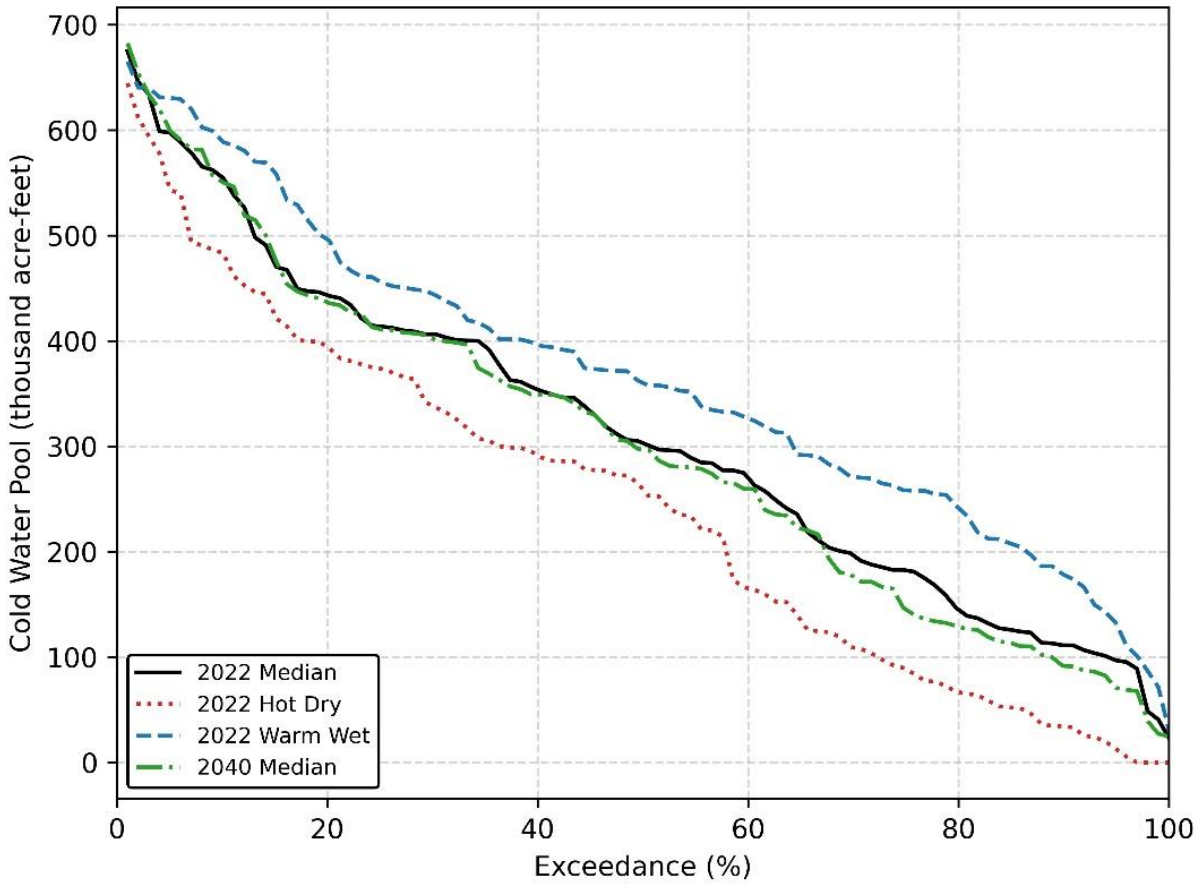

Figure F.2-4-30. Volume of water at the end of April less than 52 °F in Folsom Lake for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2021

F.2-4.2.2.3 Stanislaus

Figure F.2-4-31 and Figure F.2-4-32 evaluate the temperature outcomes in the Stanislaus River under the climate sensitivities using the Alternative 2v1 with TUCPs logic. The 2022 Hot Dry scenario has the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures. The 2040 Median temperatures are slightly higher than the 2022 Median due to instream warming.

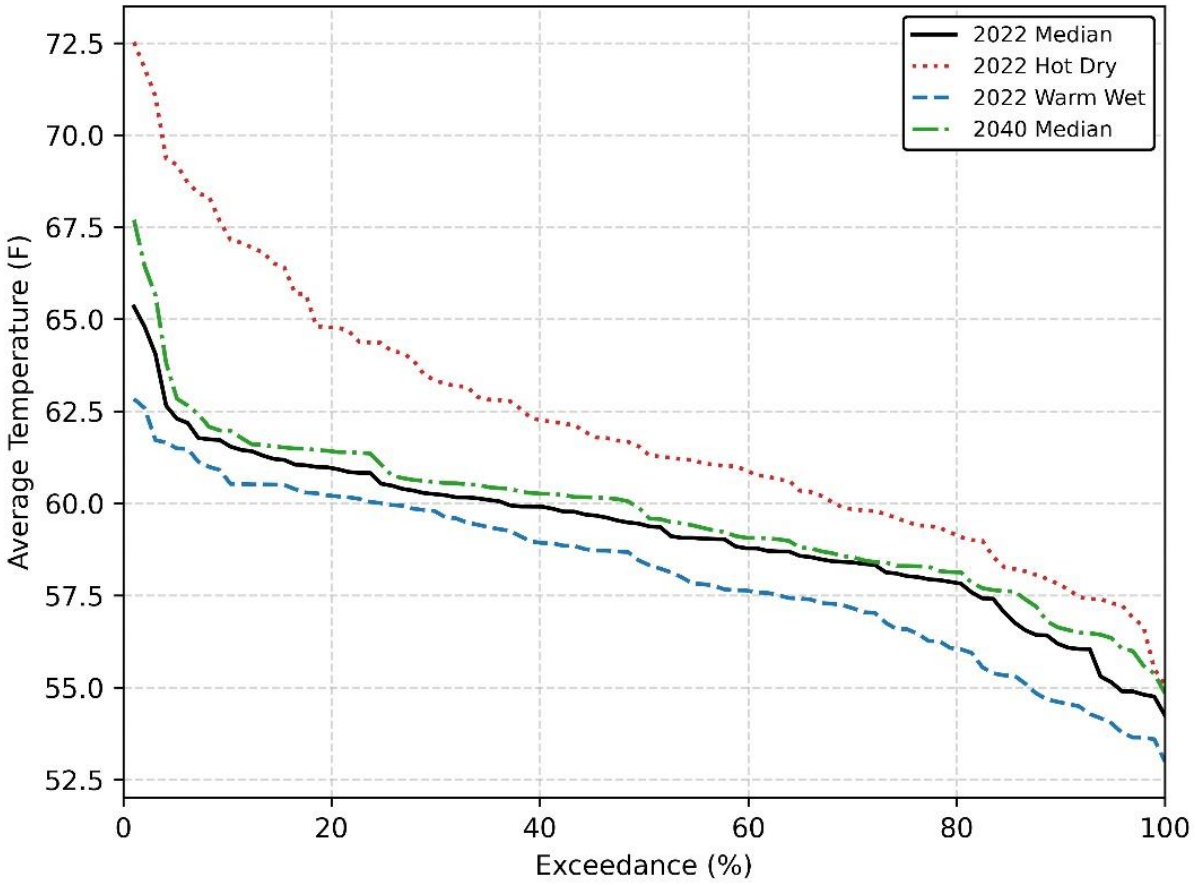

Figure F.2-4-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2019

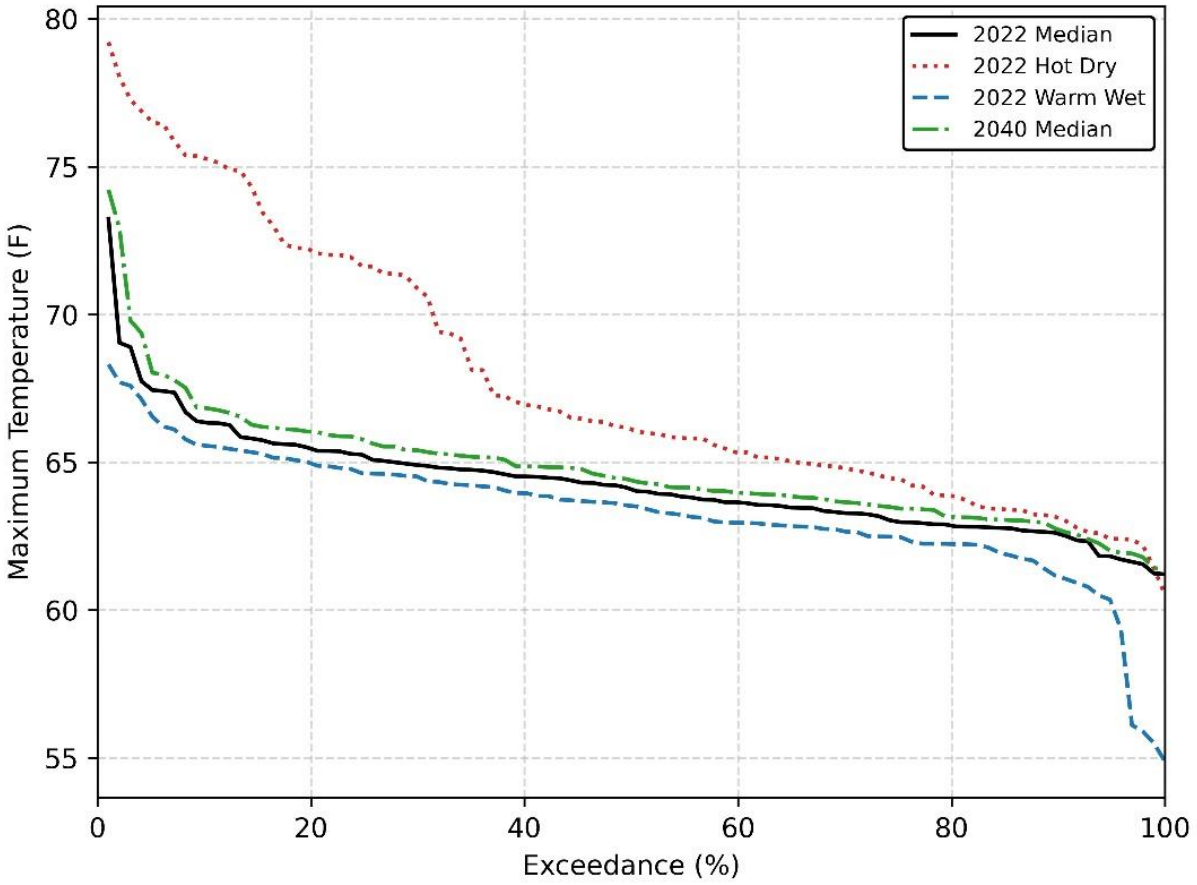

Figure F.2-4-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 2v1 with TUCPs under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Appendix F.2-6 Climate Sensitivity Analysis, Alternative 2v2

F.2-6.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative (Alt) 2v2 under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used for quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-6.2 Climate Change Comparison

F.2-6.2.1 CalSim 3

Figure F.2-6-21 through Figure F.2-6-21 show CalSim 3 simulation results for Alternative 2v2. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 2v2 were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough
- Sacramento River at Verona
- Sacramento River at Freeport
- Flow though Yolo Bypass

- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-6-1) and end of September (Figure F.2-6-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 20% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows, long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of reservoir management season, the differences are less notable. Summer months are commonly when river flows are due primarily to releases from storage instead of runoff events. Flows under 2040 Median climate are mostly similar to flows under 2022 Median climate.

Clear Creek below Whiskeytown (Figure F.2-6-7) flow changes are similar to the changes observed in the Sacramento River watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in fall and winter months. For Spring Creek inflow to Keswick Reservoir (Figure F.2-6-8), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-6-9) and end of September (Figure F.2-6-10 Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-6-11), changes to flow are similar to the changes in the Sacramento watershed. In all months, 2022 Warm and Wet flows are higher, 2022 Hot and Dry

flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May and June due to lower Folsom inflows in spring months. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. As compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in January of 2040 Median conditions due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-6-12), changes are similar to the changes in the Sacramento watershed. Flows across all climate conditions are most in June and July, months when releases consist of stored water. Otherwise, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows.

For long-term monthly average San Joaquin River flows, changes to flow are similar to the changes in the Sacramento watershed. San Joaquin River at Gravelly Ford (Figure F.2-6-13) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced.

For long-term monthly average flows in the Delta (Figure F.2-6-16 through Figure F.2-6-21), changes are generally similar to the changes in the Sacramento watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows. Flows across all climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure F.2-6-20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

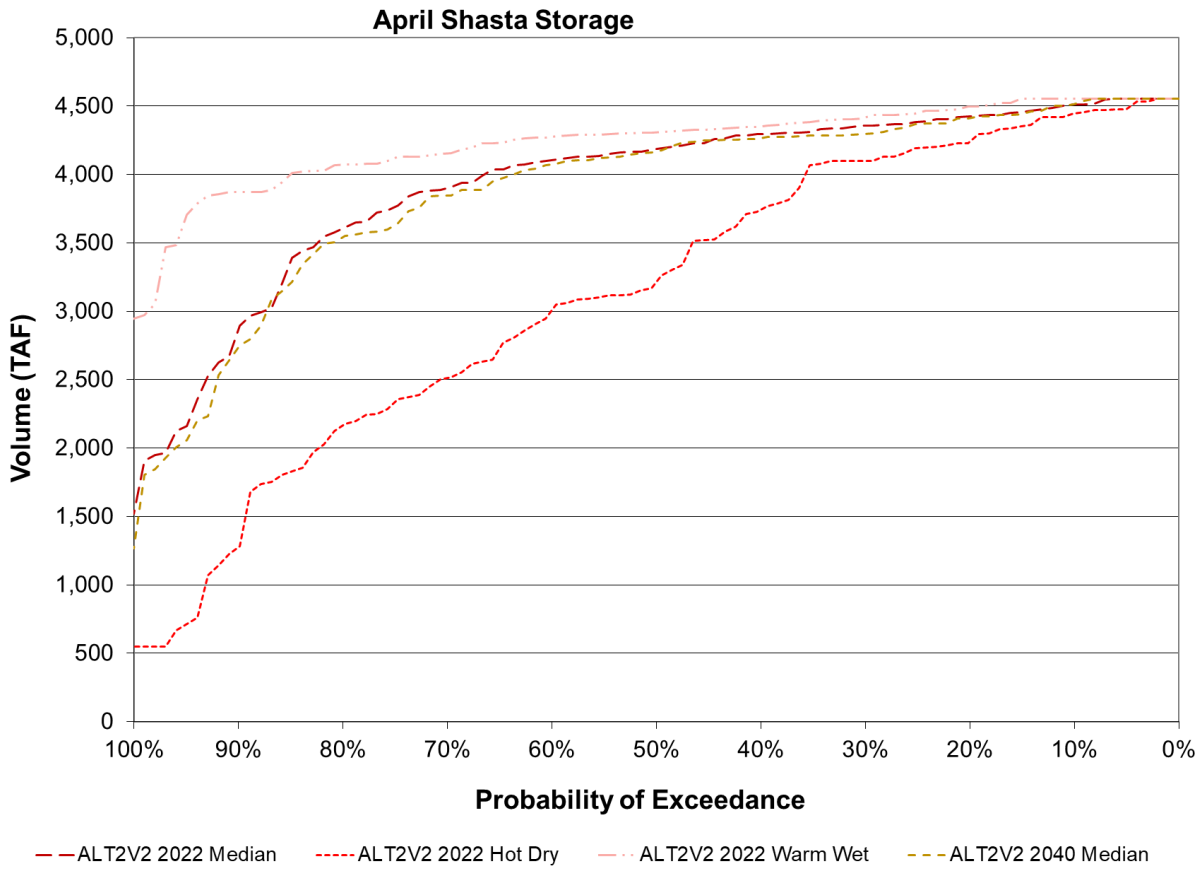

Figure F.2-6-1. End of April Shasta Storage

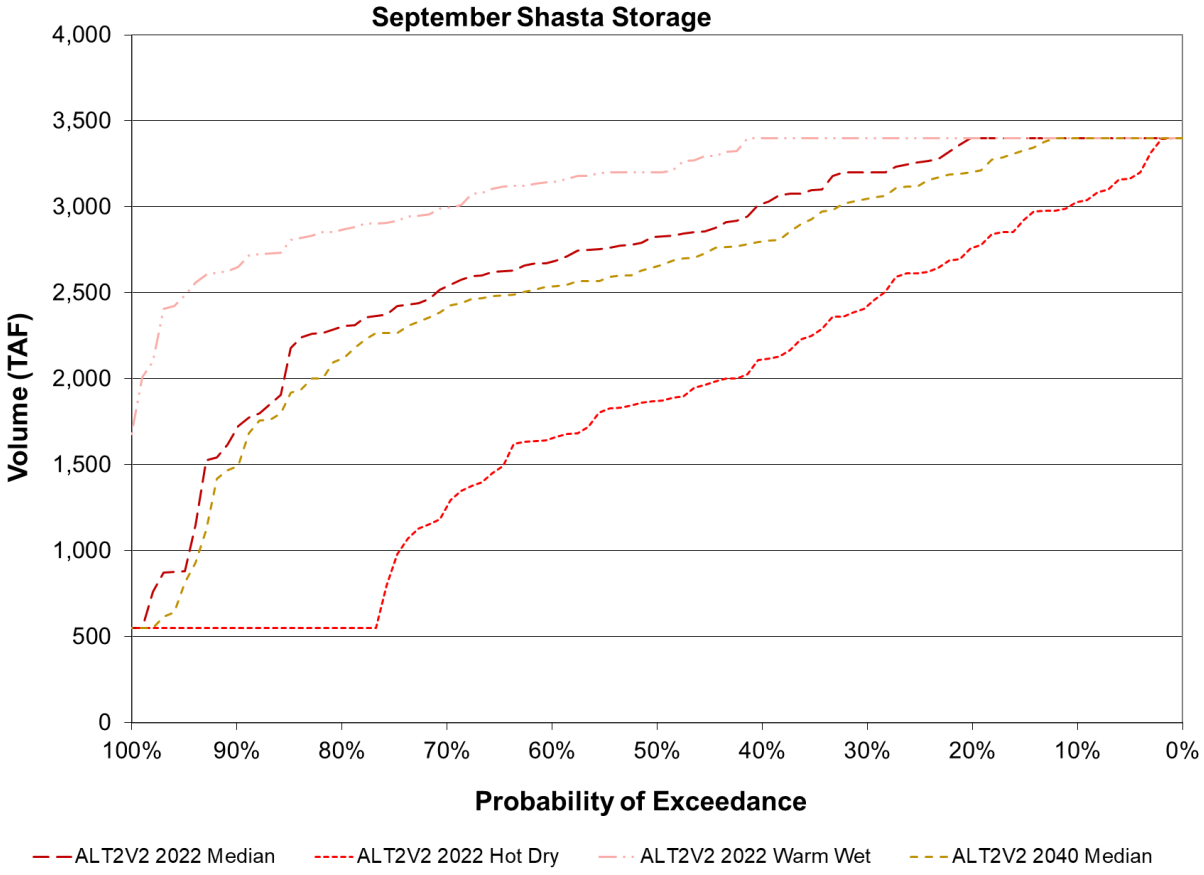

Figure F.2-6-2. End of September Shasta Storage

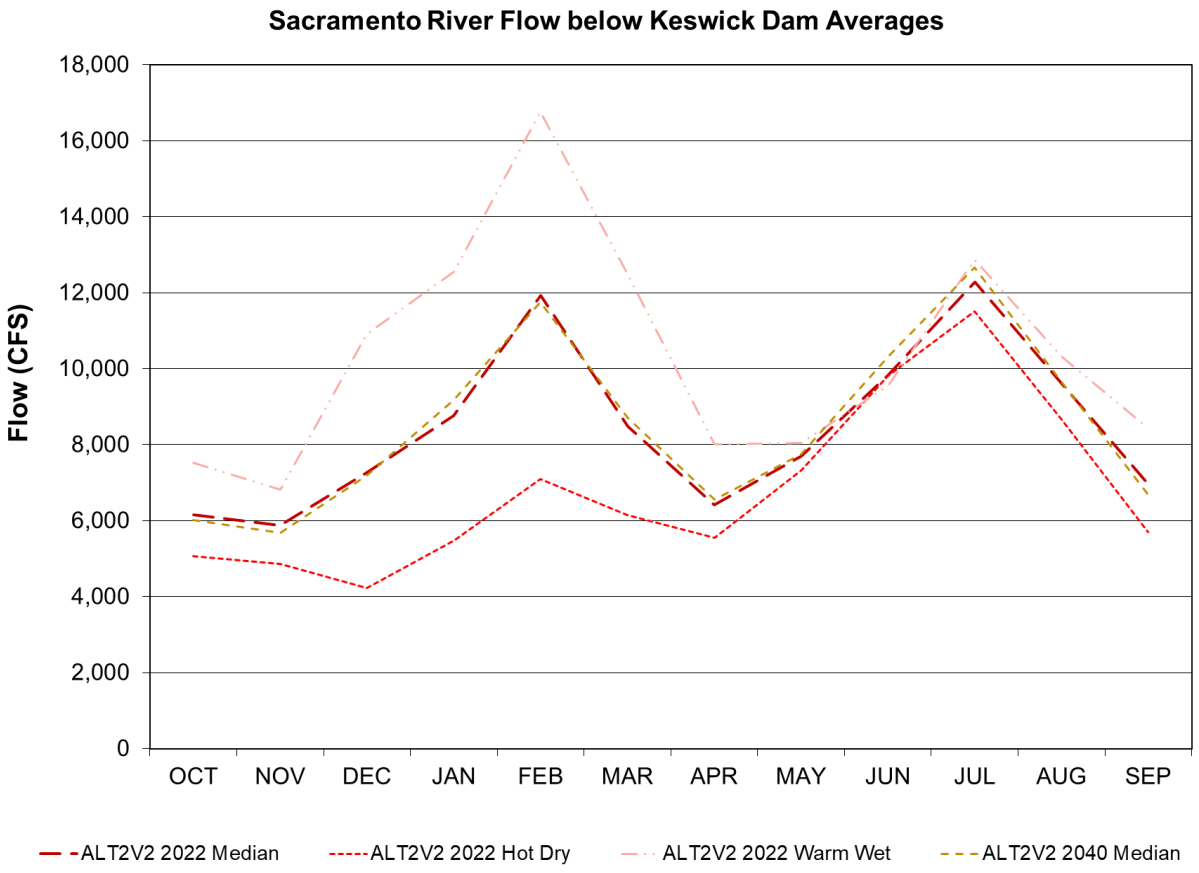

Figure F.2-6-3. Long-term Average Sacramento River flow below Keswick Dam

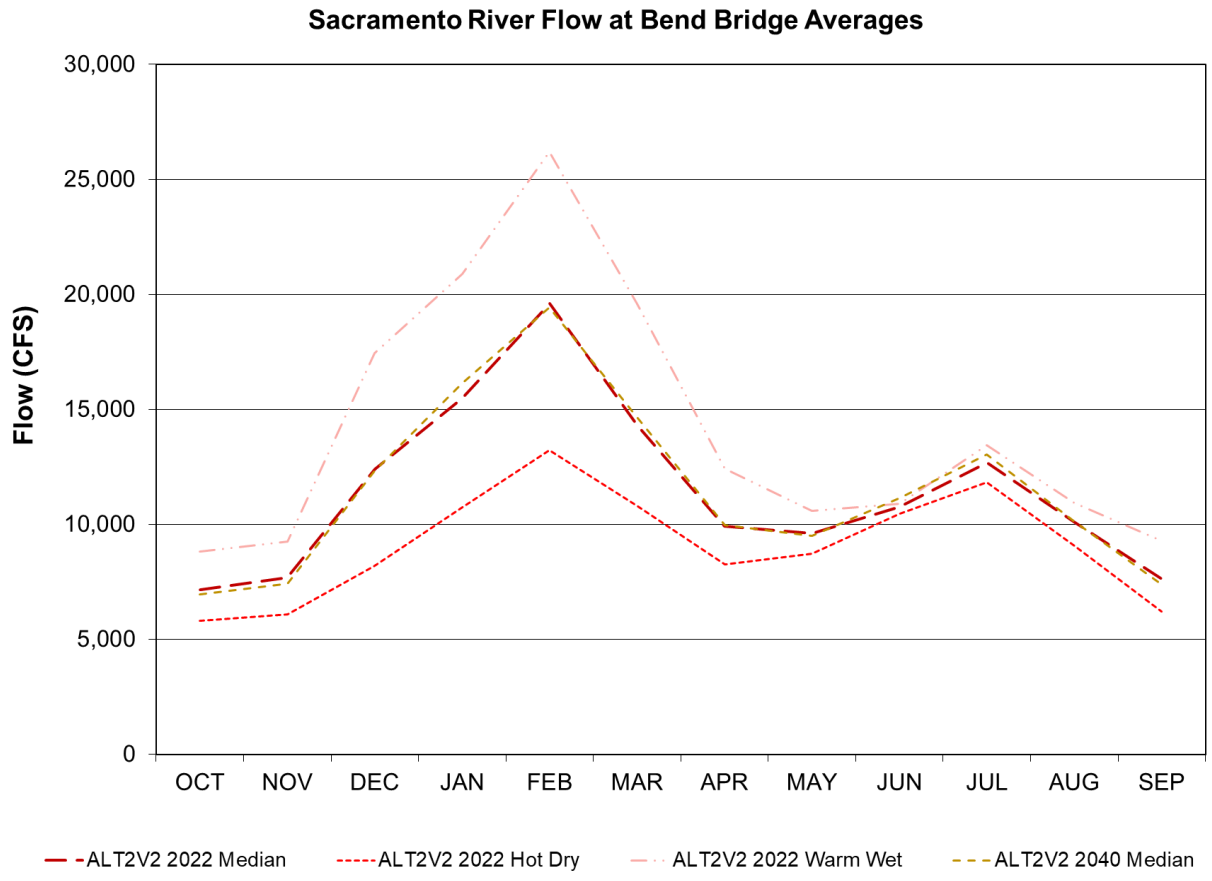

Figure F.2-6-4. Long-term Average Sacramento River flow at Bend Bridge

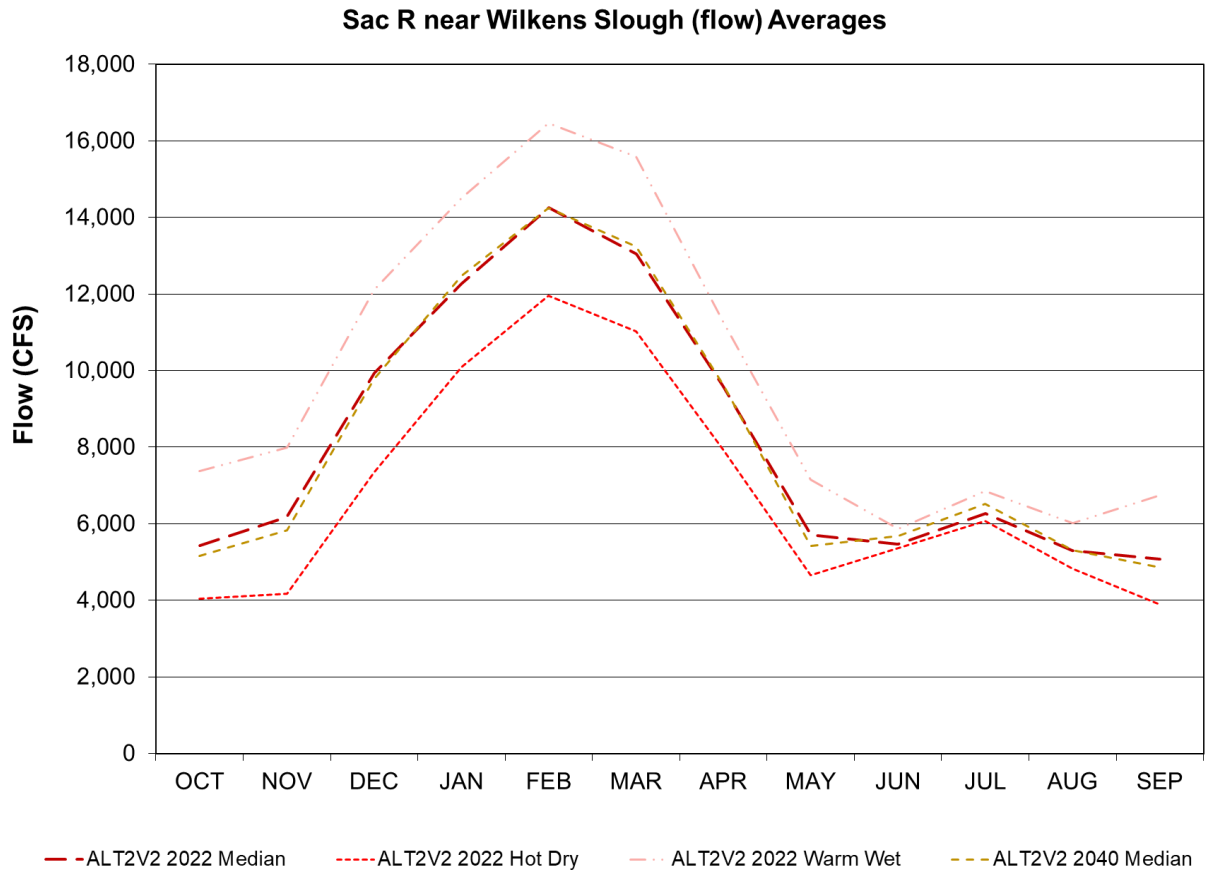

Figure F.2-6-5. Long-term Average Sacramento River flow near Wilkins Slough

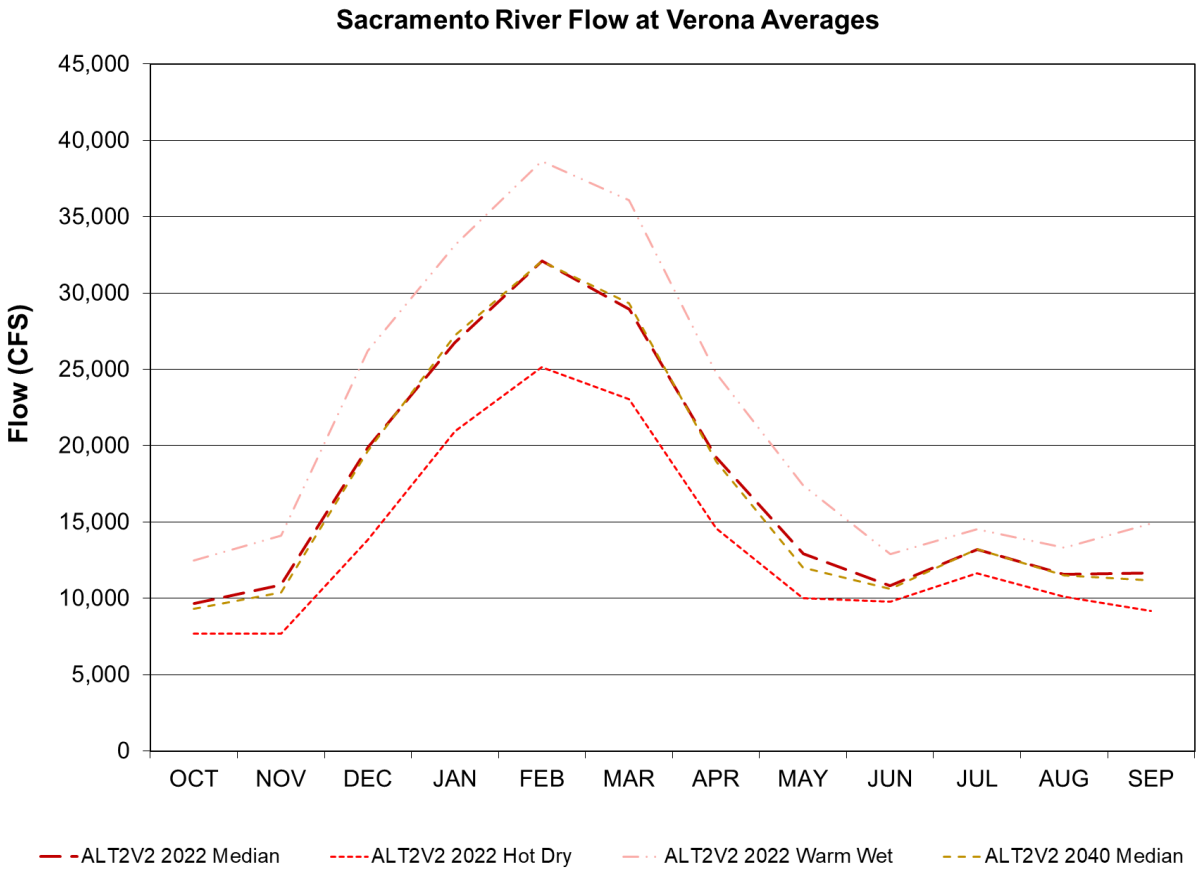

Figure F.2-6-6. Long-term Average Sacramento River flow at Verona

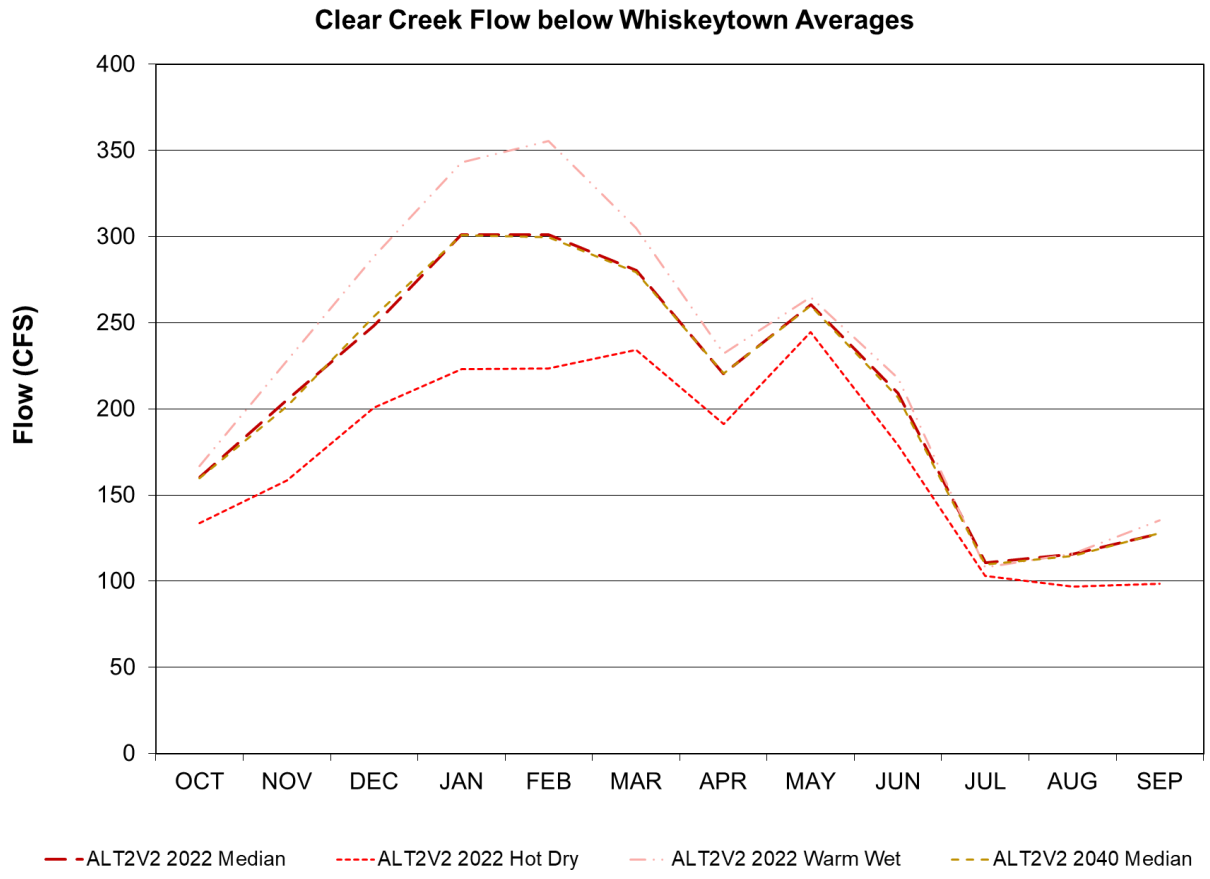

Figure F.2-6-7. Long-term Average Clear Creek flow below Whiskeytown

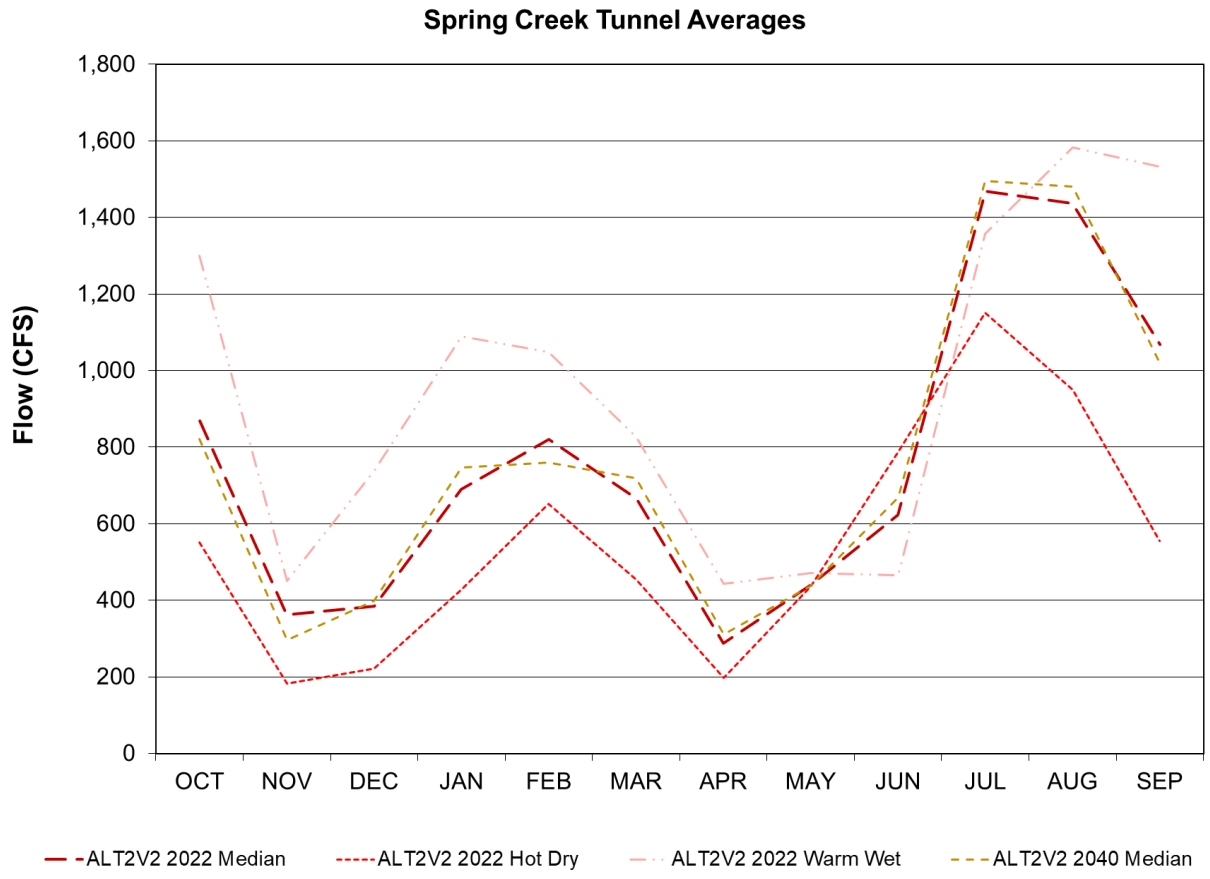

Figure F.2-6-8. Long-term Average Spring Creek Tunnel Flow

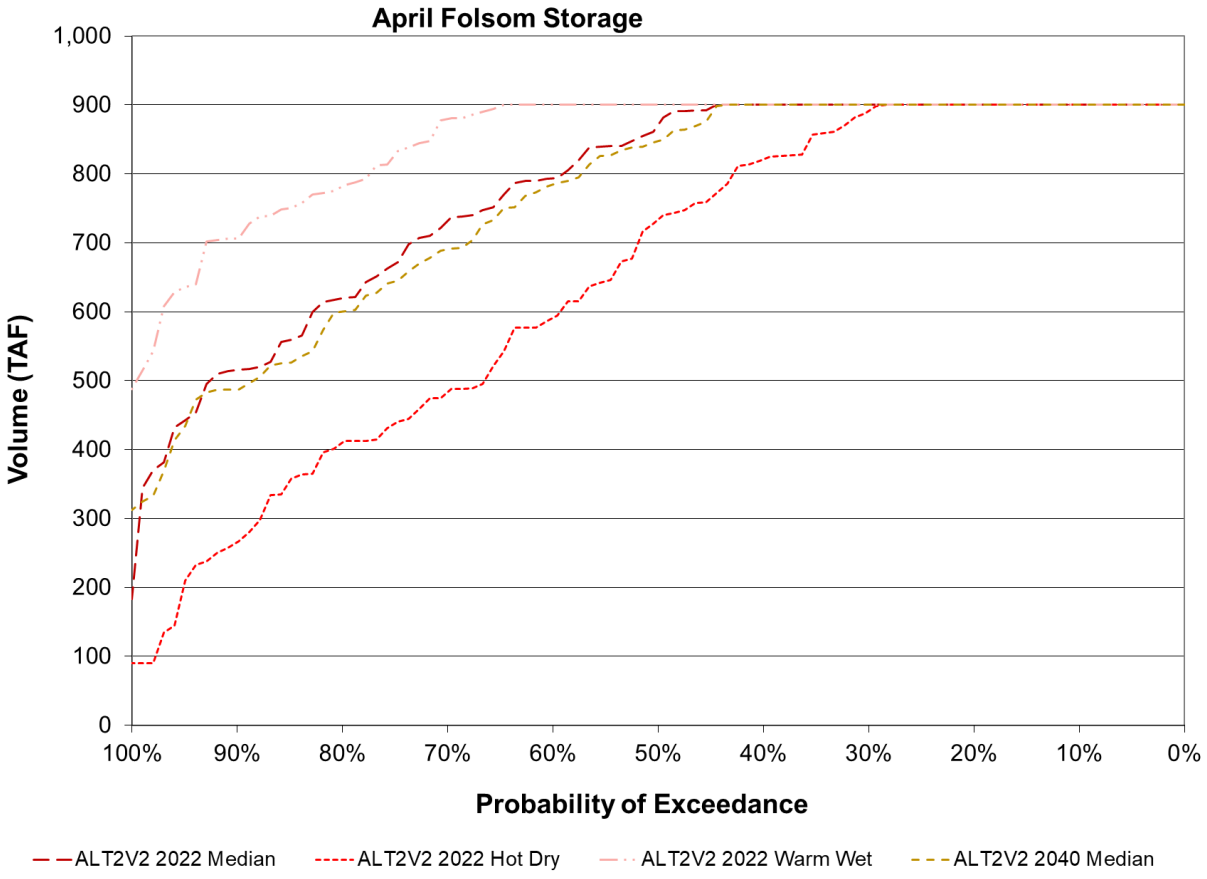

Figure F.2-6-9. End of April Folsom Storage

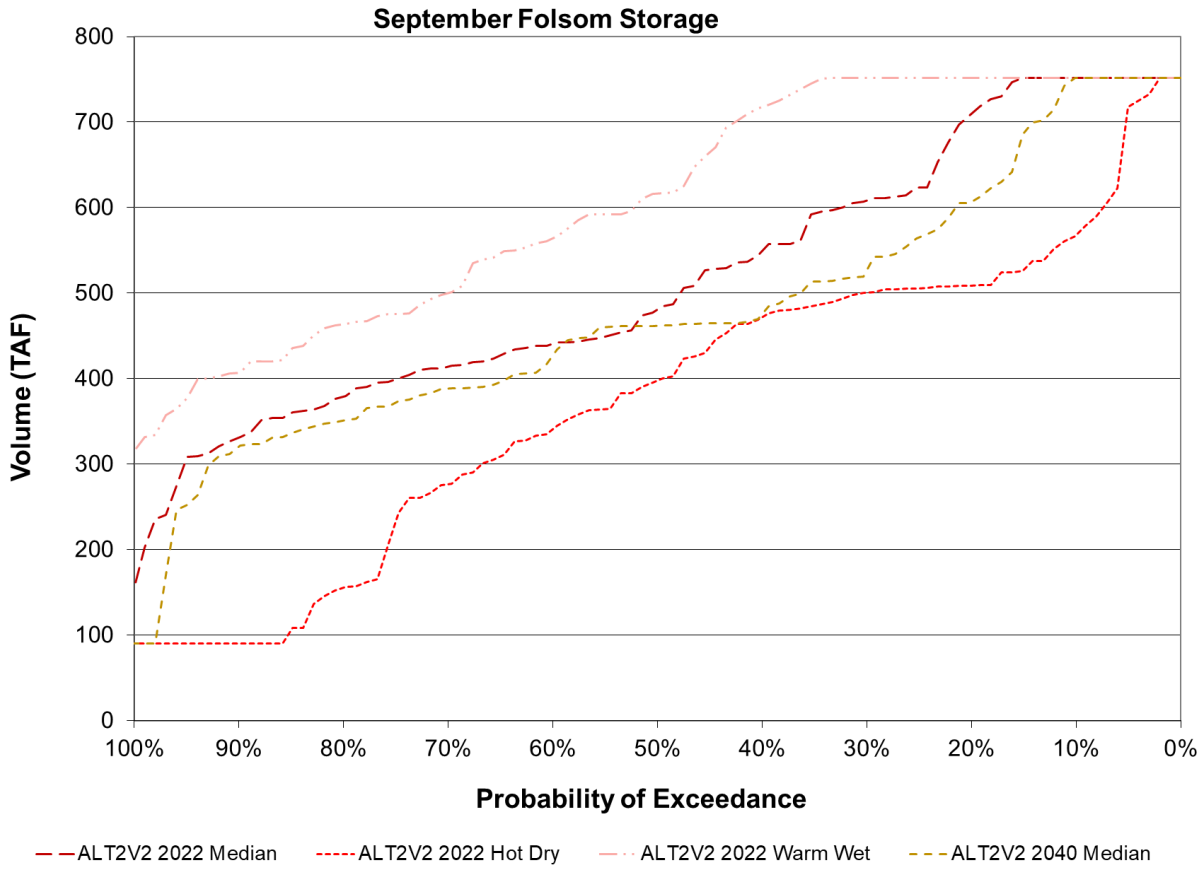

Figure F.2-6-10. End of September Folsom Storage

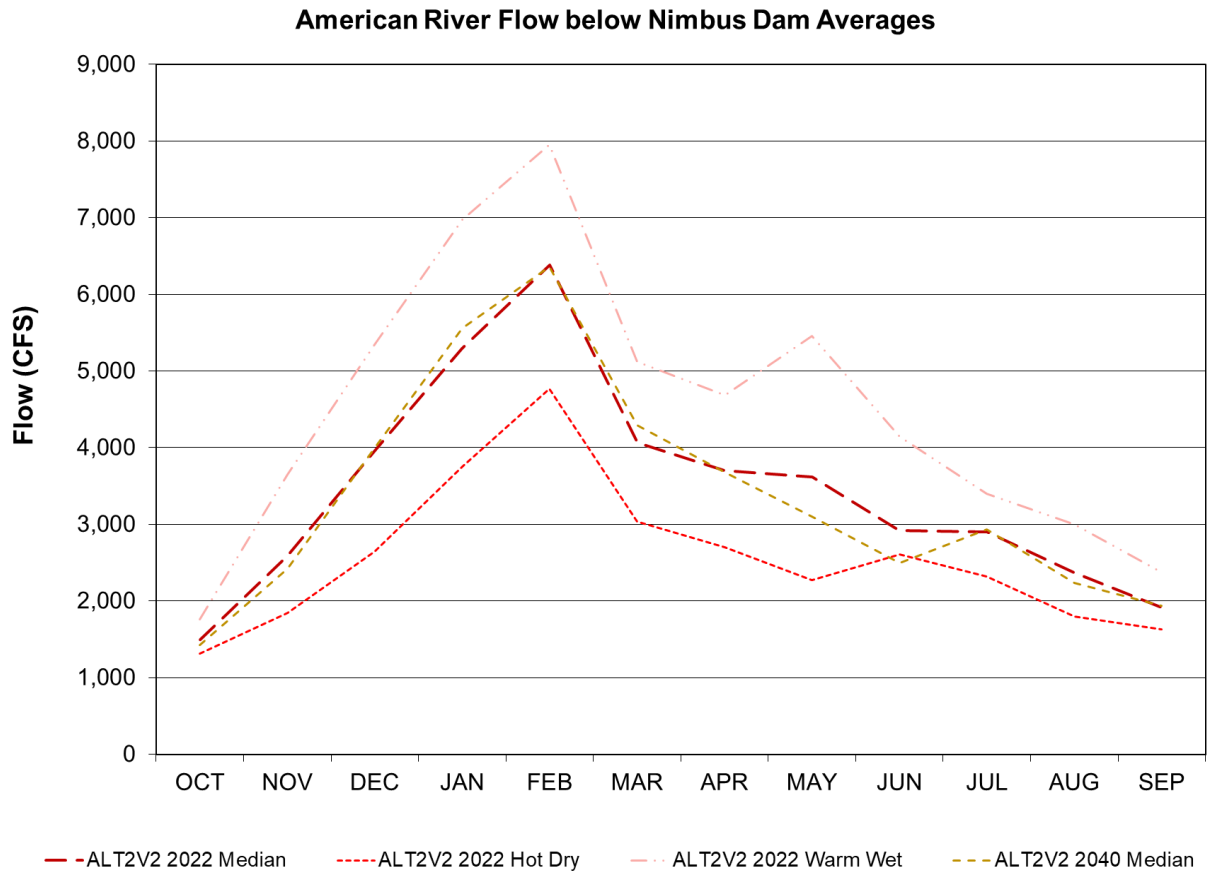

Figure F.2-6-11. Long-term Average American River flow below Nimbus Dam

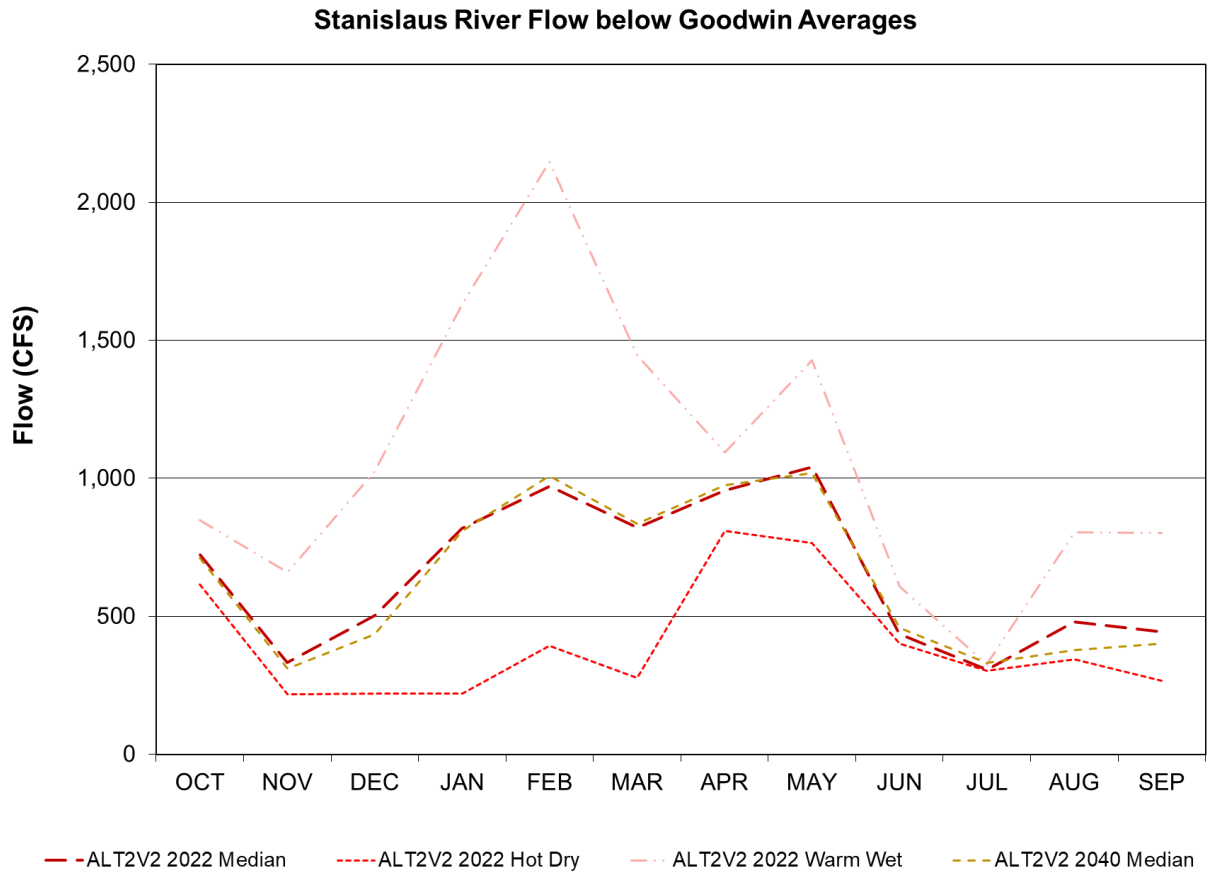

Figure F.2-6-12. Long-term Average Stanislaus River flow below Goodwin

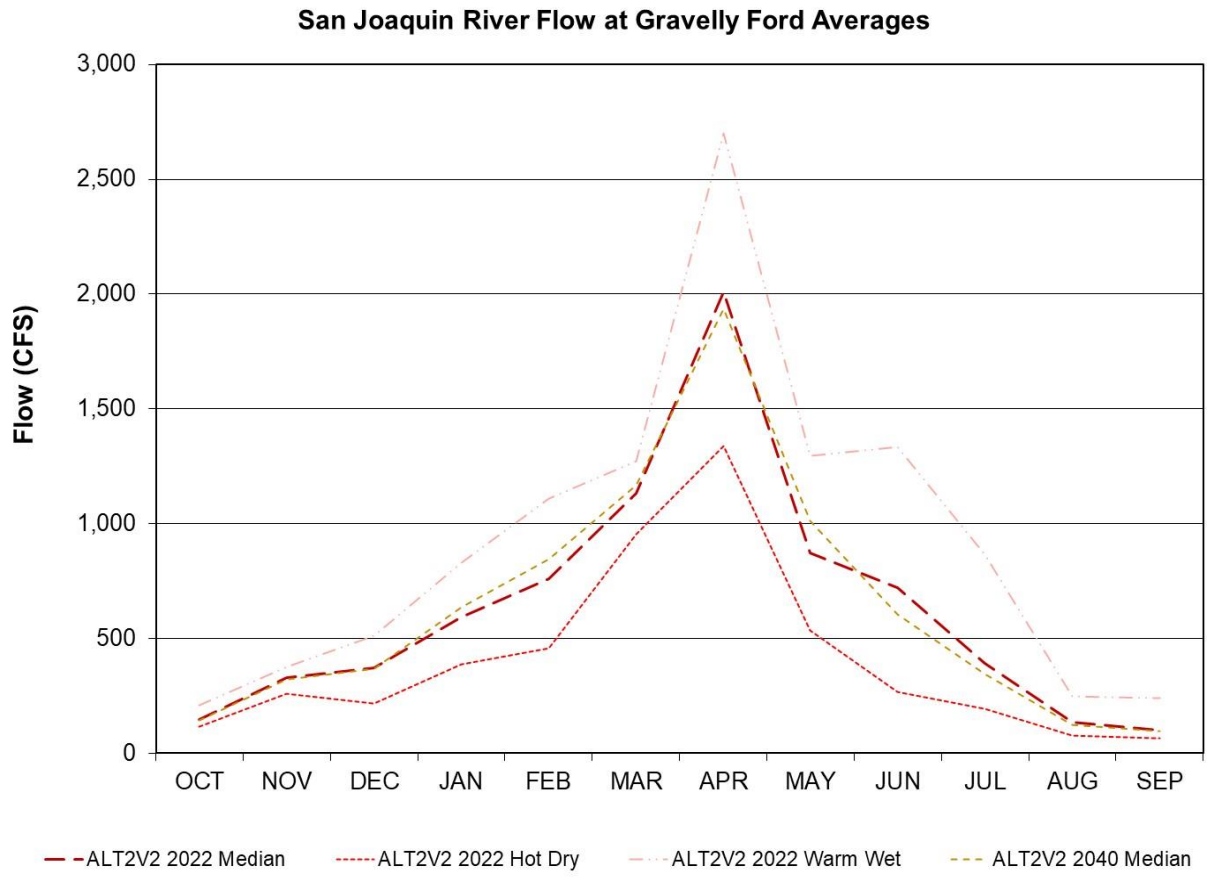

Figure F.2-6-13. Long-term Average San Joaquin River flow at Gravelly Ford

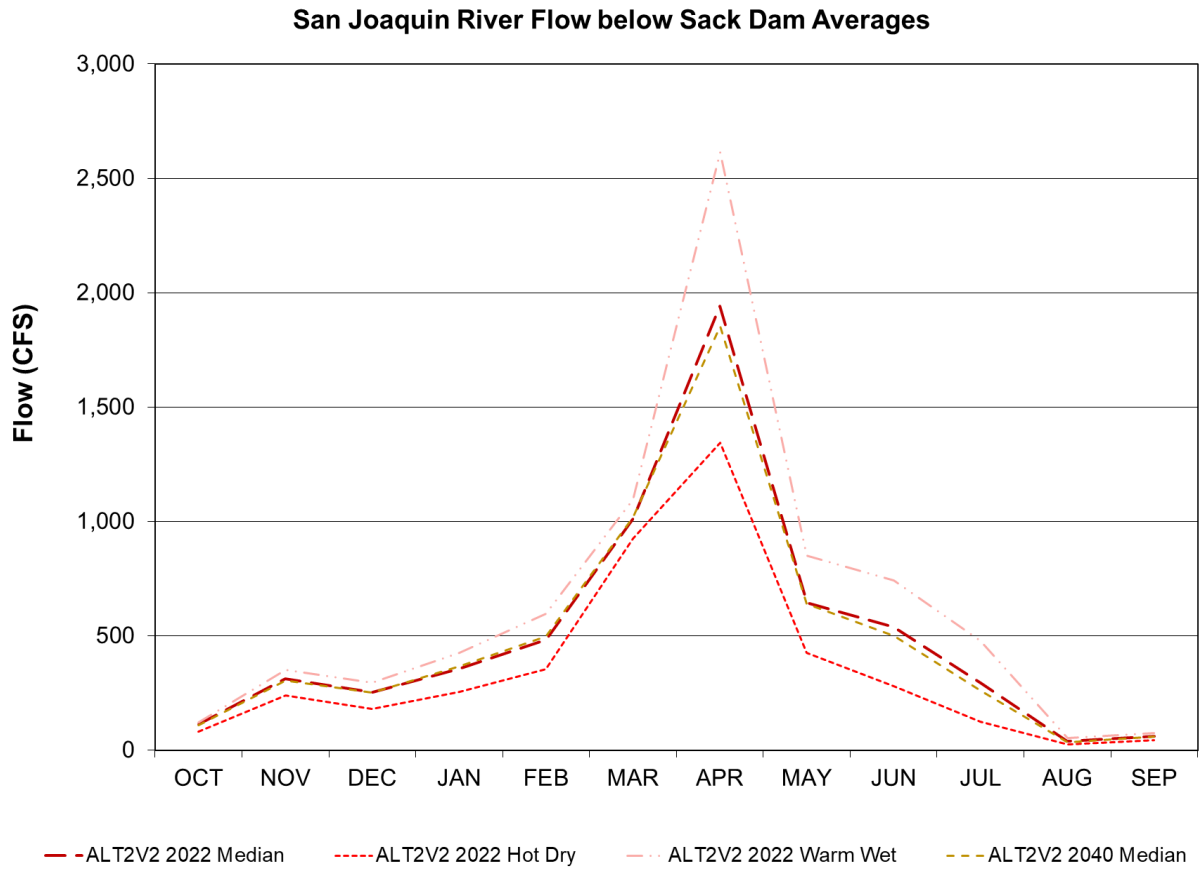

Figure F.2-6-14. Long-term Average San Joaquin River flow below Sack Dam

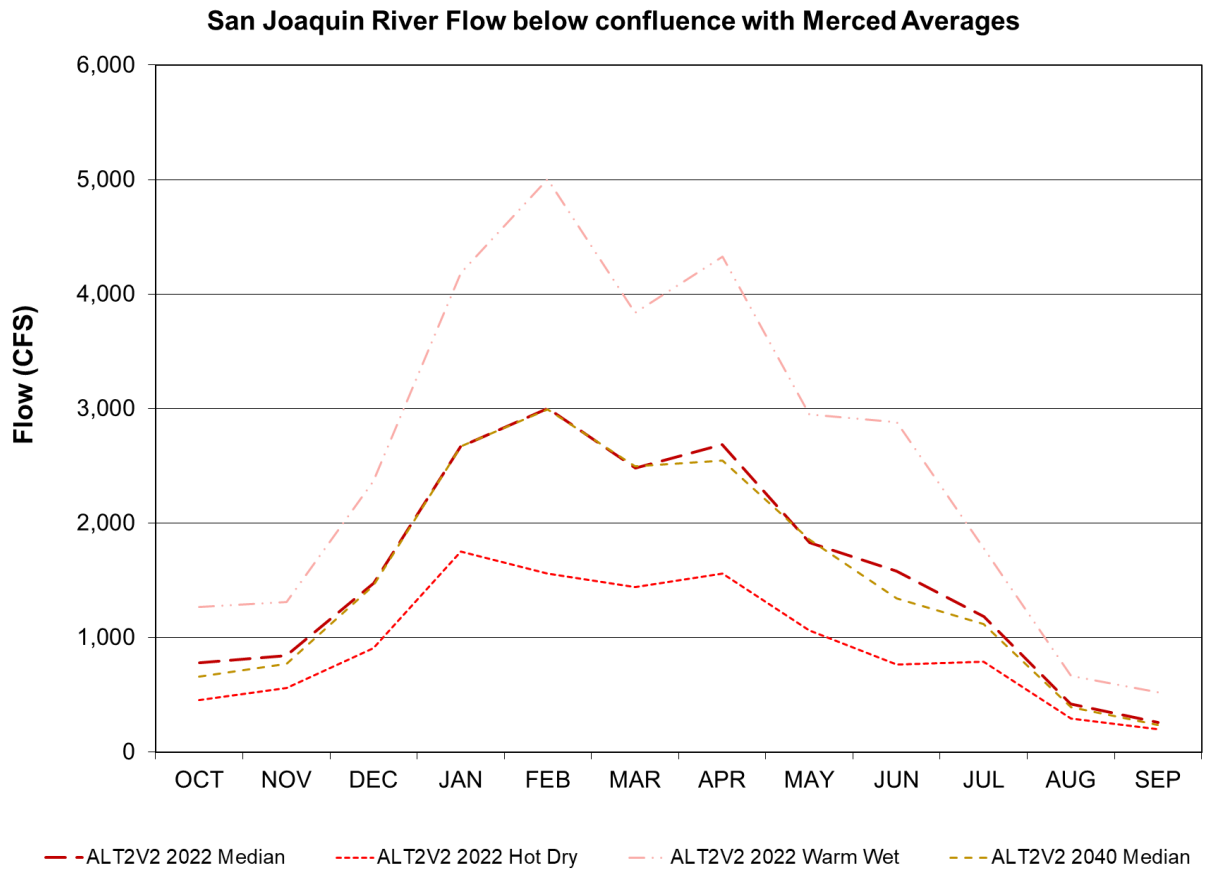

Figure F.2-6-15. Long-term Average San Joaquin River flow below Confluence with Merced River

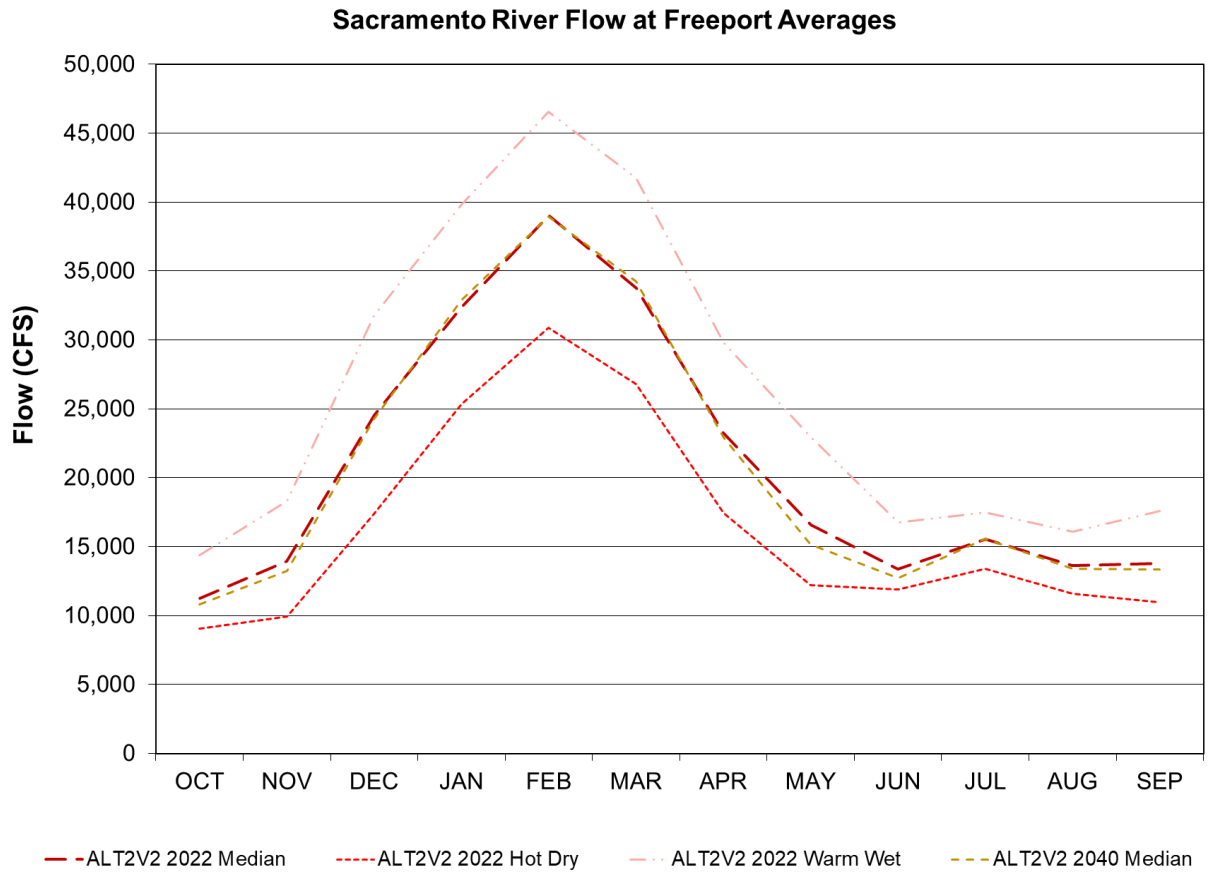

Figure F.2-6-16. Long-term Average Sacramento River flow at Freeport

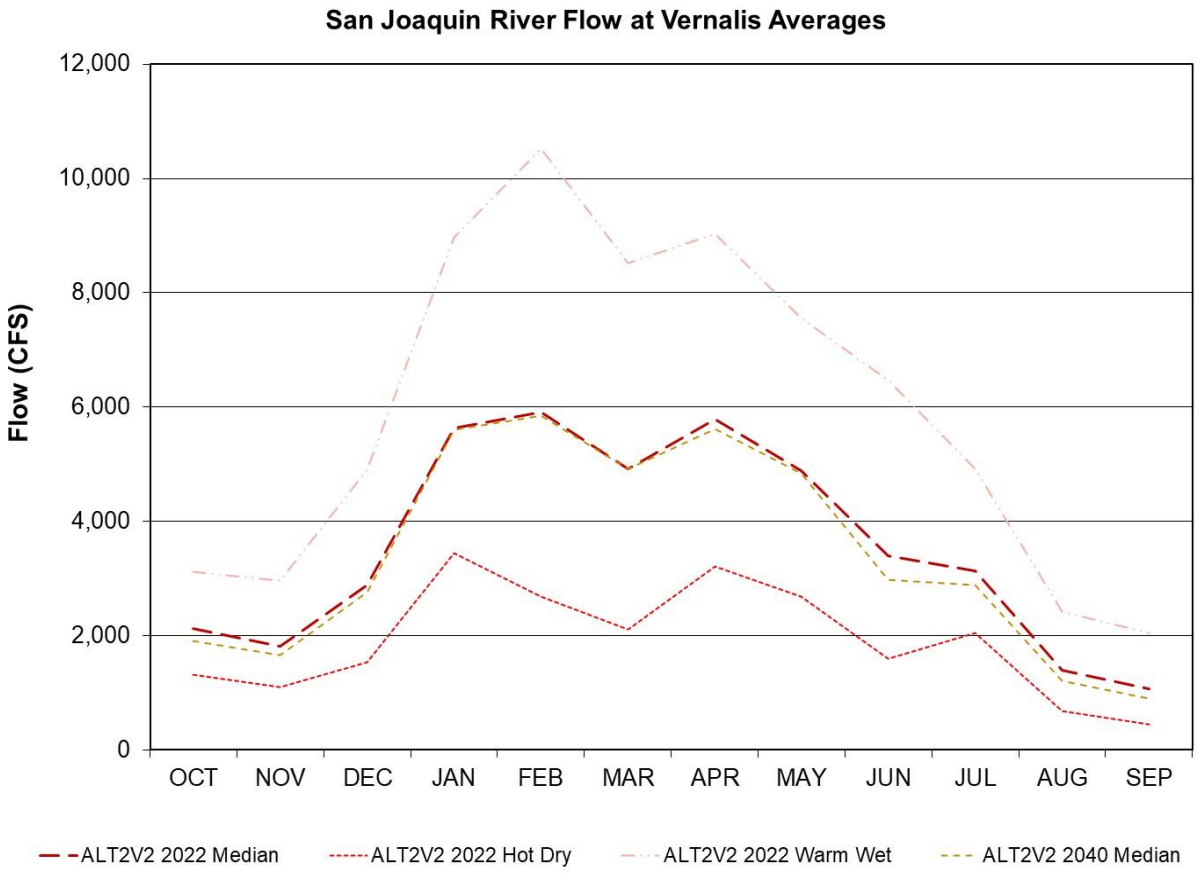

Figure F.2-6-17. Long-term Average San Joaquin River flow at Vernalis

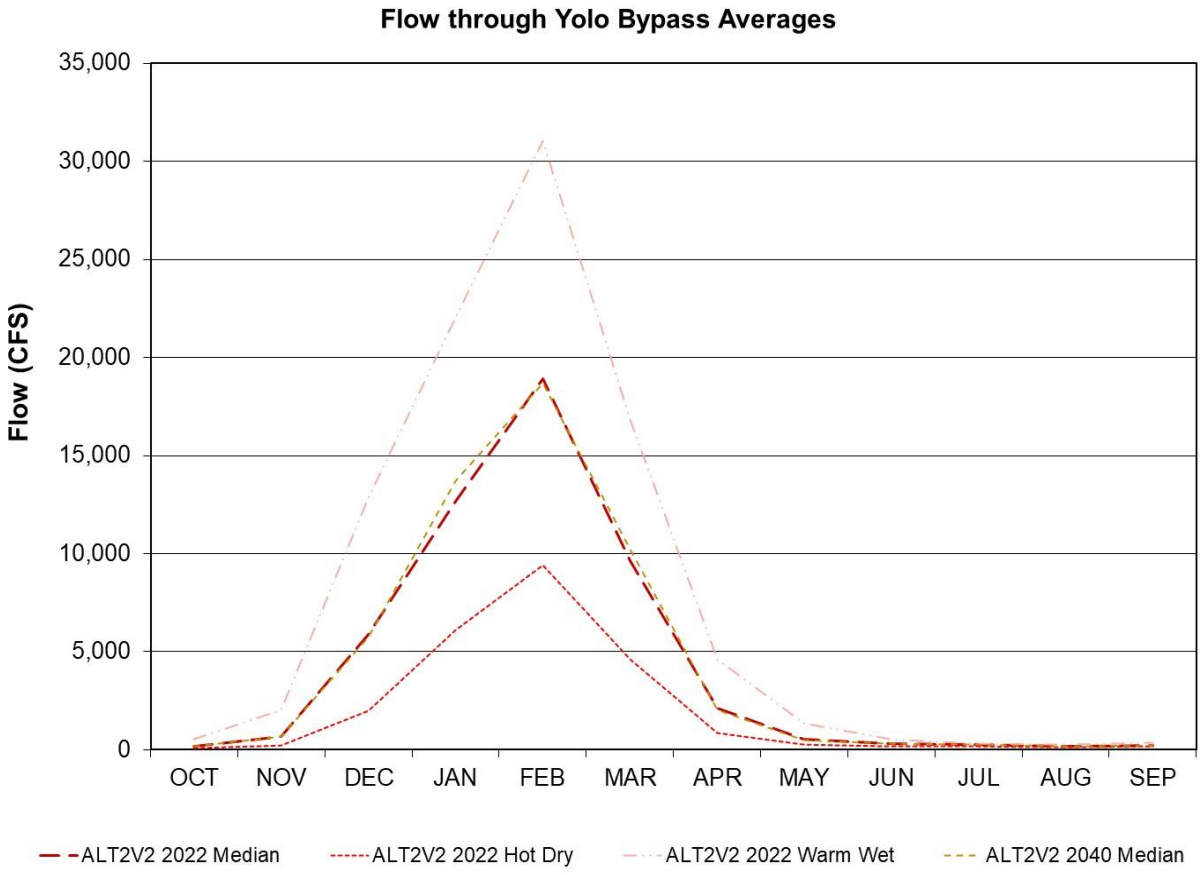

Figure F.2-6-18. Long-term Average Yolo Bypass Flow

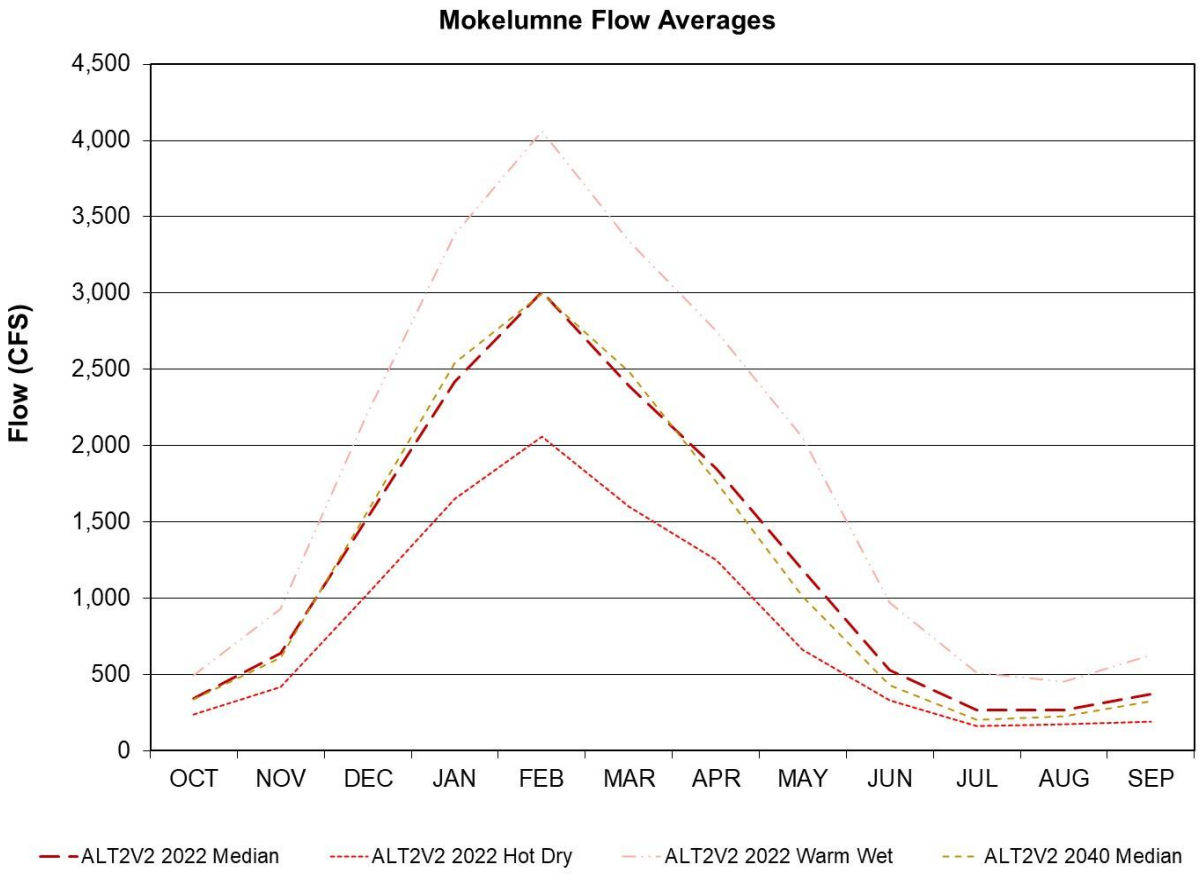

Figure F.2-6-19. Long-term Average Mokelumne River Flow

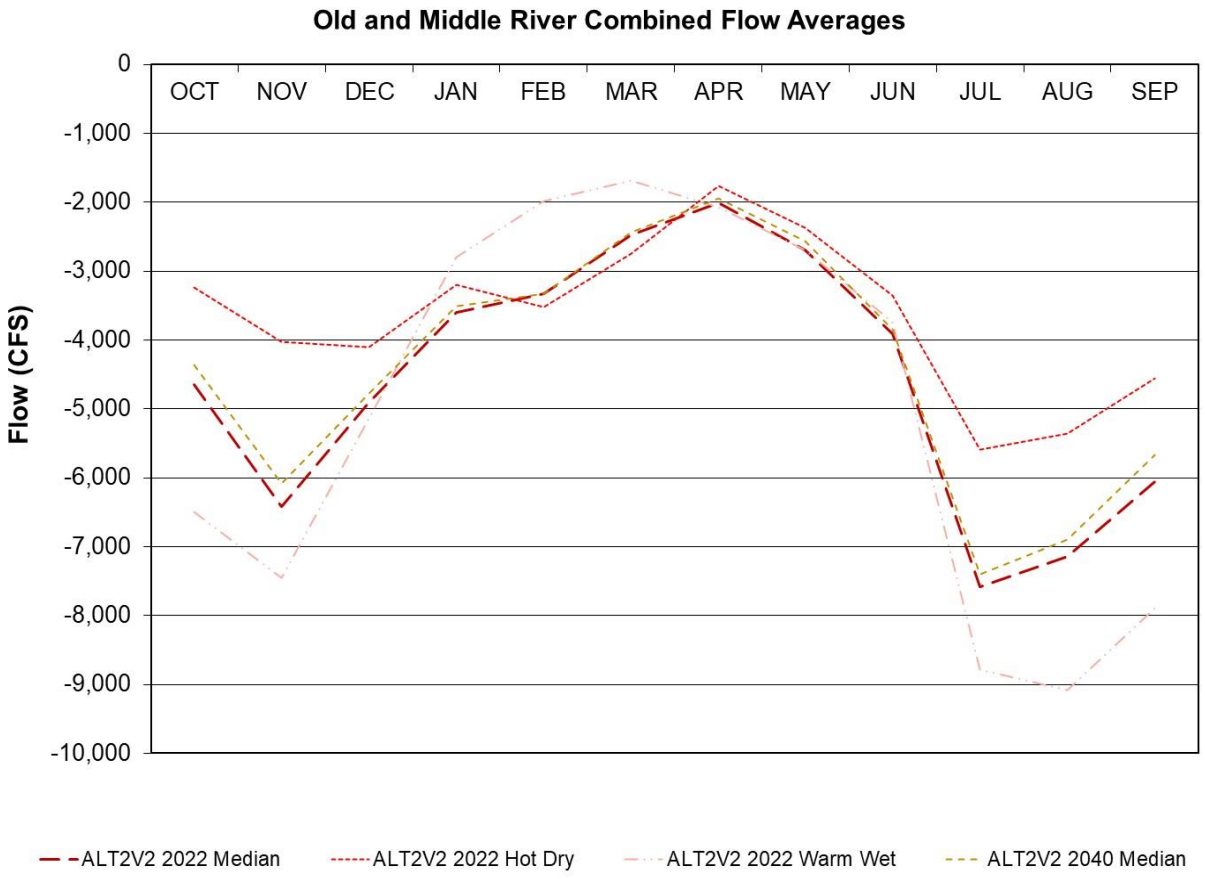

Figure F.2-6-20. Long-term Average Old and Middle River Combined Flow

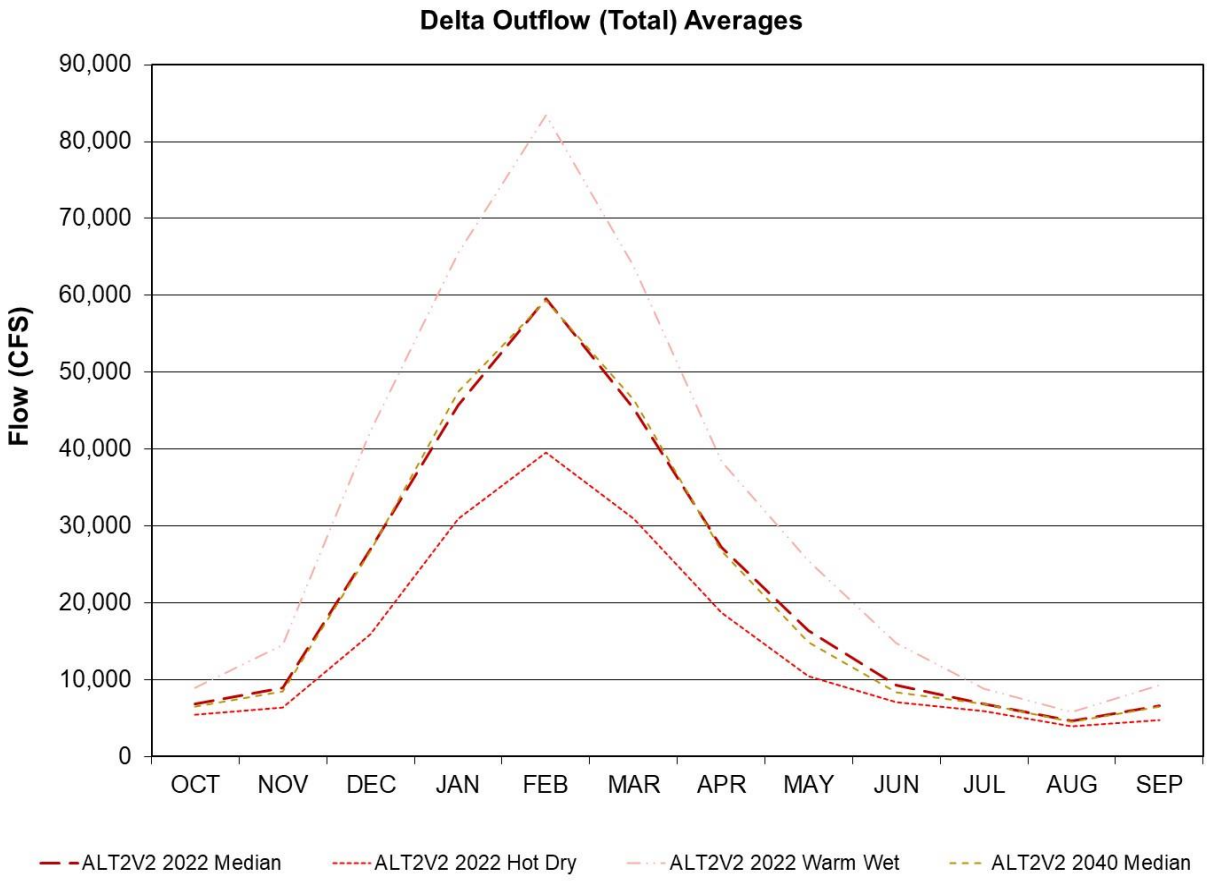

Figure F.2-6-21. Long-term Average Delta Outflow

F.2-6.2.2 HEC5Q

F.2-6.2.2.1 Sacramento River

Figure F.2-6-22 through Figure F.2-6-27 summarize temperature outcomes under the climate sensitivities for Alt 2v2 with the mixed location temperature logic. The mixed location logic applies a 53.5 °F target at a location ranging among Airport Road, Clear Creek, and Hwy 44 depending on the water year bin type. TDM was estimated using the standard LTO parameterization.

The Alt 2v2 TDM estimate (Figure F.2-6-22) displays large climate variability. The 2022 Median climate scenario exceeds 10% TDM in approximately 20% of simulated years. The smoothness of the TDM exceedance curve without a discrete transition in behavior implies a continuous expenditure of cold-water resources without a clear indicator for lower potential target temperatures. However, the smoothness of the curve does not guarantee that the temperature logic is optimal. Under the 2022 Warm Wet scenario, TDM is generally reduced below the 30% exceedance, with maximum TDM reducing from approximately 100% to 70% compared to the 2022 Median scenario. The 2022 Hot Dry scenario shifts TDM to higher values than the 2022 Median scenario due to less water available and generally warmer conditions. The 2040 Median scenario generally tracks the 2022 scenario, but at a somewhat higher TDM.

The TDM outcomes follow the same trend as the Sacramento River temperatures. Figure F.2-6-23 and Figure F.2-6-24 give the average and maximum May through end of October temperatures in the Sacramento River below Clear Creek with Figure F.2-6-25 and Figure F.2-6-26 providing the same information for Red Bluff. TDM outcomes correlate with the average and maximum temperatures across the climate scenarios. The volume of water less than 52 °F at the end of April, given in Figure F.2-6-27, also correlates with TDM outcomes. The similarity of the 2022 Median and 2040 Median cold-water pools with different temperature and TDM outcomes demonstrates the importance of instream warming.

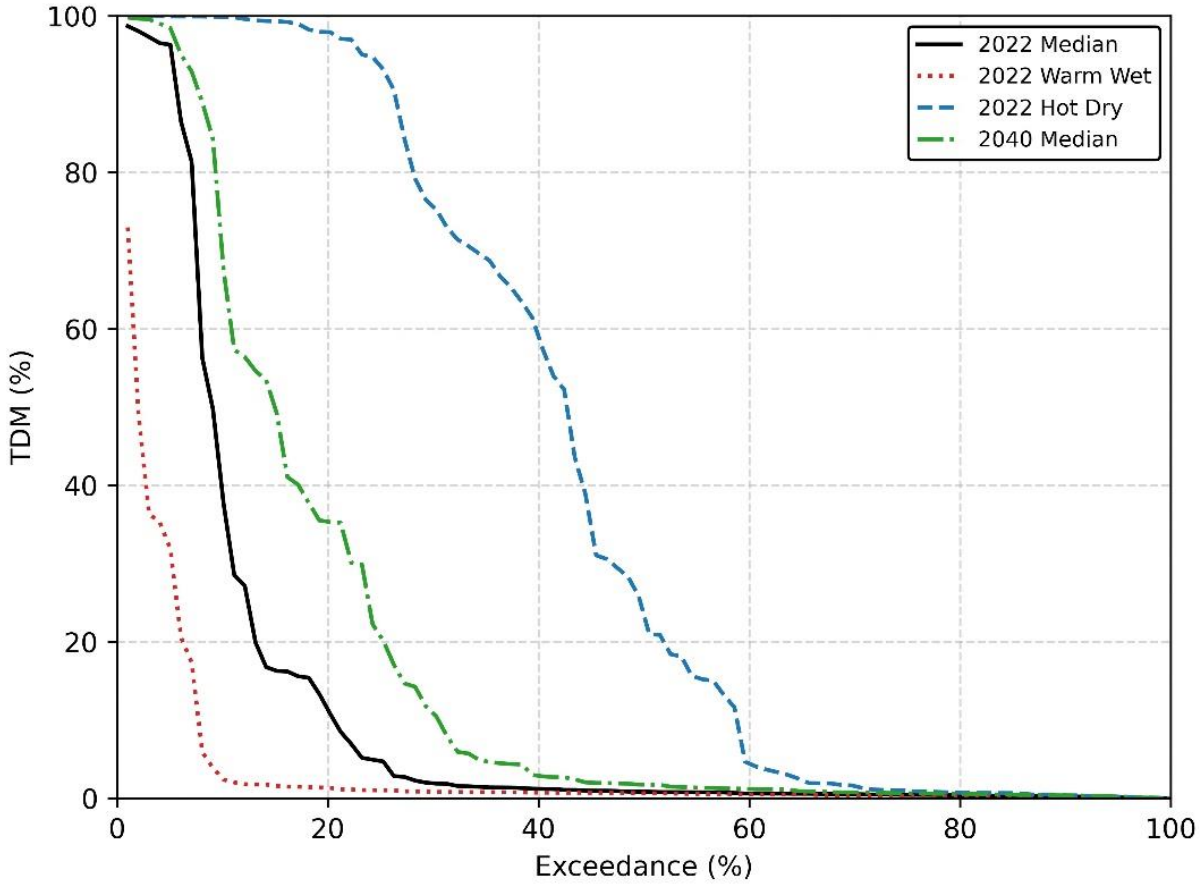

Figure F.2-6-22. Martin model TDM exceedance plot for the Alt2v2 alternative under various climate assumptions for water years 1923 through 2021

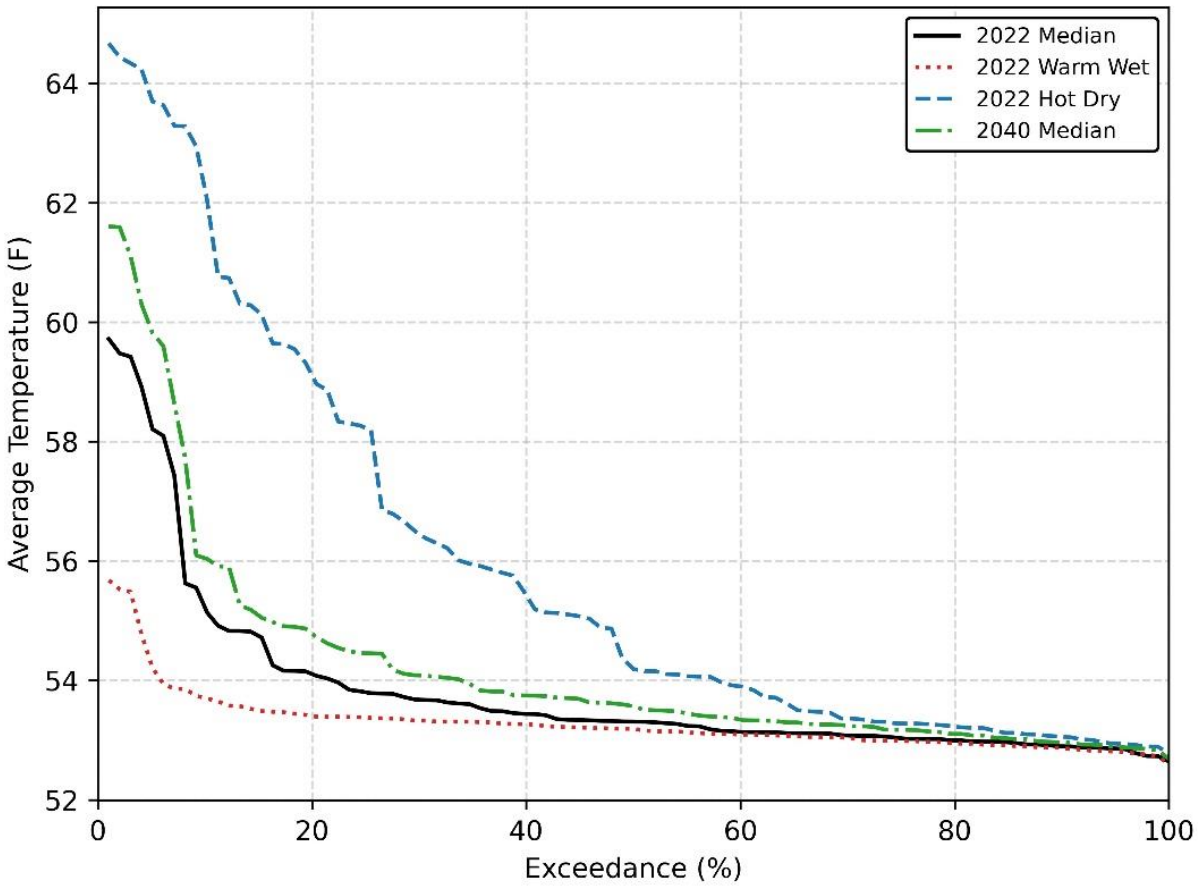

Figure F.2-6-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for the Alt2v2 alternative under various climate assumptions for water years 1923 through 2020

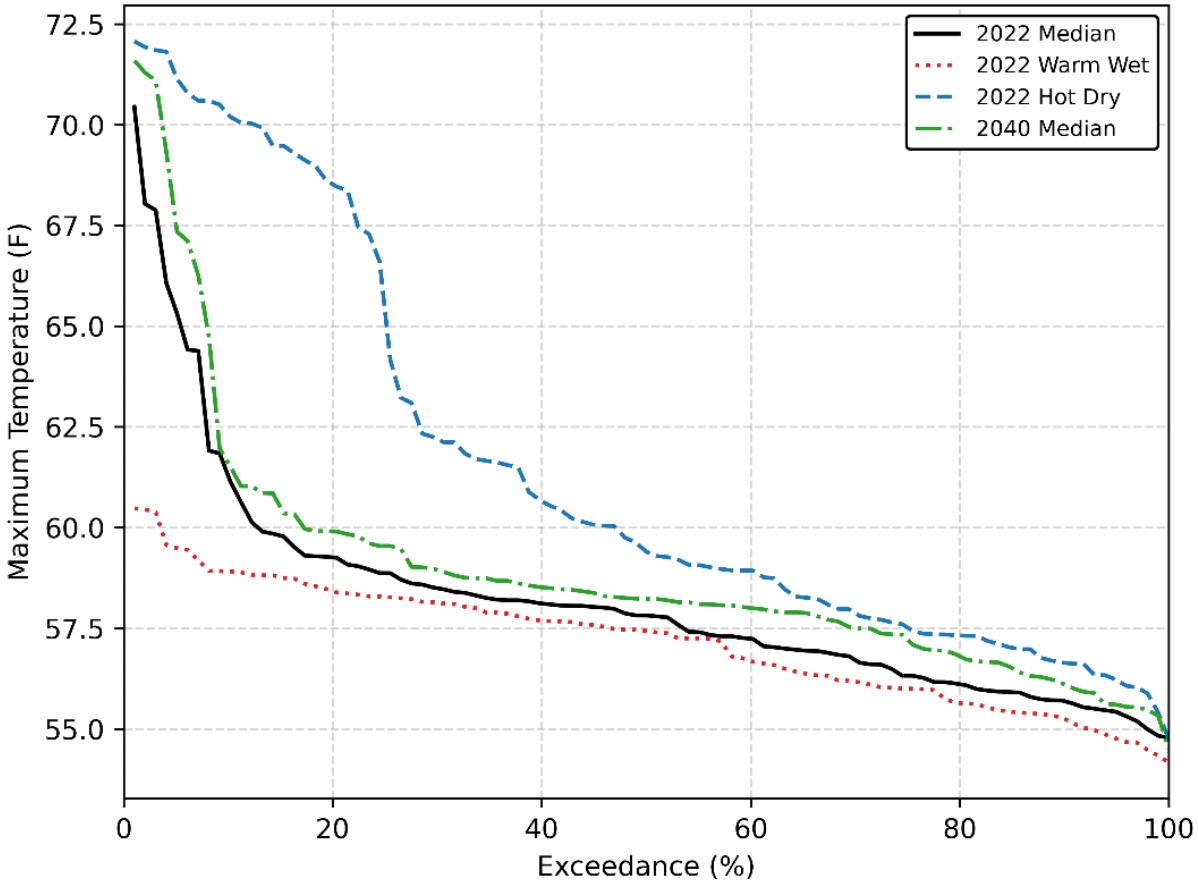

Figure F.2-6-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Atl2v2 alternative under various climate assumptions for water years 1923 through 2020

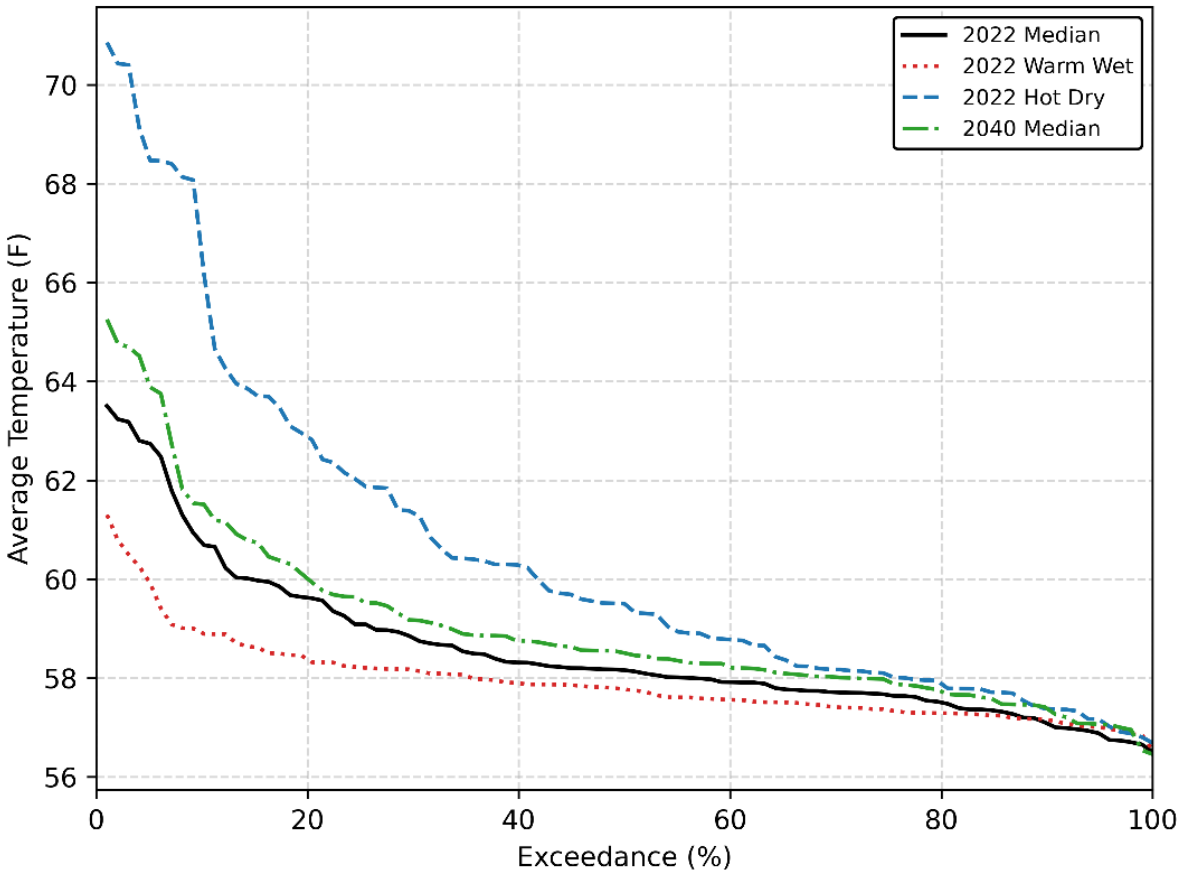

Figure F.2-6-25. Average water year temperatures on the Sacramento River at Red Bluff for the Alt2v2 alternative under various climate assumptions from May through end of October for water years 1923 through 2020

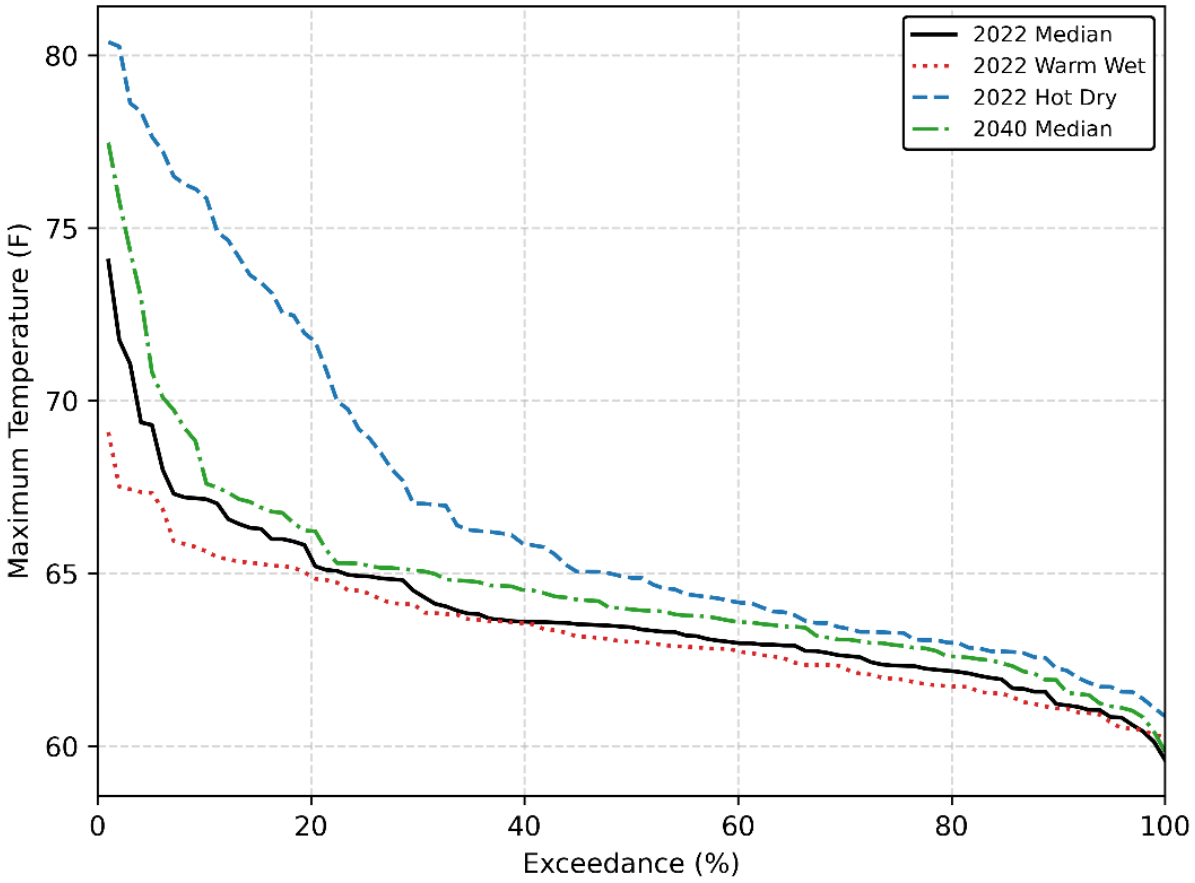

Figure F.2-6-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for Atl2v2 alternative under various climate assumptions for water years 1923 through 2020

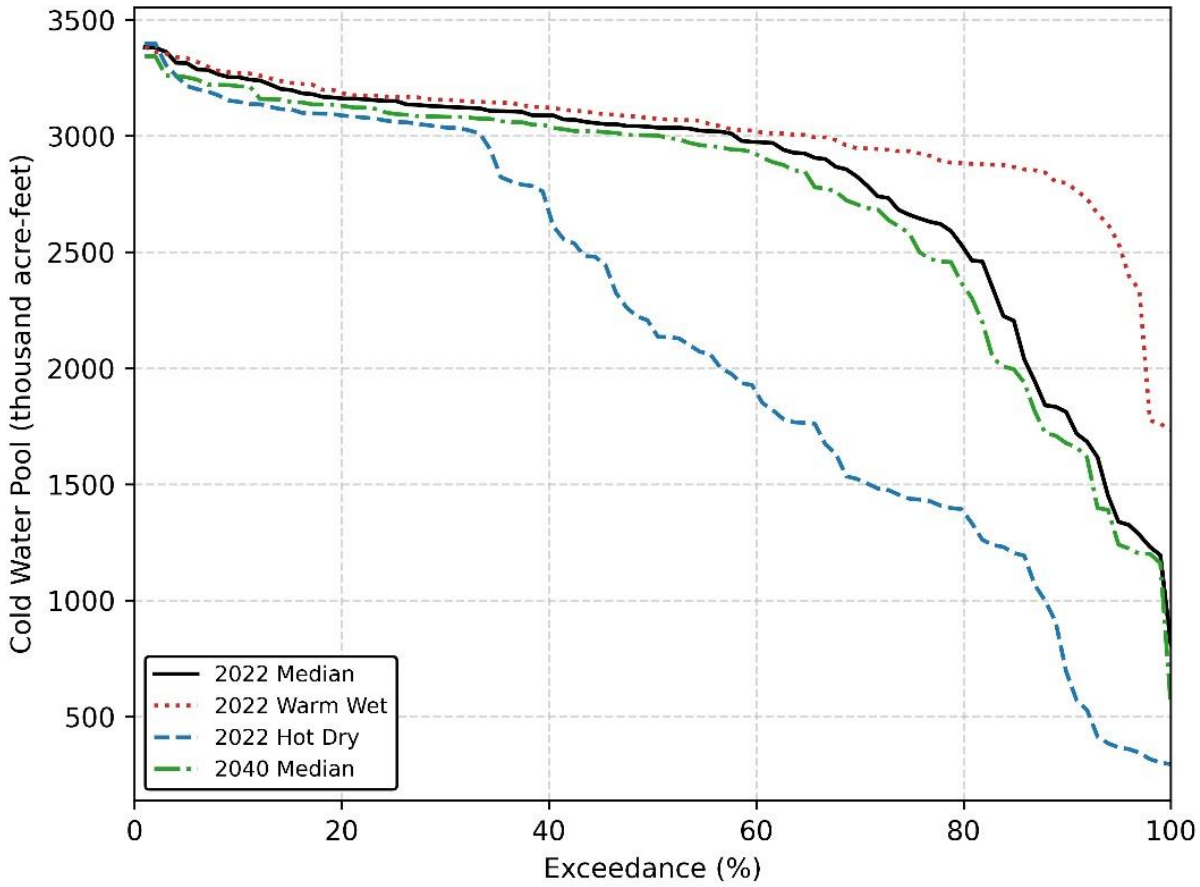

Figure F.2-6-27. Volume of water at the end of April less than 52 °F in Shasta Lake for the Alt2v2 alternative under various climate assumptions for water years 1923 through 2021

F.2-6.2.2.2 American River

Figure F.2-6-28 through Figure F.2-6-30 focus on the American River basin. Average May through end of October temperatures (Figure F.2-6-28) at the Watt Avenue compliance location are higher in the 2022 Hot Dry and 2040 Median scenarios as compared to the 2022 Median condition. Interestingly, although the 2022 Hot Dry scenario is hotter than the 2040 Median at the highest temperatures, the differences in the scenarios are minimal at the coolest temperatures. The 2022 Warm Wet scenario, with generally more water available in the system and cooler temperatures, has lower May through end of October temperatures than the 2022 Median scenario. This scaling is maintained through the maximum May through end of October temperatures as well.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. The 2022 Warm Wet scenario has meaningfully larger end of April cold water pool (52 °F) as compared to the 2022 Median condition. Conversely, the 2022 Hot Dry scenario has meaningfully less cold water available than the 2022 Median. The availability of cold water is translated into temperature performance at Watt Avenue and compounded by the in-stream

warming. The 2022 Median and 2040 Median scenarios have similar end of April cold-water pool resources; however, the 2040 Median condition performs about a degree warmer than the 2022 Median. This difference is due in part to the greater in-stream warming as well as greater warming in the reservoir proper to reduce the cold water available in the temperature management season that is present under the 2040 Median scenario.

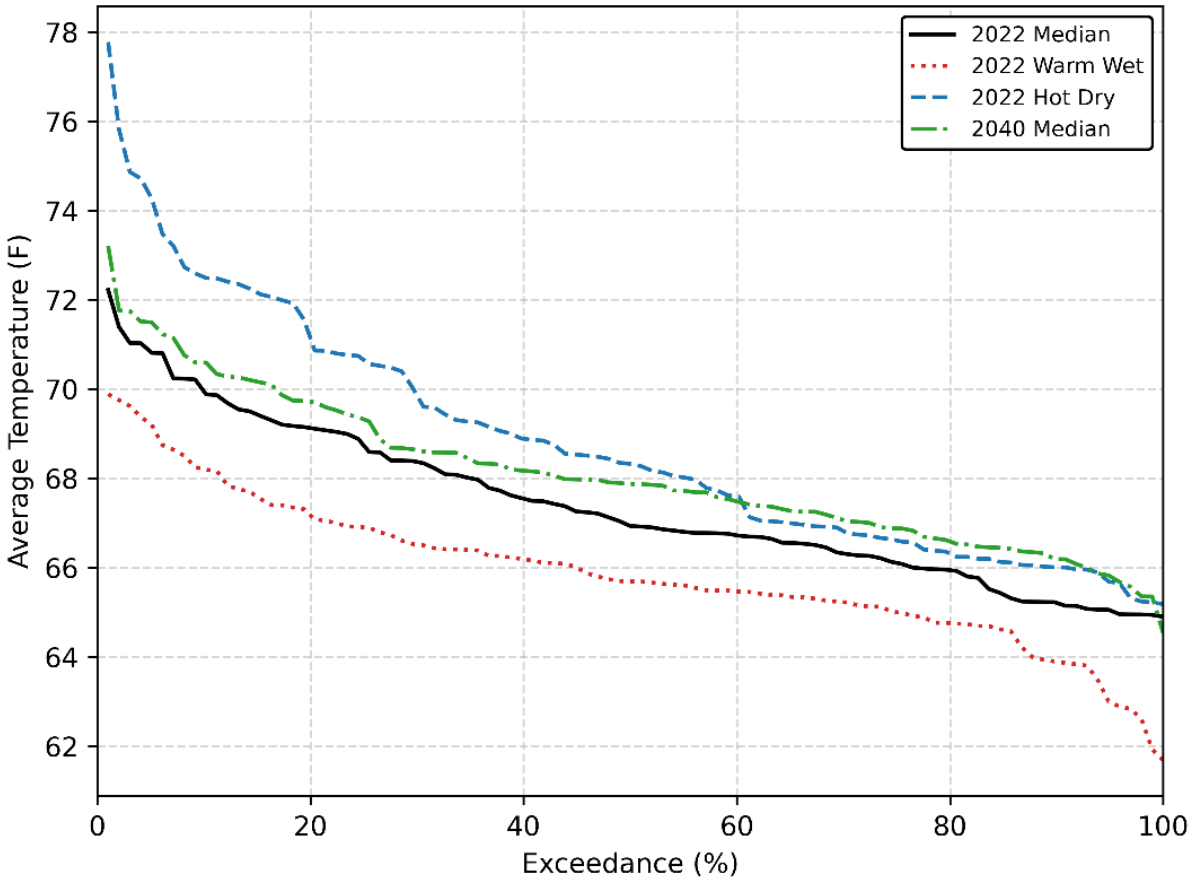

Figure F.2-6-28. Average May through end of October temperatures on the American River at Watt Avenue for the Atl2v2 alternative under various climate assumptions for water years 1923 through 2020

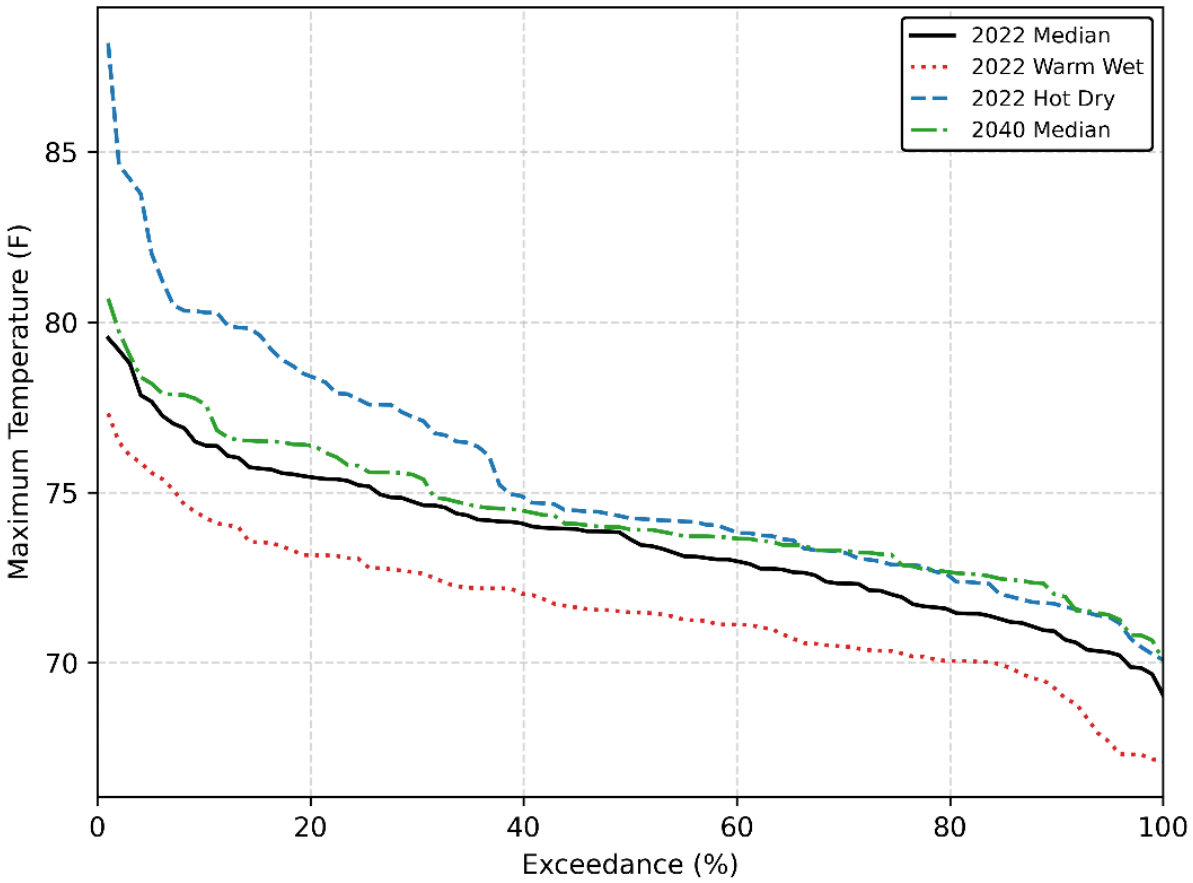

Figure F.2-6-29. Maximum May through end of October temperatures on the American River at Watt Avenue for the Alt2v2 alternative under various climate assumptions for water years 1923 through 2020

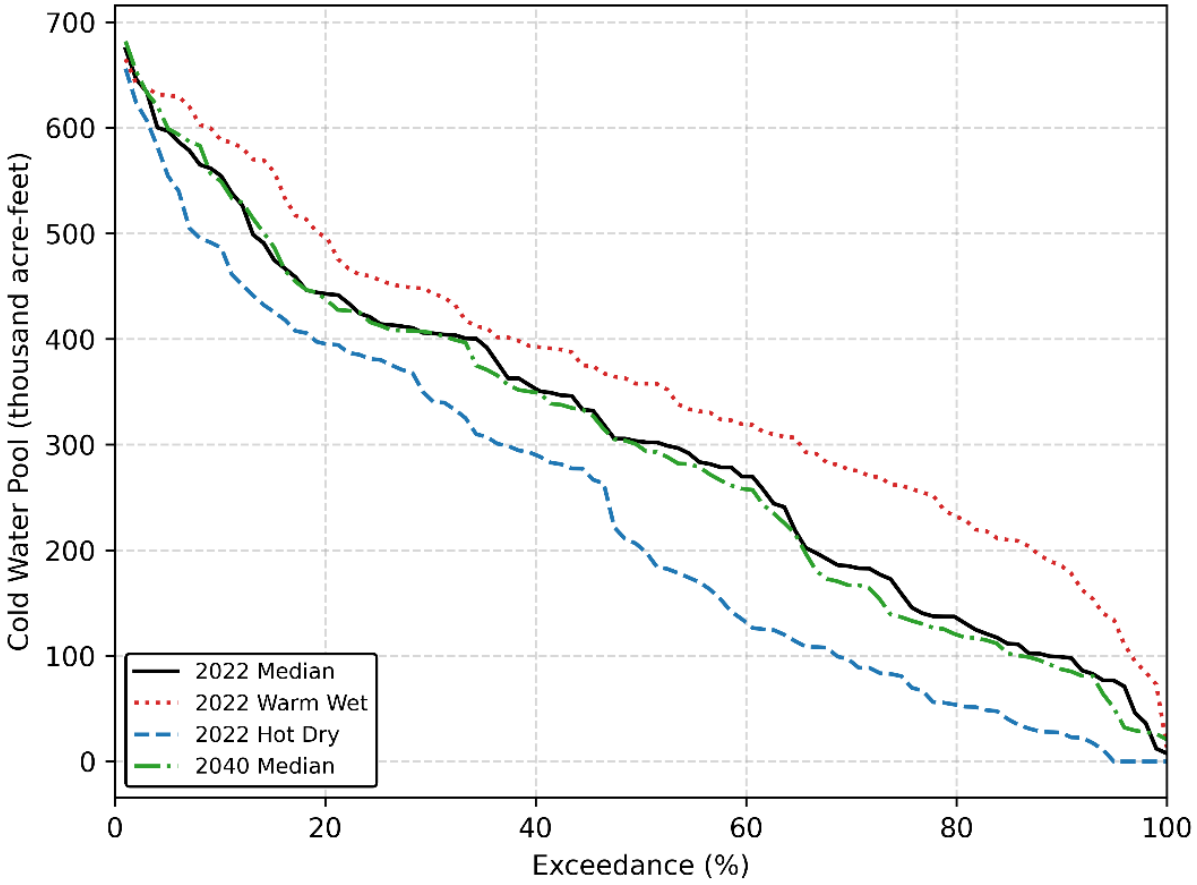

Figure F.2-6-30. Volume of water at the end of April less than 52 °F in Folsom Lake for the Alt2v2 alternative under various climate assumptions for water years 1923 through 2021

F.2-6.2.2.3 Stanislaus River

Figure F.2-6-31 and Figure F.2-6-32 summarize the temperature outcomes under the climate sensitivities for Alt2v2 in the Stanislaus basin. Average May through end of October temperatures at the Orange Blossom Bridge compliance location is hotter for the 2022 Hot Dry and 2040 Median scenarios when compared to the 2022 Median scenario. The 2022 Hot Dry scenario is hotter than the 2040 Median scenarios for all exceedances and the difference in temperatures between the two grows as the temperatures increase. The 2022 Warm Wet scenario average May through end of October temperatures at the Orange Blossom Bridge compliance location is cooler than the 2022 Median scenario due to generally more water available in the system and cooler temperatures. At high temperatures, the maximum May through October temperatures at the Orange Blossom Bridge compliance location follow a similar trend as the average May through October temperatures. At low temperatures, the 2022 Median, 2022 Hot Dry, and 2040 Median scenarios have similar maximum temperatures. The 2022 Warm Wet scenario has lower maximum temperatures at low temperatures when compared to the other scenarios.

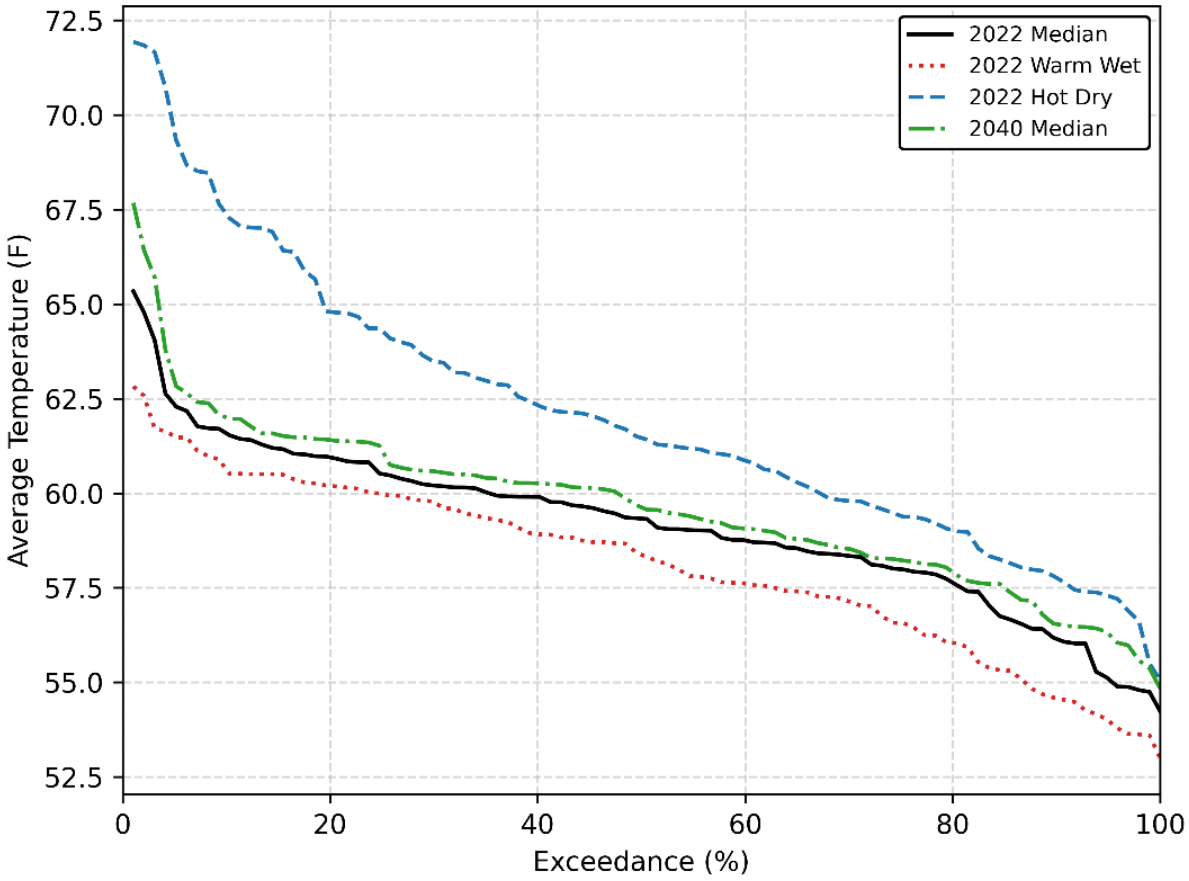

Figure F.2-6-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom Bridge for the Atl2v2 alternative under various climate assumptions for water years 1923 through 2019

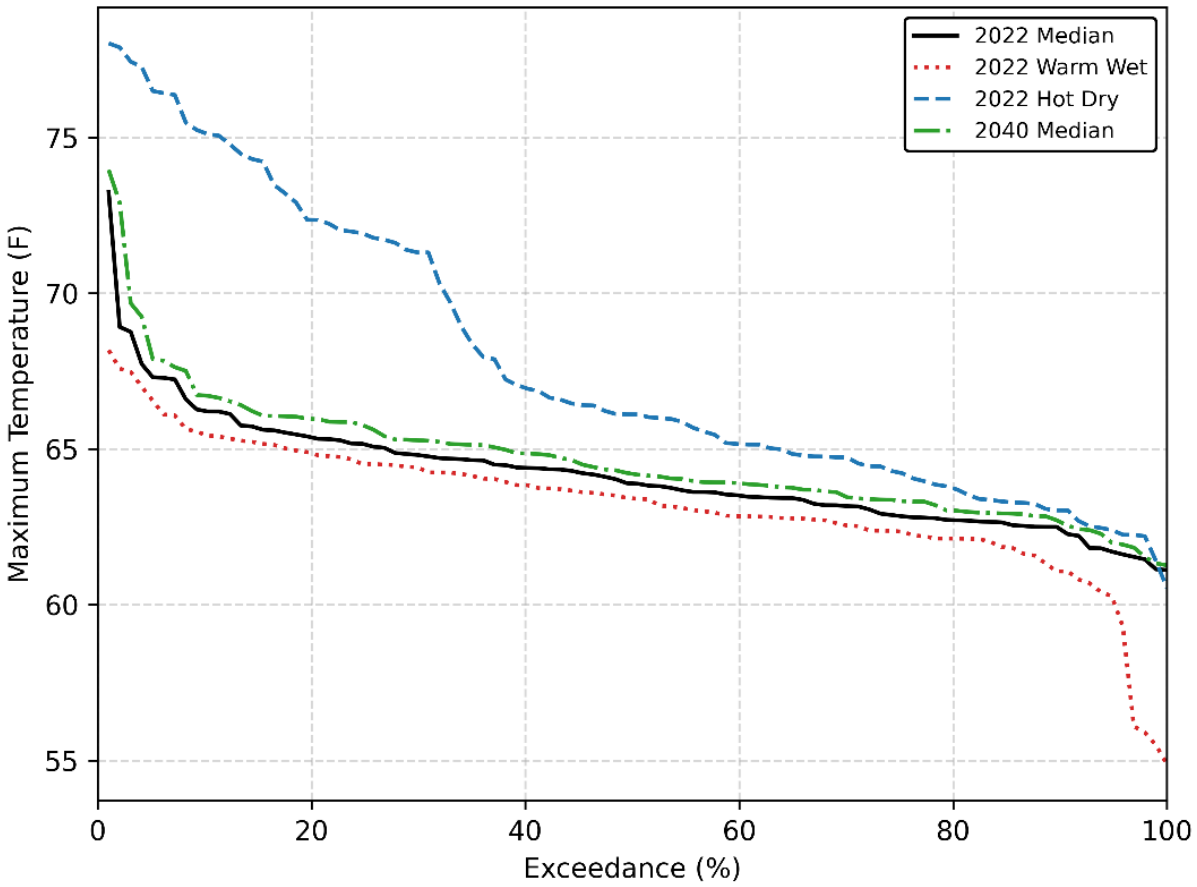

Figure F.2-6-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom Bridge for the Atl2v2 alternative under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Appendix F.2-5 2021 LTO Climate Sensitivity Analysis – Alt2v3

F.2-5.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative 2v3 without Temporary Urgency Change Petitions (TUCPs), under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-5.2 Climate Change Comparison

F.2-5.2.1 CalSim 3

Figure F.2-5-1 through Figure F.2-5-21 show CalSim 3 simulation results for Alternative 2v3 without TUCPs. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 2v3 without TUCPs were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough

- Sacramento River at Verona
- Sacramento River at Freeport
- Flow though Yolo Bypass
- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-5-1) and end of September (Figure F.2-5-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 22% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows (Figure F.2-5-3 through Figure F.2-5-8), long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of the reservoir management season, the differences are less notable, as river flows are due primarily to releases from storage instead of runoff events. Flows under the 2040 Median climate scenario are similar to flows under the 2022 Median climate scenario.

Clear Creek below Whiskeytown (Figure F.2-5-9) shows flow differences along the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall and winter months, with the least difference in summer months, especially the month of July. For Spring Creek inflow to Keswick Reservoir (Figure F.2-5-10), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-5-11) and end of September (Figure F.2-5-12) Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-5-13), flow differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months, with the summer months also showing some minor differences.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-5-14), flow differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. Flows across all climate conditions are similar in June and July, months when releases consist of stored water.

For long-term monthly average San Joaquin River flows, differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. San Joaquin River at Gravelly Ford (Figure F.2-5-15) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam (Figure F.2-5-16) are similar to those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced (Figure F.2-5-17).

For long-term monthly average flows in the Delta (Figure F.2-5-18 through Figure F.2-5-21), flow differences mostly follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. Flows across these climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River (Figure F.2-5-20) is an exception to the general trend, and the combined long-term flow averages for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

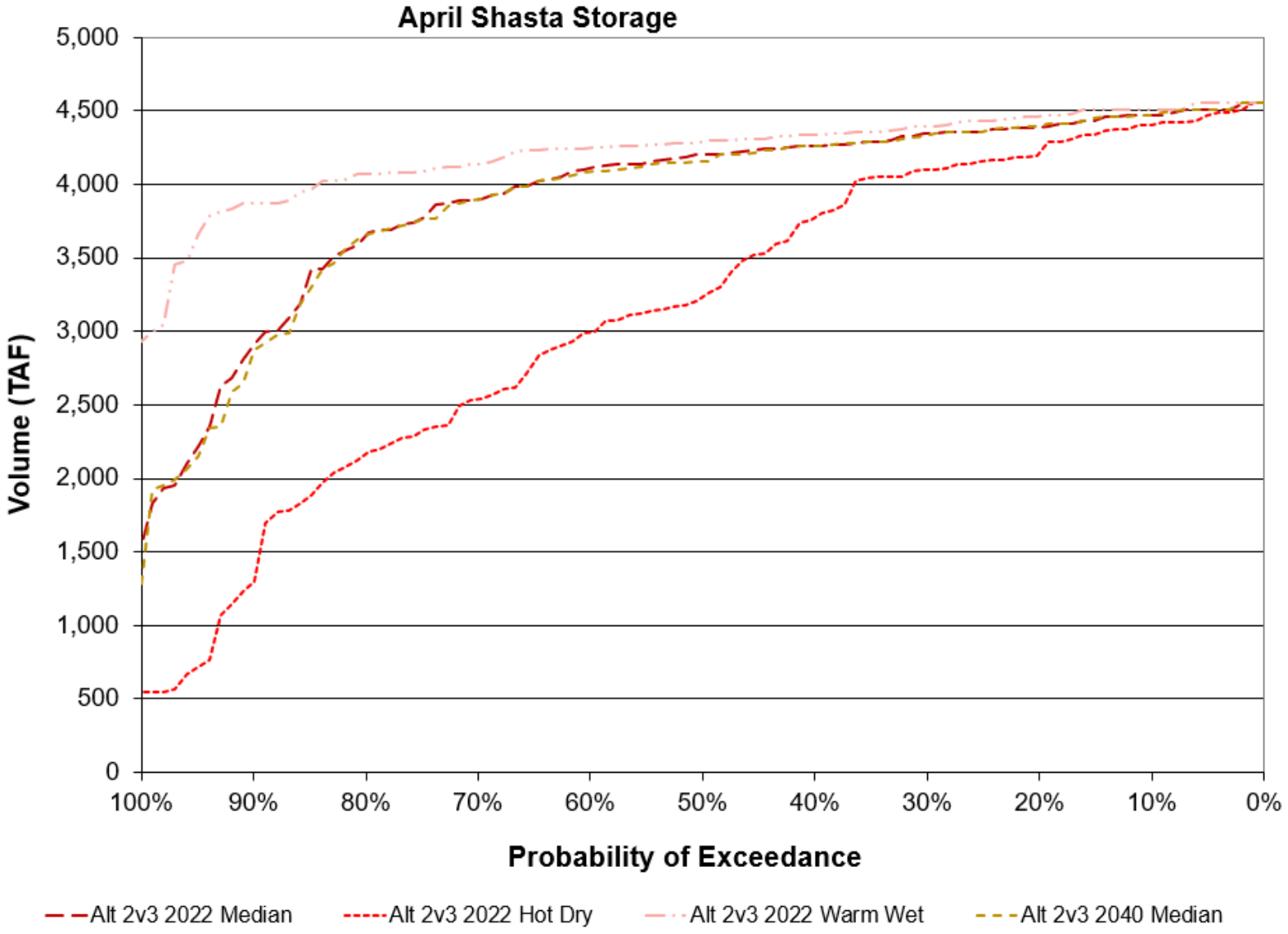

Figure F.2-5-1. End of April Shasta Storage

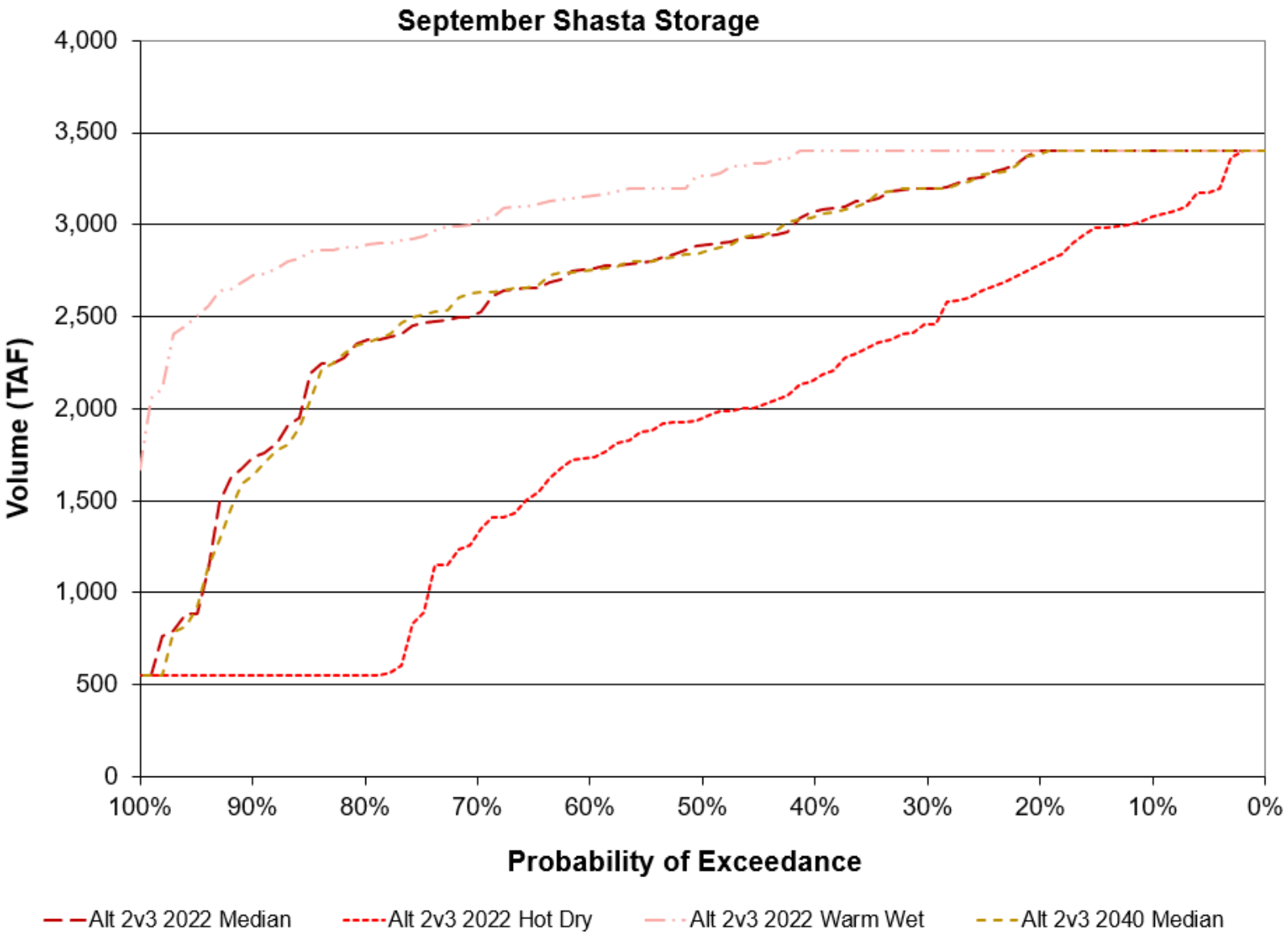

Figure F.2-5-2. End of September Shasta Storage

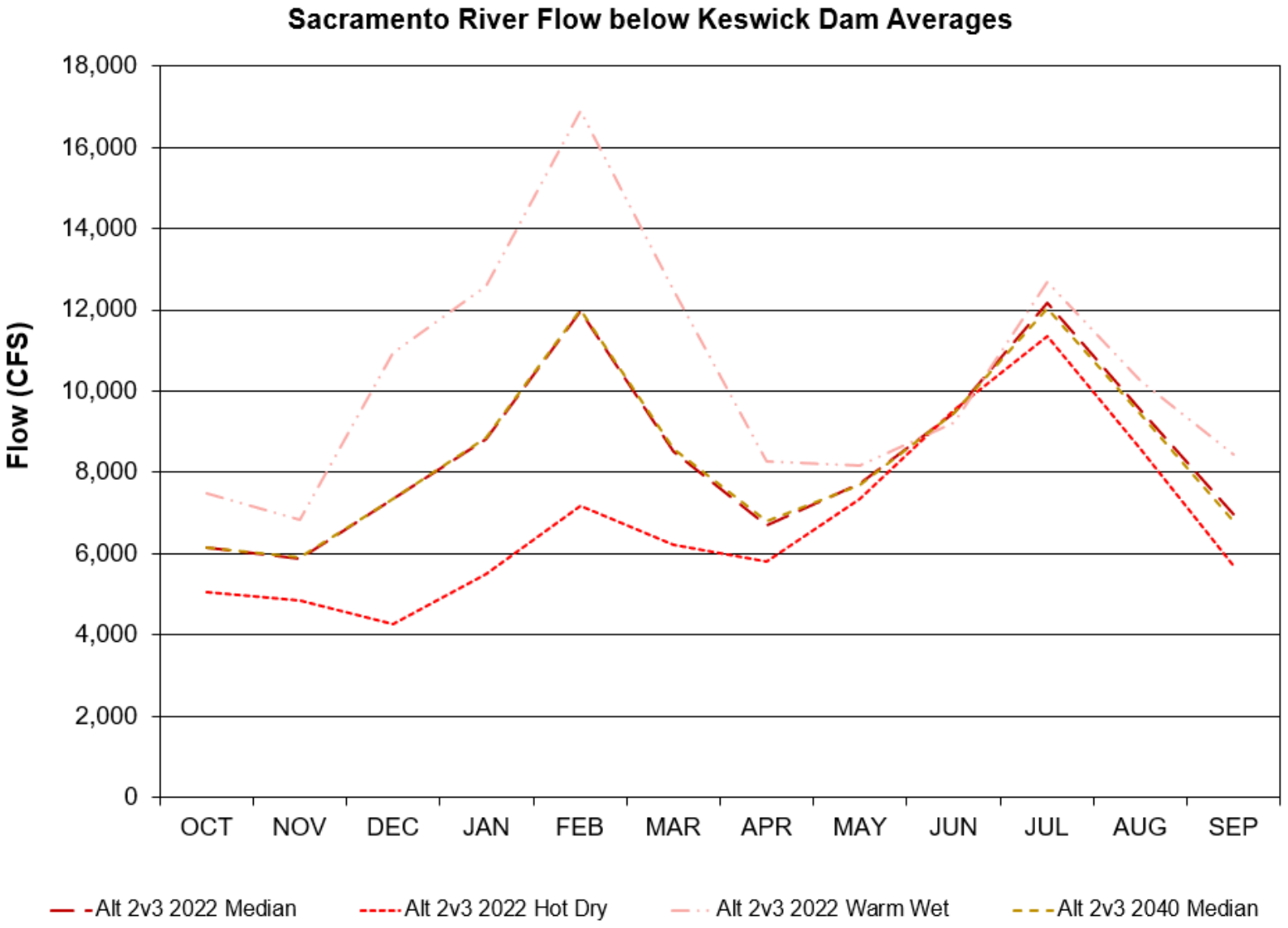

Figure F.2-5-3. Long-term Average Sacramento River flow below Keswick Dam

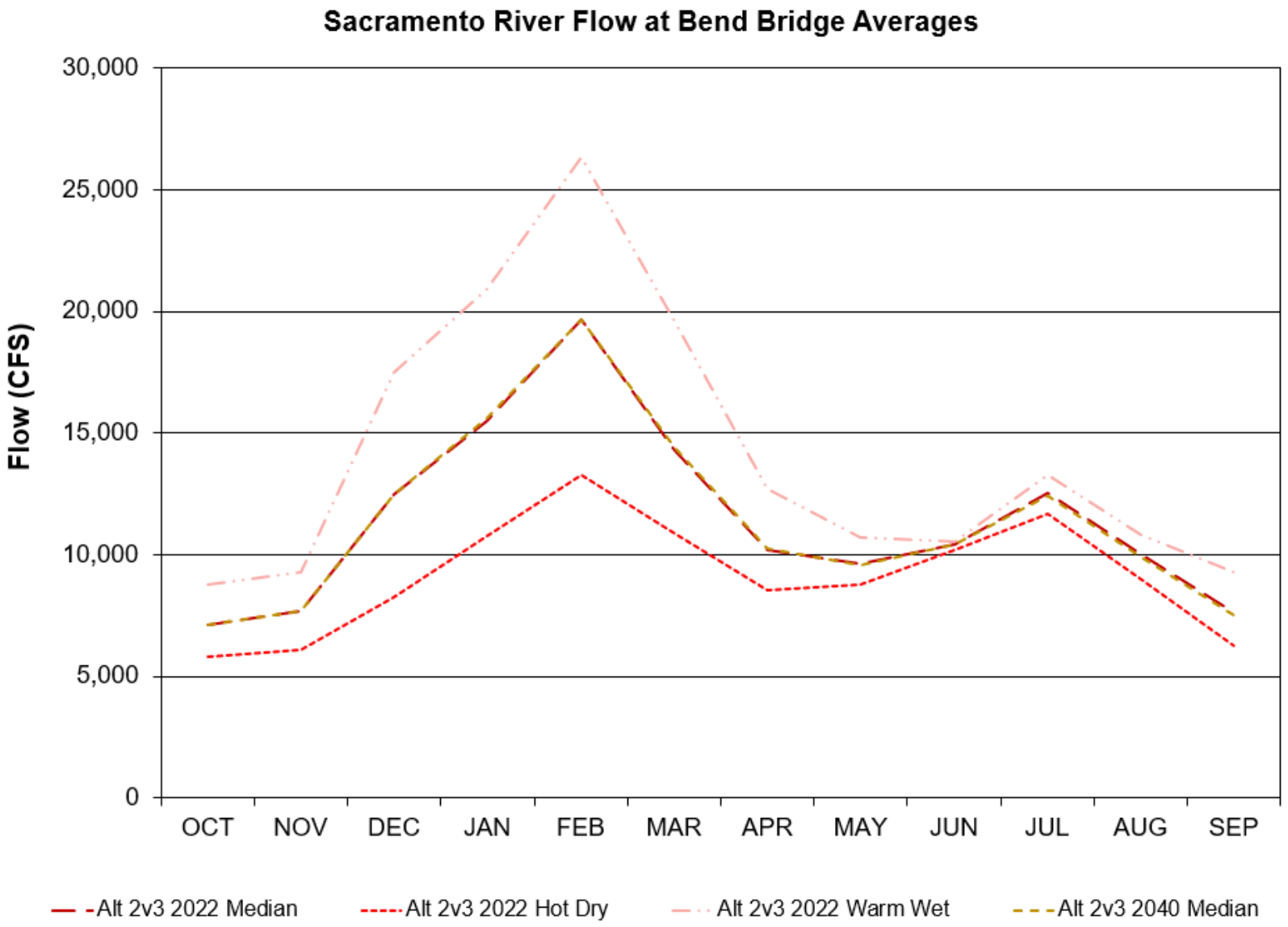

Figure F.2-5-4. Long-term Average Sacramento River flow at Bend Bridge

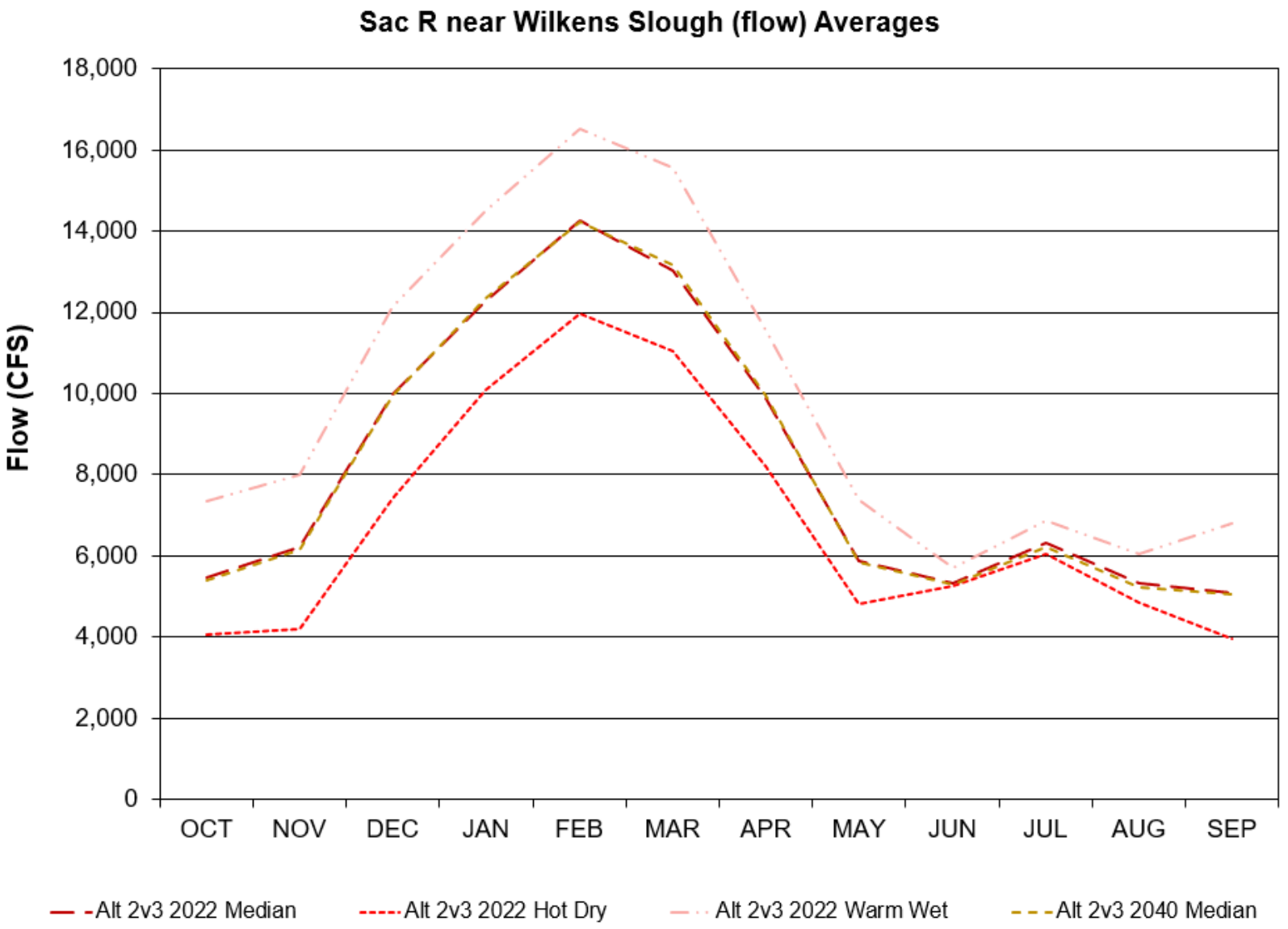

Figure F.2-5-5. Long-term Average Sacramento River flow near Wilkins Slough

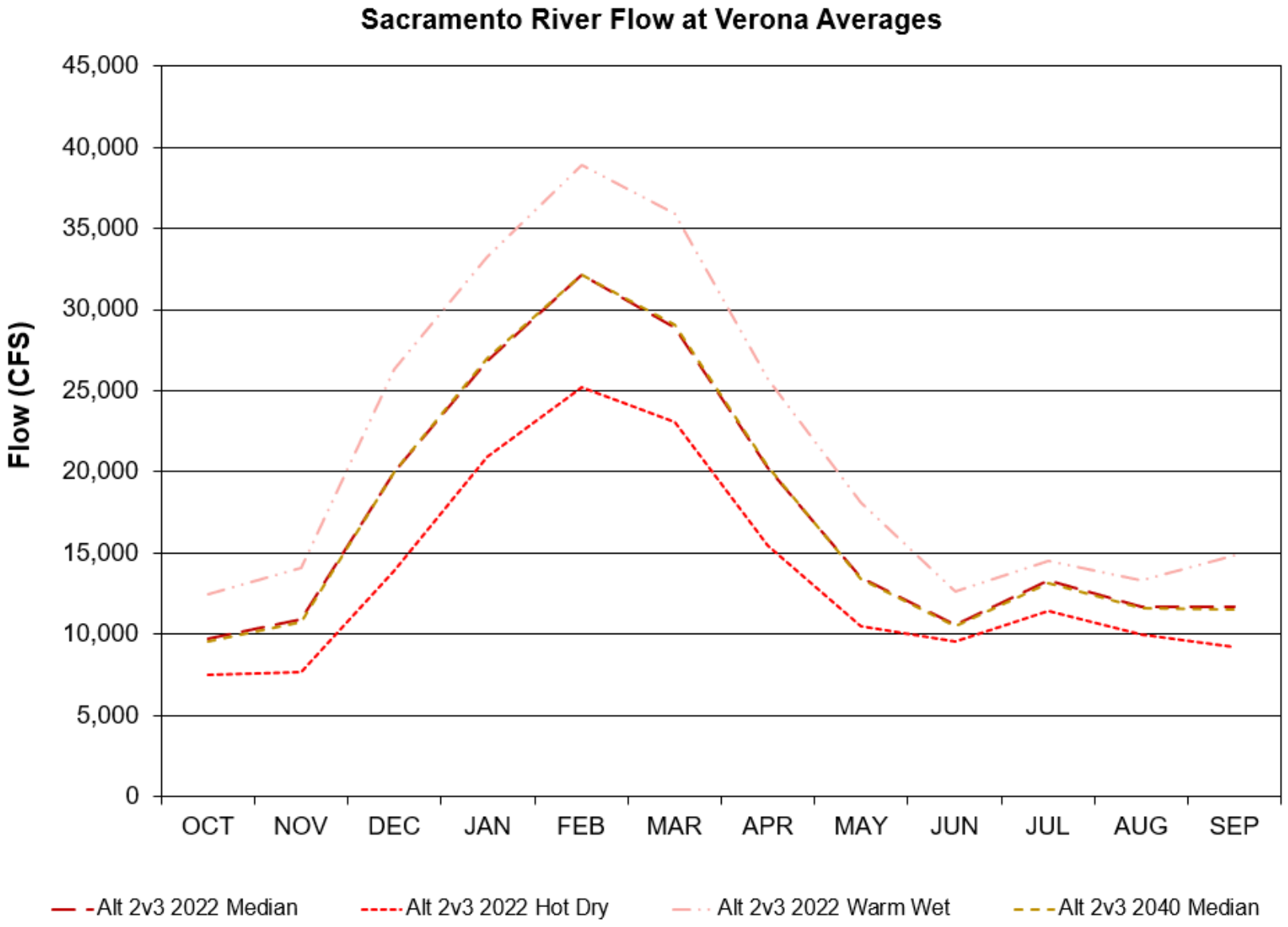

Figure F.2-5-6. Long-term Average Sacramento River flow at Verona

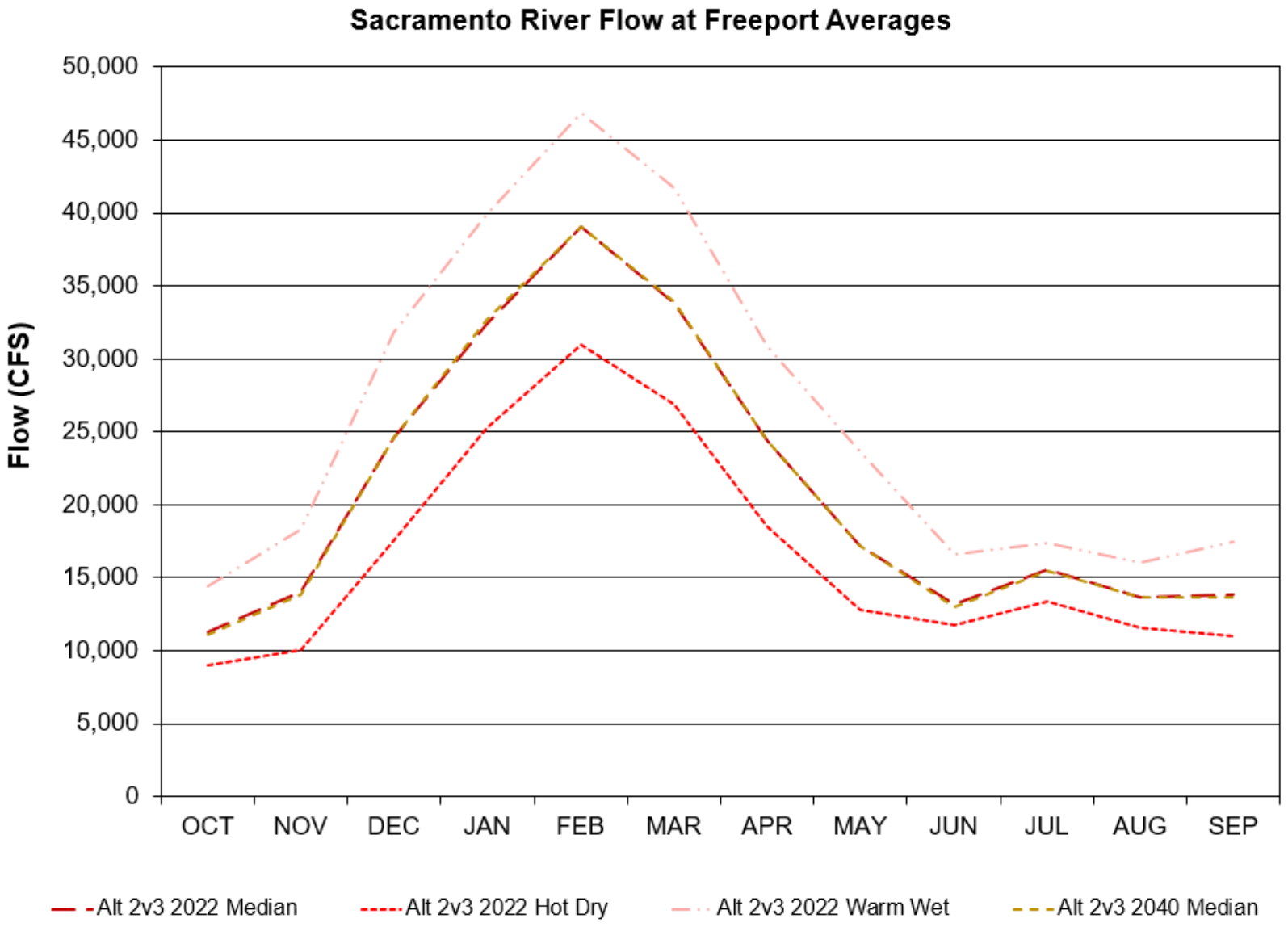

Figure F.2-5-7. Long-term Average Sacramento River flow at Freeport

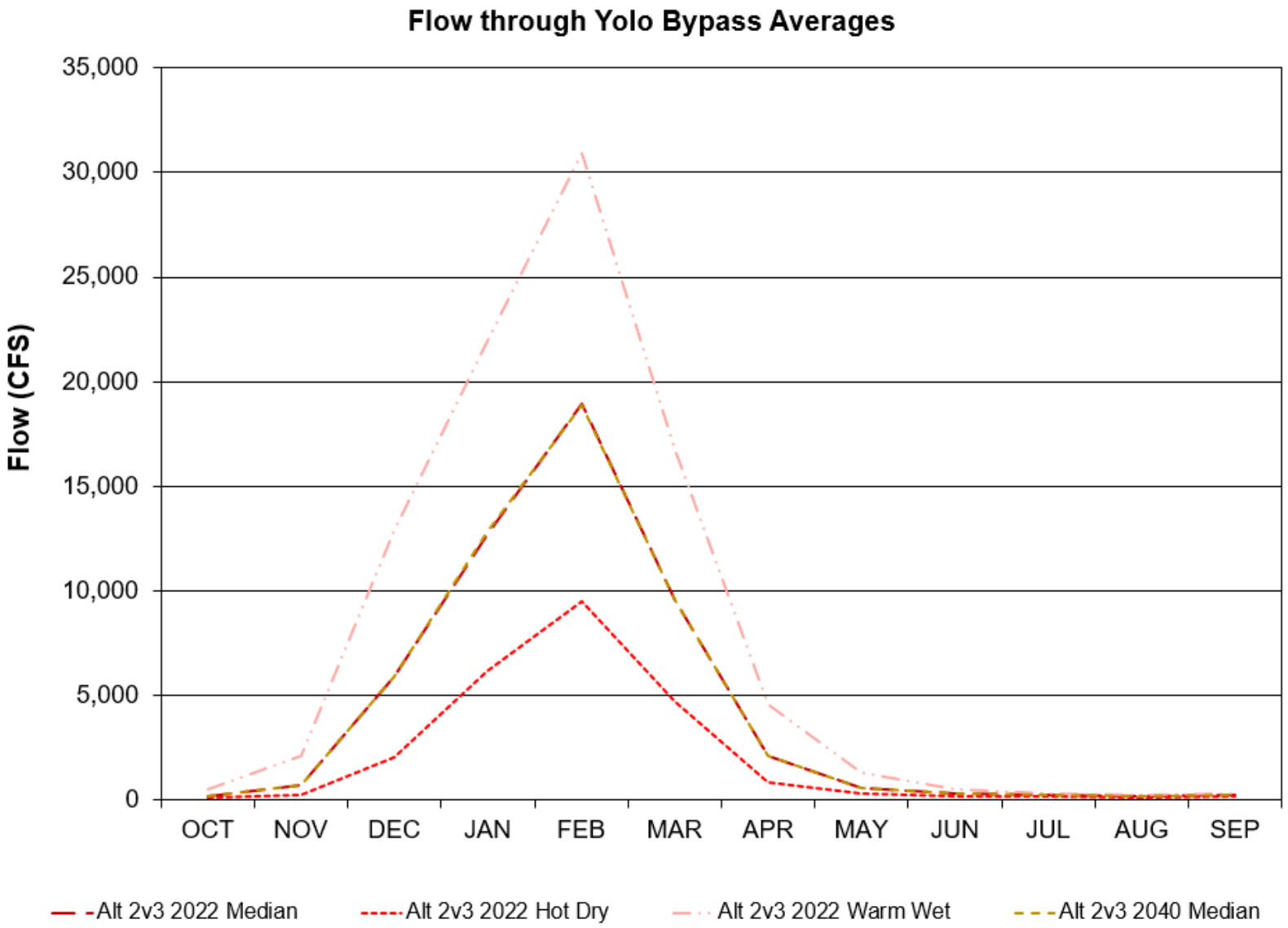

Figure F.2-5-8. Long-term Average Yolo Bypass Flow

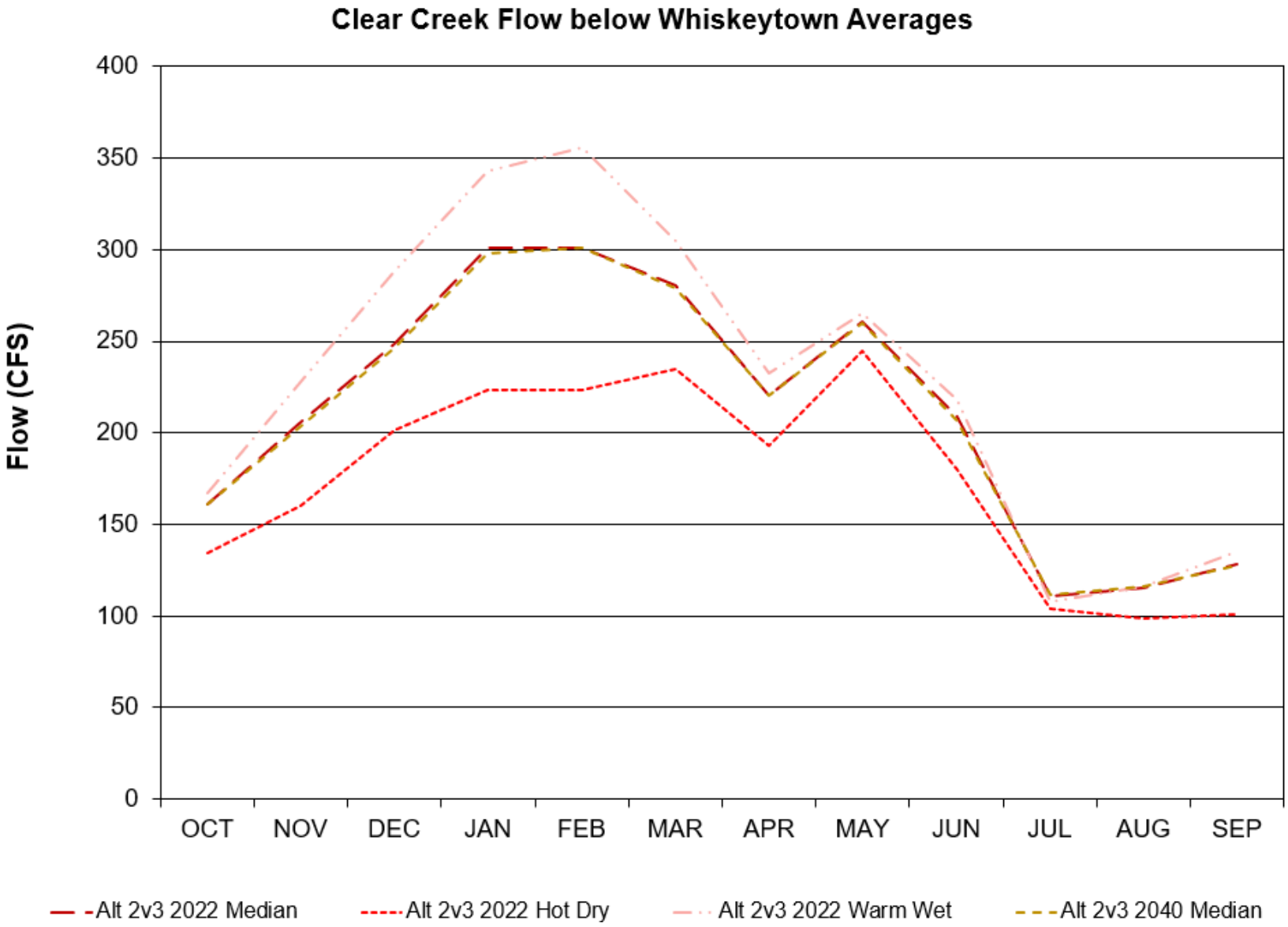

Figure F.2-5-9. Long-term Average Clear Creek flow below Whiskeytown

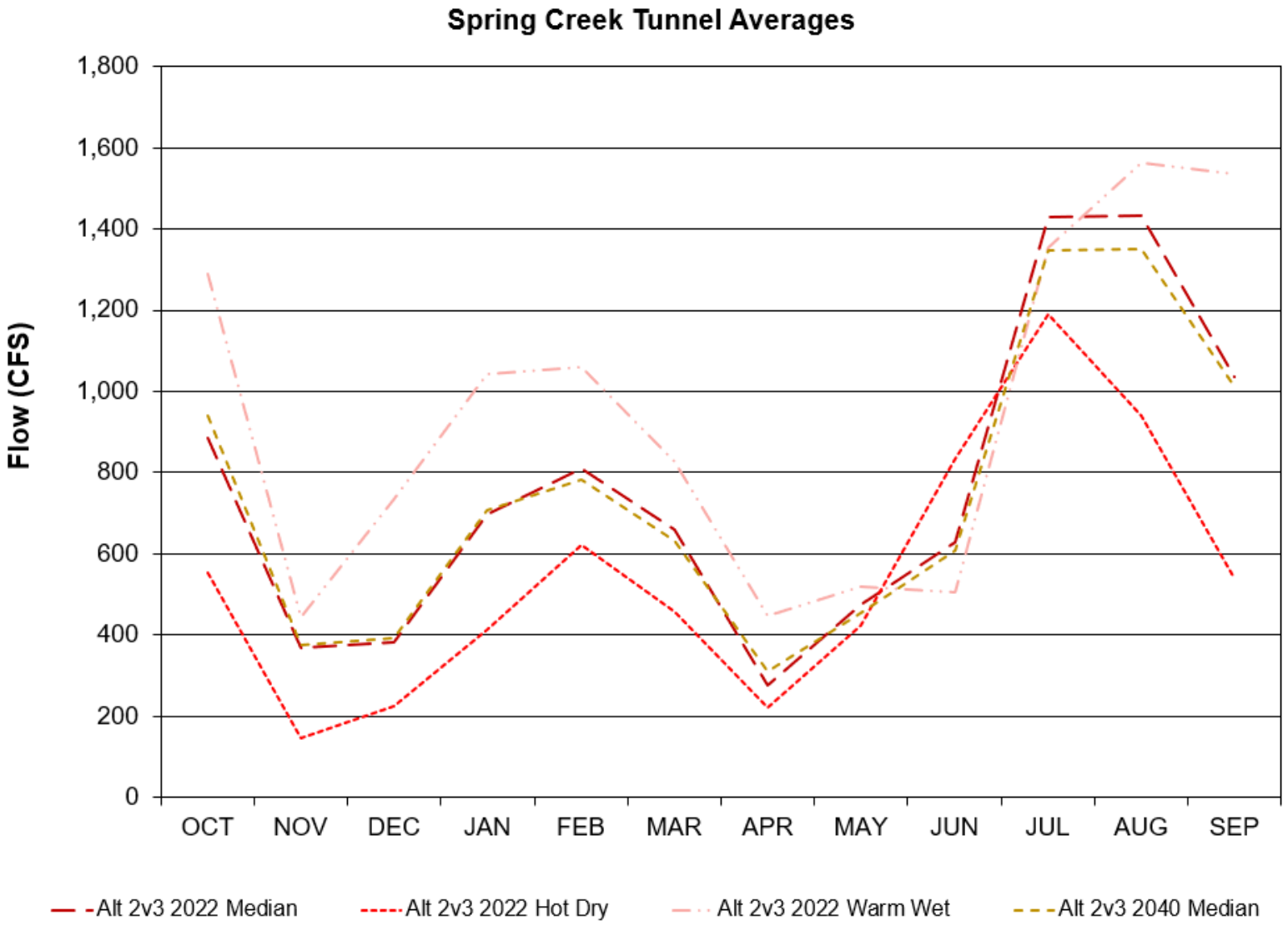

Figure F.2-5-10. Long-term Average Spring Creek Tunnel Flow

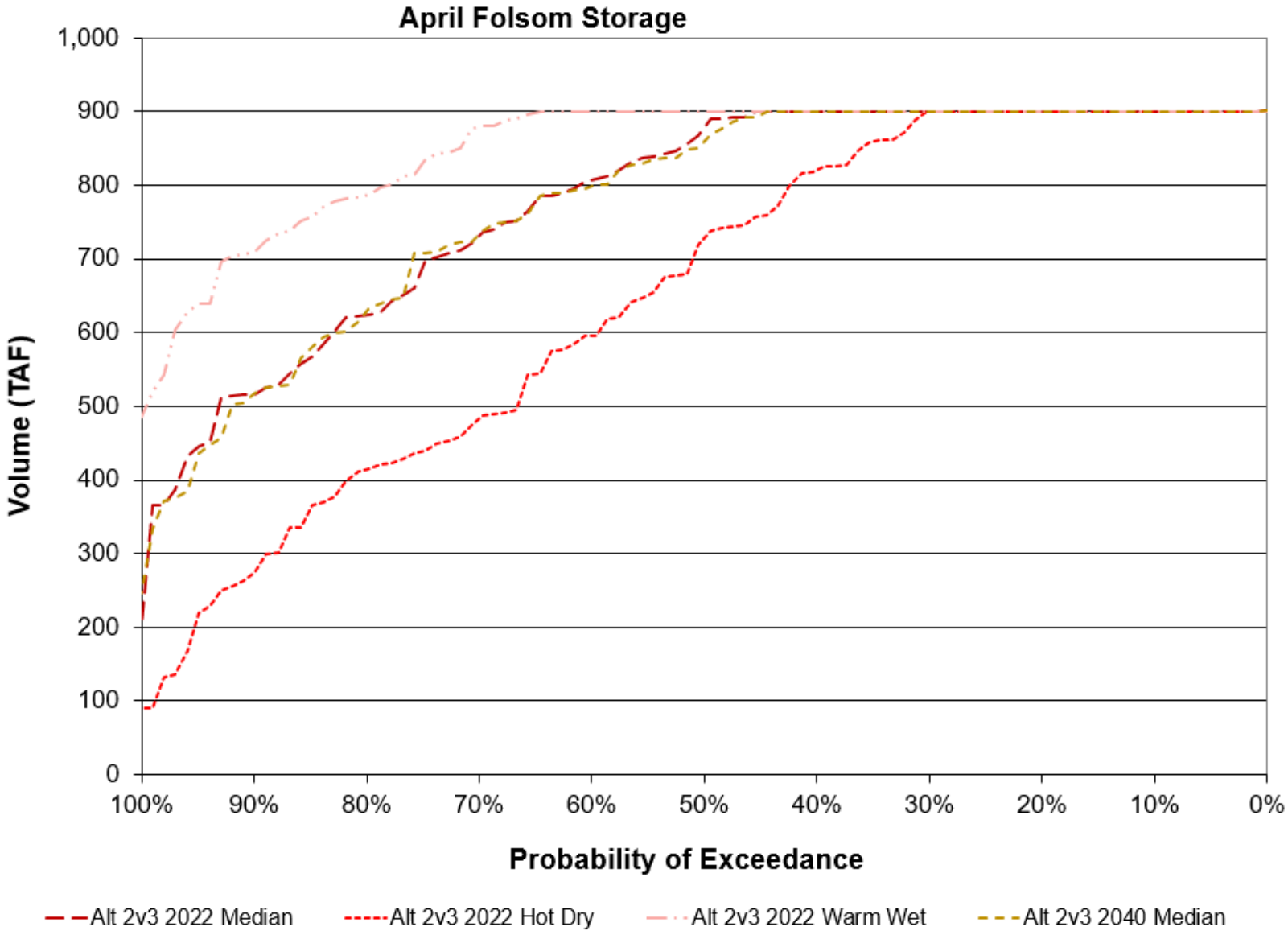

Figure F.2-5-11. End of April Folsom Storage

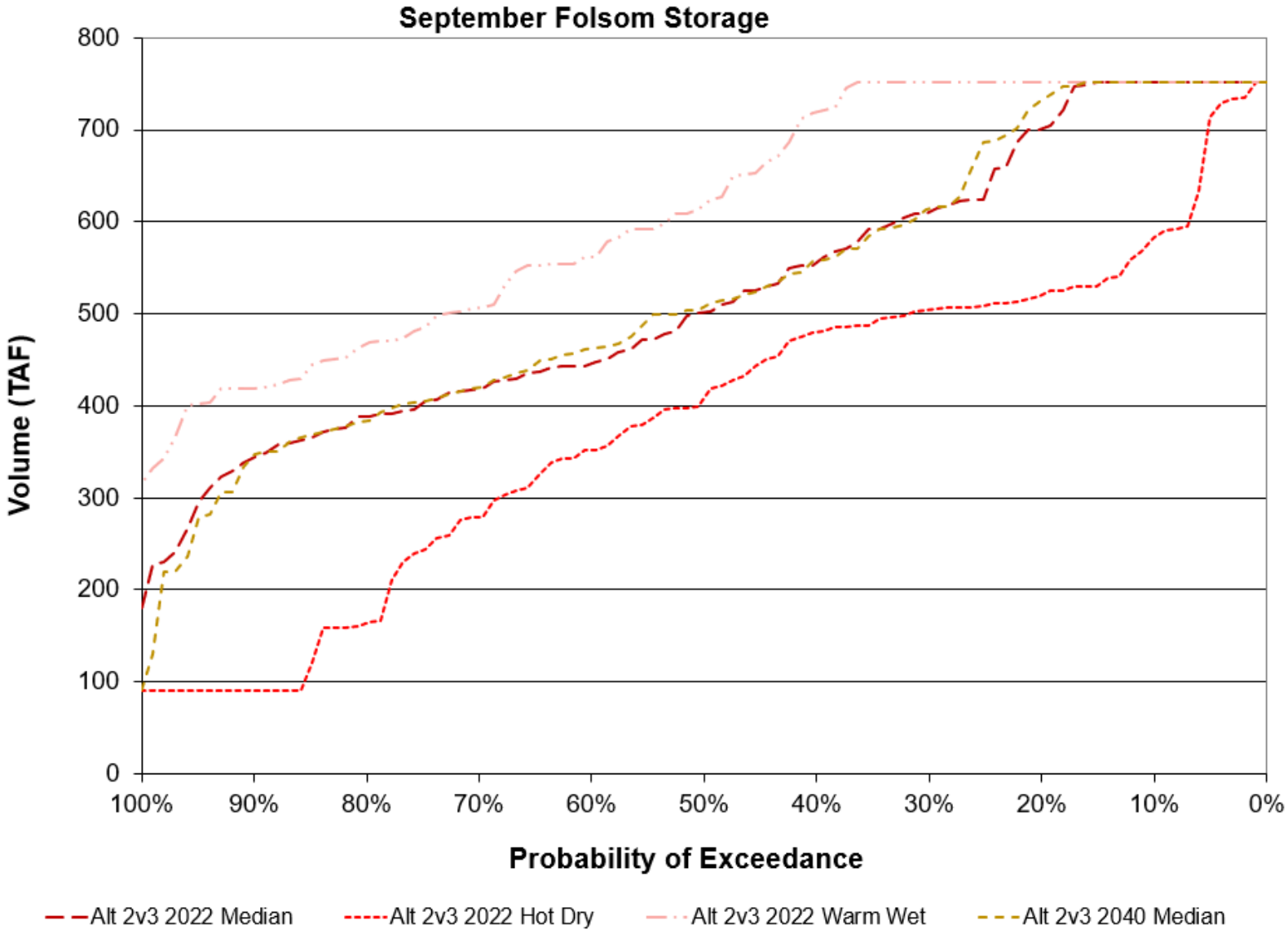

Figure F.2-5-12. End of September Folsom Storage

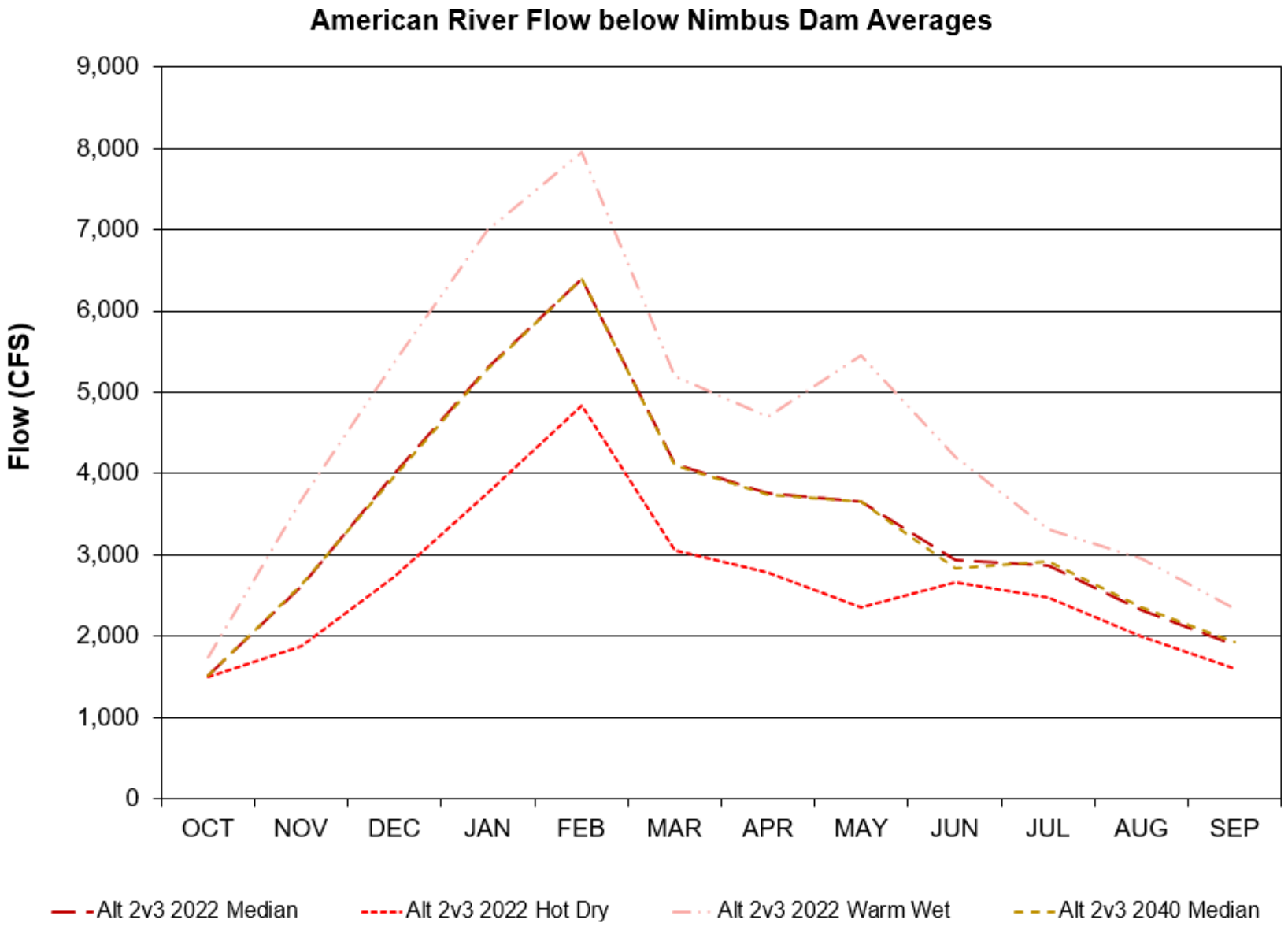

Figure F.2-5-13. Long-term Average American River flow below Nimbus Dam

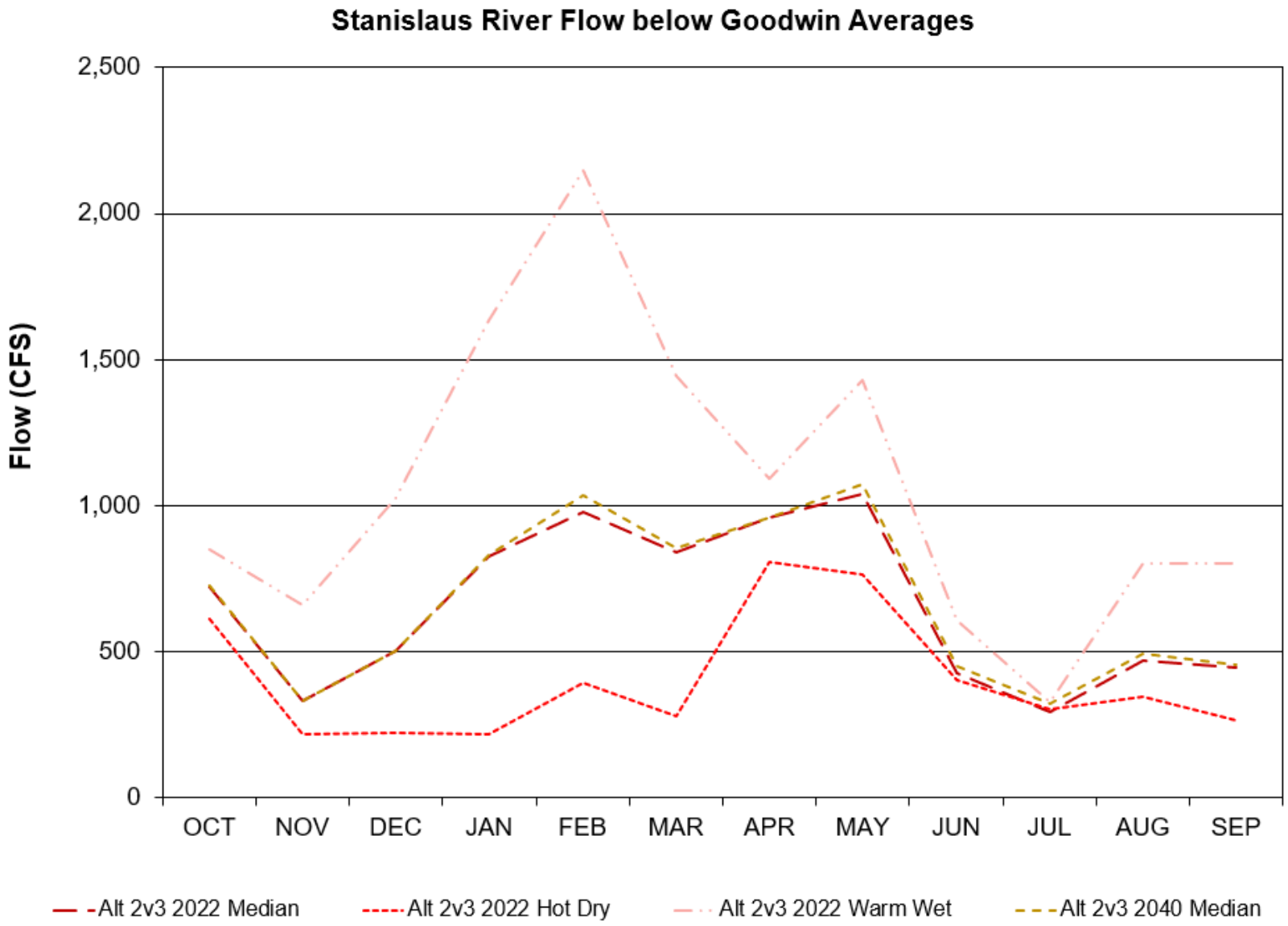

Figure F.2-5-14. Long-term Average Stanislaus River flow below Goodwin

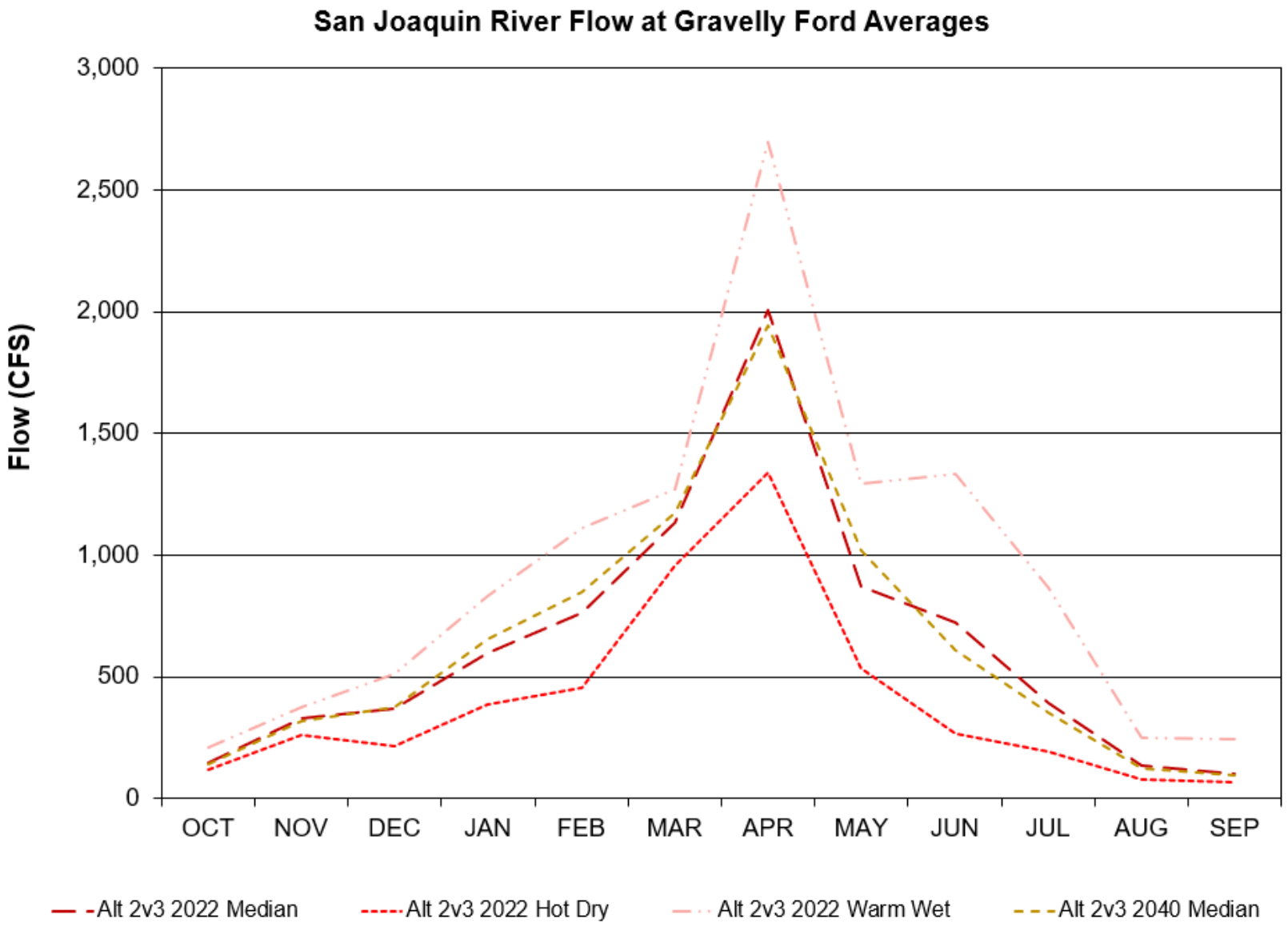

Figure F.2-5-15. Long-term Average San Joaquin River flow at Gravelly Ford

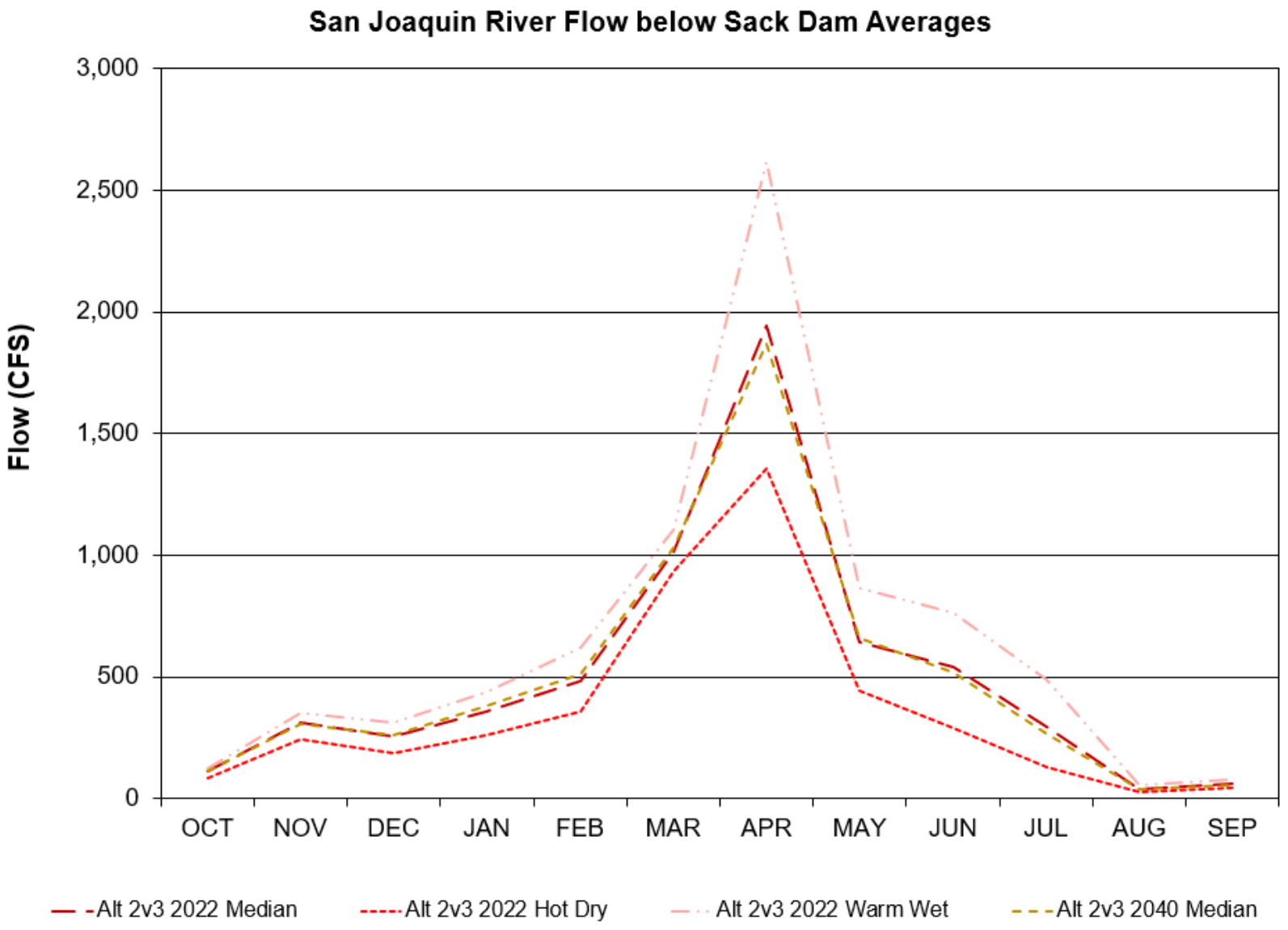

Figure F.2-5-16. Long-term Average San Joaquin River flow below Sack Dam

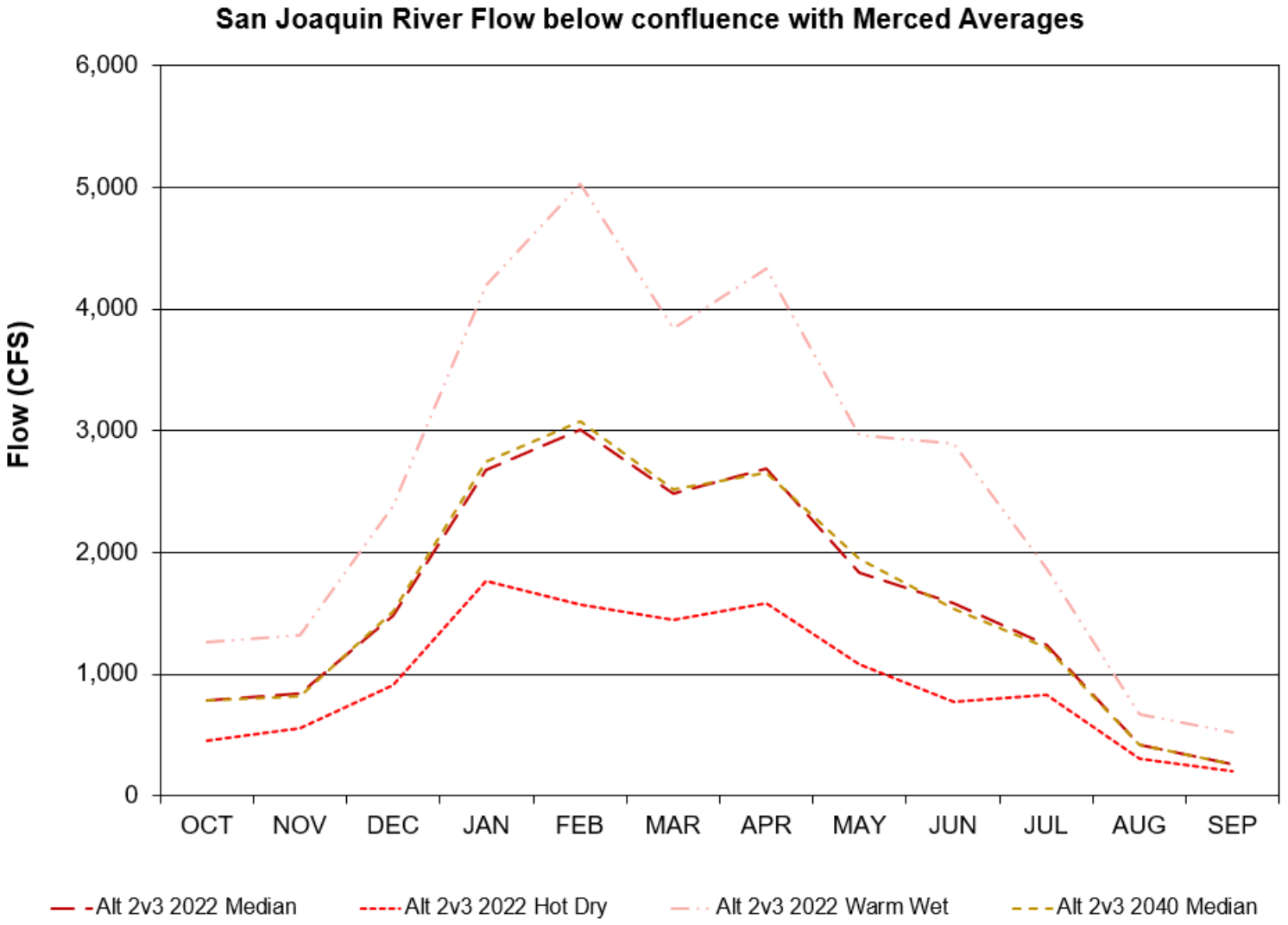

Figure F.2-5-17. Long-term Average San Joaquin River flow below Confluence with Merced River

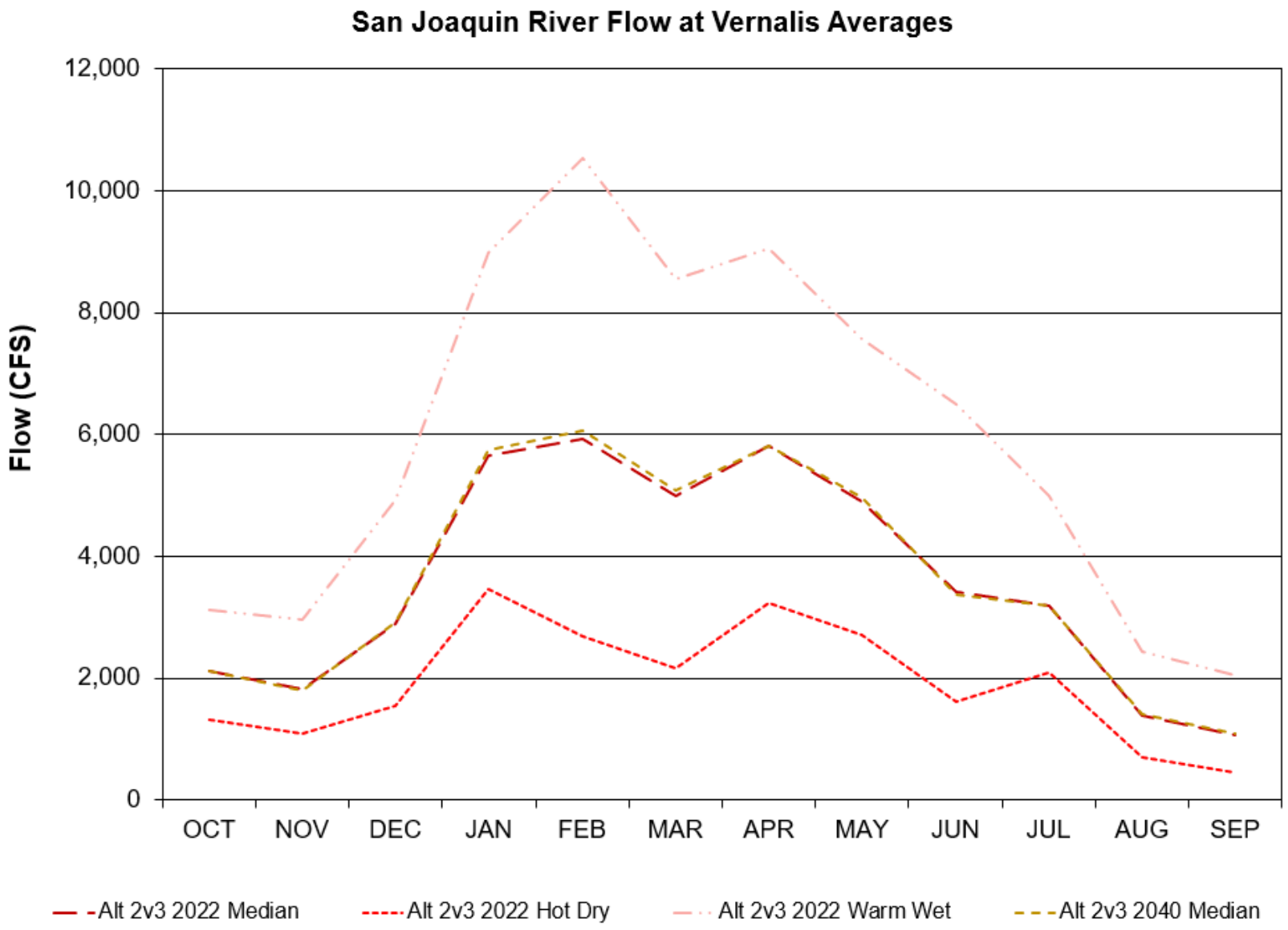

Figure F.2-5-18. Long-term Average San Joaquin River flow at Vernalis

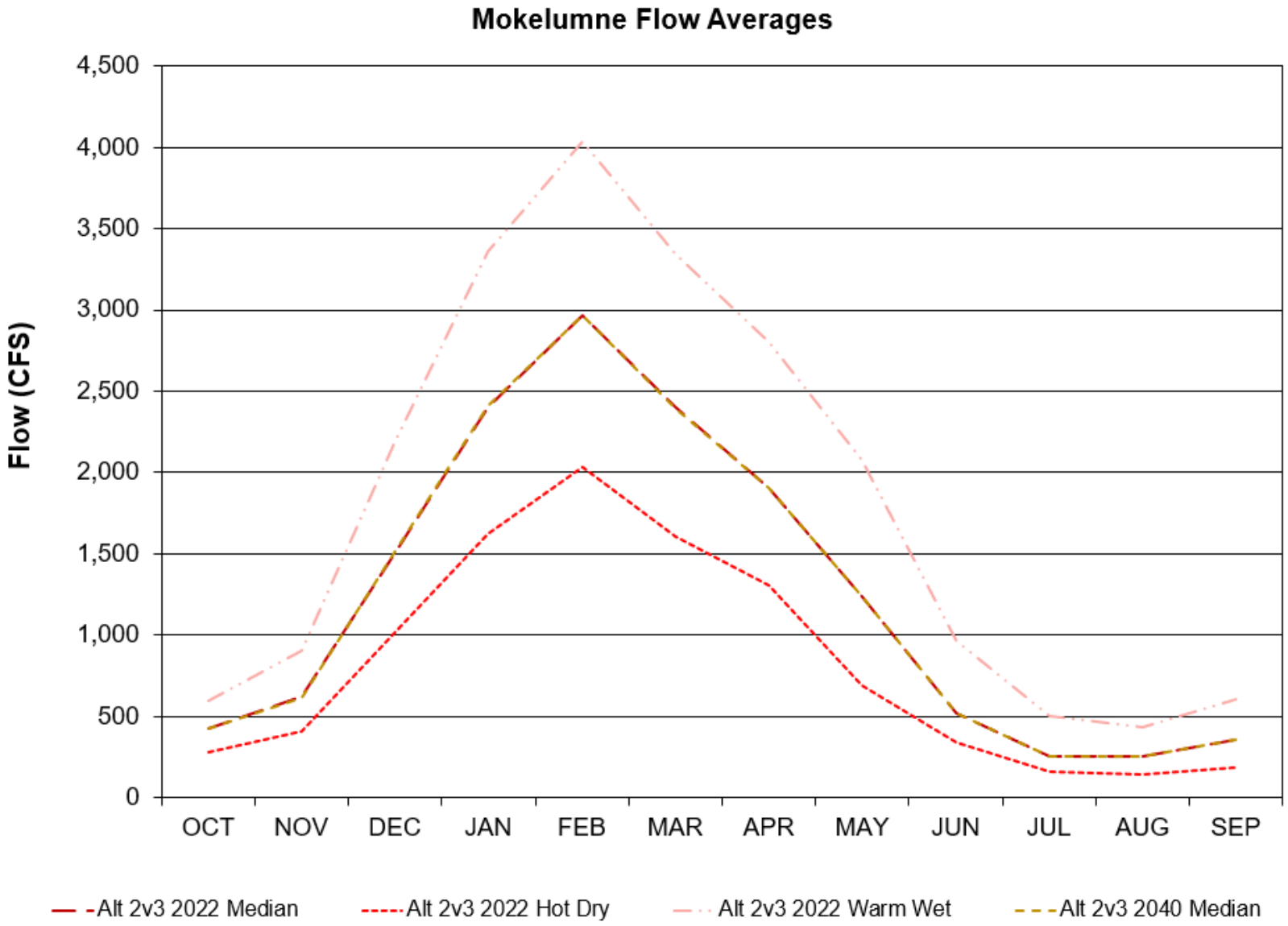

Figure F.2-5-19. Long-term Average Mokelumne River Flow

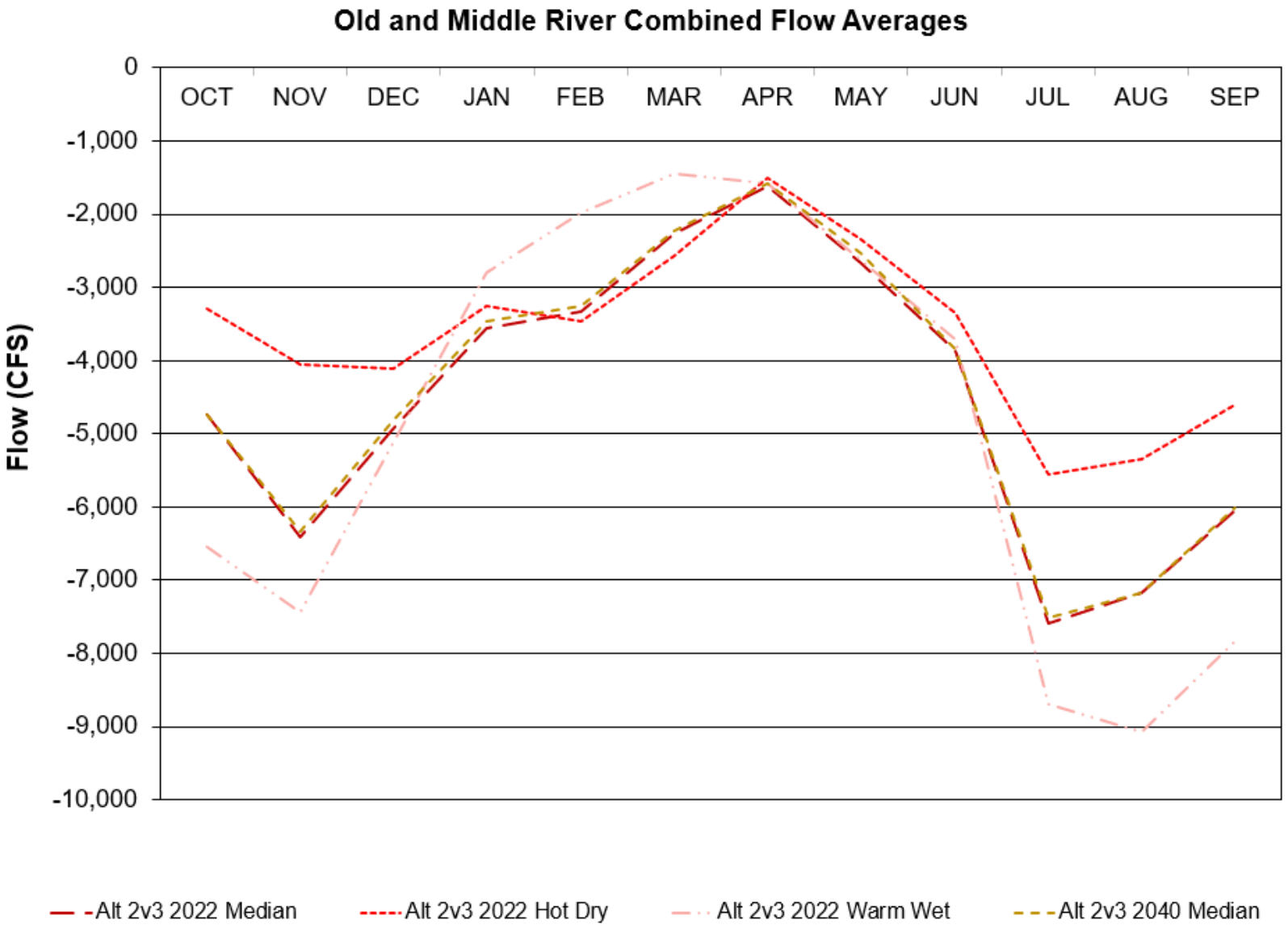

Figure F.2-5-20. Long-term Average Old and Middle River Combined Flow

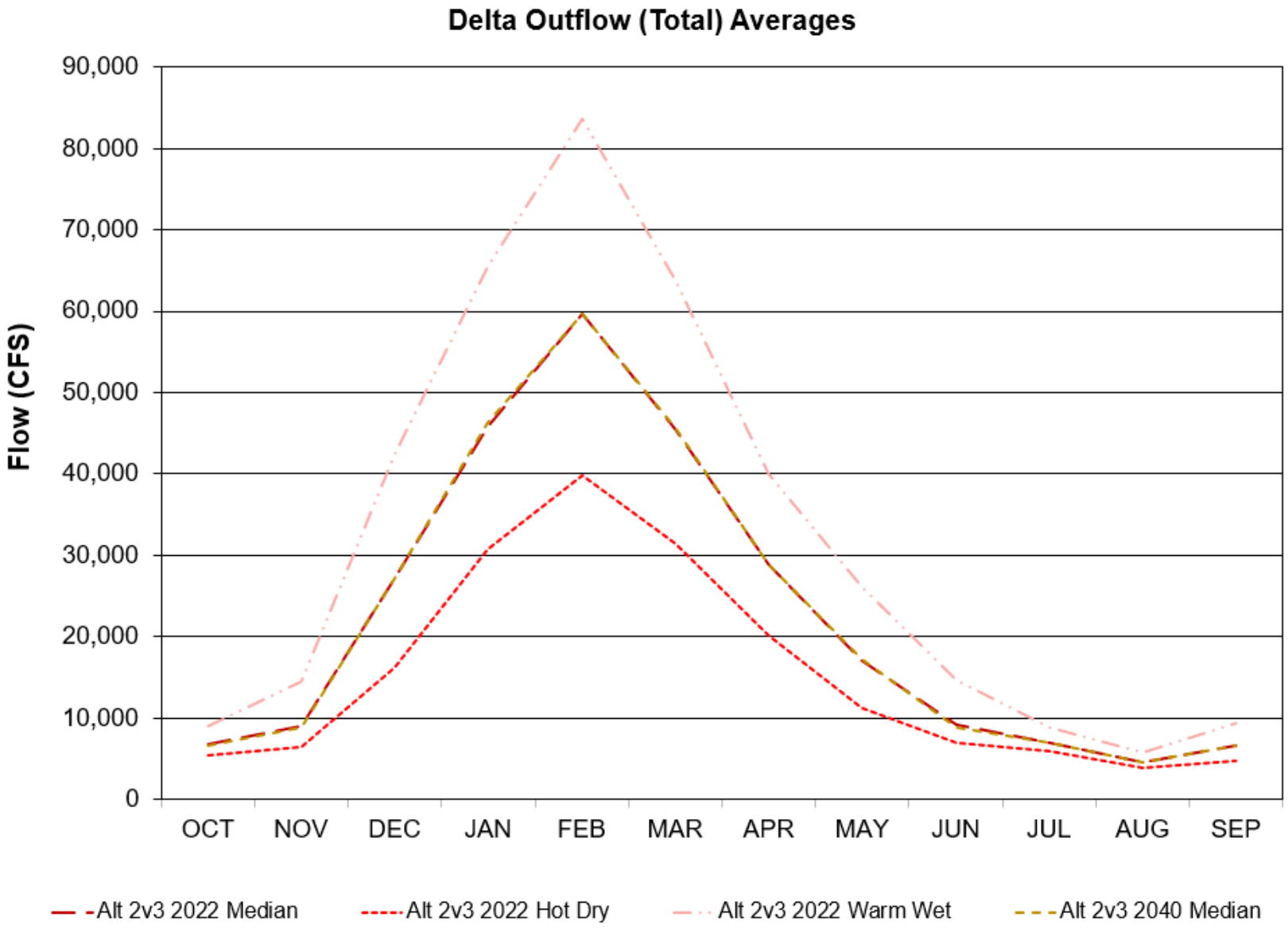

Figure F.2-5-21. Long-term Average Delta Outflow

F.2-5.2.2 HEC5Q

F.2-5.2.2.1 Sacramento

Figure F.2-5-22 through Figure F.2-5-27 summarize temperature outcomes of Alternative 2v3 without TUCPs under the climate sensitivities using the mixed location and 2021 tiers temperature logic. The mixed location logic applies a 53.5 degrees Fahrenheit (°F) target at a location ranging among Airport Road, Clear Creek, and Hwy 44 depending on the water year bin type. The 2021 temperature tiers logic applies three temperature tiers of 53.5 °F, 54 °F, or 56 °F at Clear Creek based on Shasta cold water pool. TDM was estimated using the standard LTO parameterization.

The Alternative 2v3 without TUCPs TDM estimate (Figure F.2-5-22) displays large climate variability. The 2022 Median climate scenario exceeds 10% TDM in approximately 20% of simulated years. The smoothness of the TDM exceedance curve without a discrete transition in behavior implies a continuous expenditure of cold-water resources without a clear indicator for lower potential target temperatures. However, the smoothness of the curve does not guarantee that the temperature logic is optimal. Under the 2022 Warm Wet scenario, TDM is generally reduced below the 30% exceedance, with maximum TDM reducing from approximately 100% for the 2022 Median scenario to approximately 70% for the mixed location logic and approximately 55% for the 2021 temperature tiers logic. The 2022 Hot Dry scenario shifts TDM to higher values than the 2022 Median scenario due to less water available and generally warmer conditions. The 2040 Median scenario generally tracks the 2022 scenario, but at a somewhat higher TDM. When comparing the 2021 temperature tiers logic to the mixed location logic, the mean TDM of each climate scenario is reduced under the 2021 temperature tiers logic.

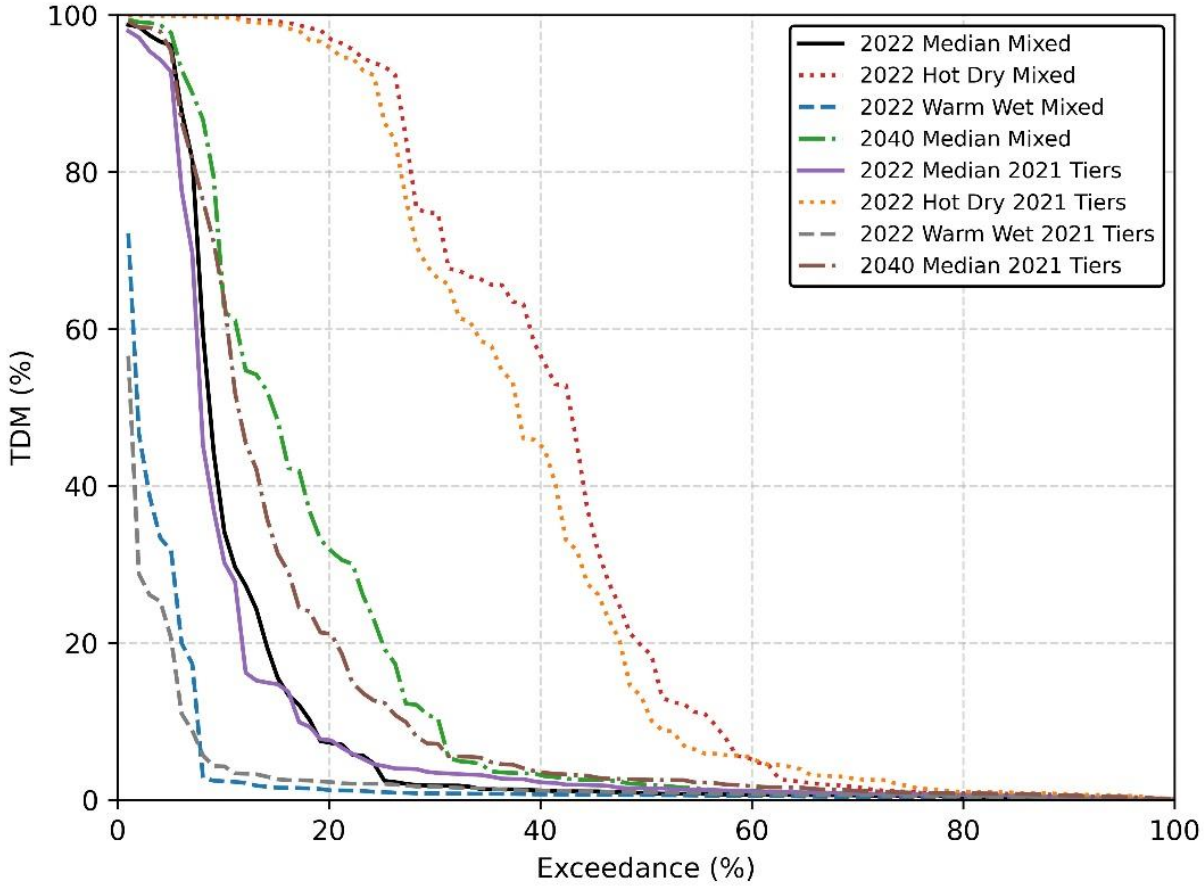

Figure F.2-5-22. Martin model TDM exceedance plot for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2021

The TDM outcomes follow the same trend as the Sacramento River temperatures. Figure F.2-5-23 and Figure F.2-5-24 give the average and maximum May through end of October temperatures in the Sacramento River below Clear Creek with Figure F.2-5-25 and Figure F.2-5-26 providing the same information for Red Bluff. TDM outcomes correlate with the average and maximum temperatures across the climate scenarios. The volume of water less than 52 °F at the end of April, given in Figure F.2-5-27, also correlates with TDM outcomes. The similarity of the 2022 Median and 2040 Median cold-water pools with different temperature and TDM outcomes demonstrates the importance of instream warming.

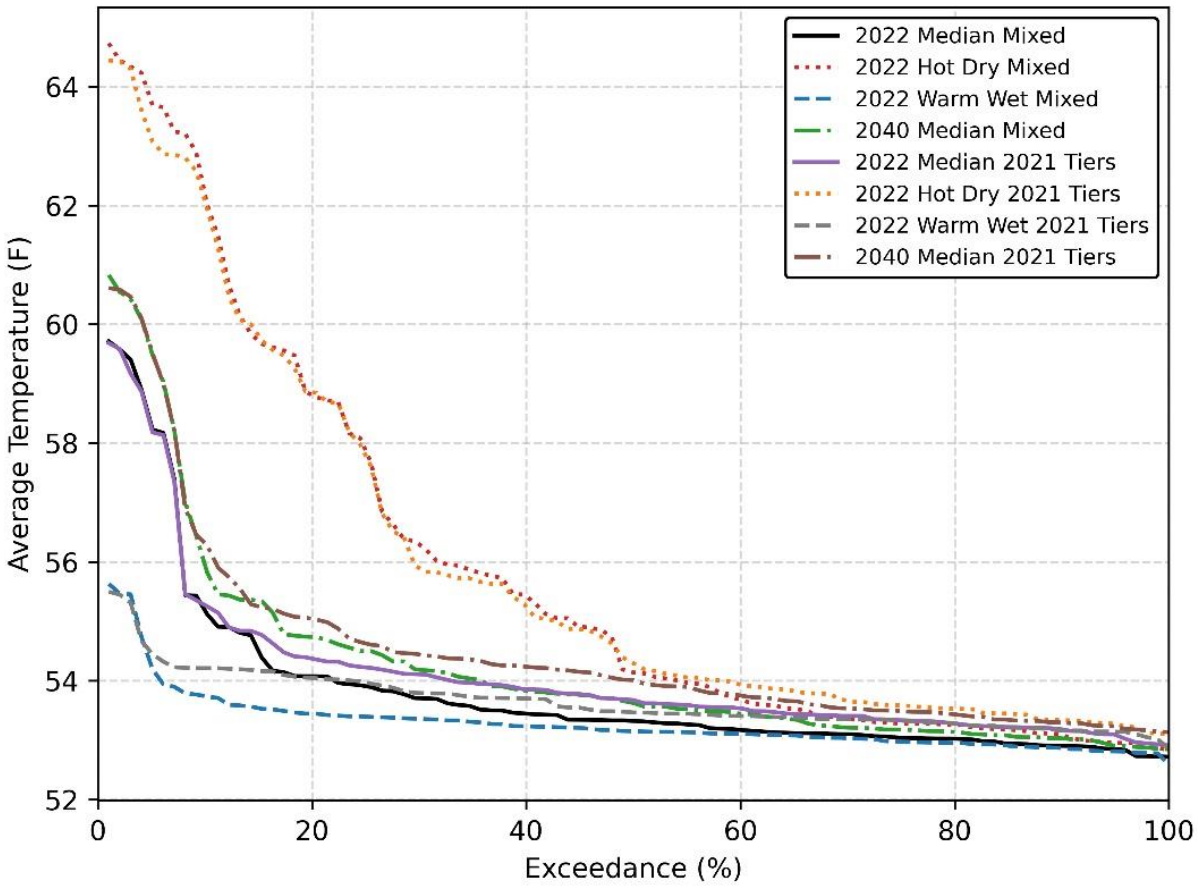

Figure F.2-5-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2020

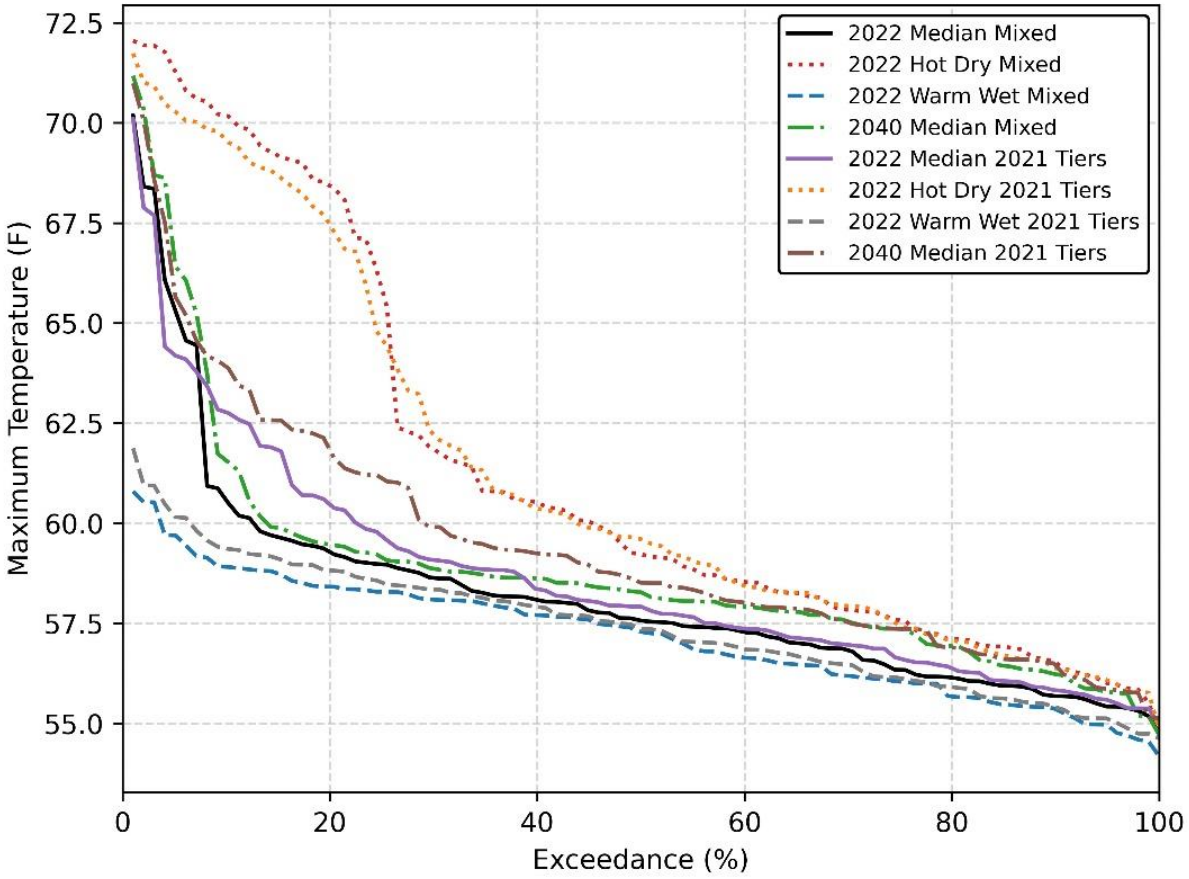

Figure F.2-5-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2020

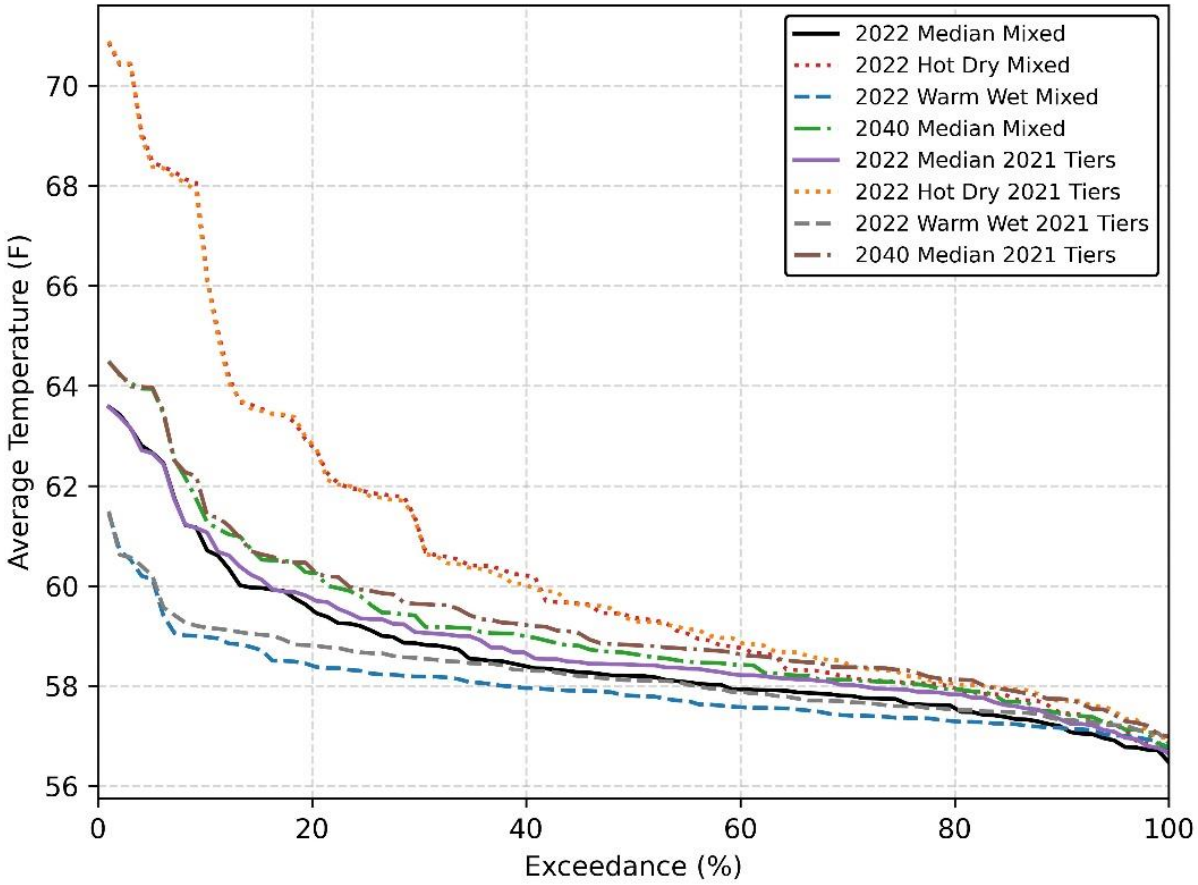

Figure F.2-5-25. Average water year temperatures on the Sacramento River at Red Bluff for the Alternative 2v3 without TUCPs under various climate assumptions from May through end of October for water years 1923 through 2020

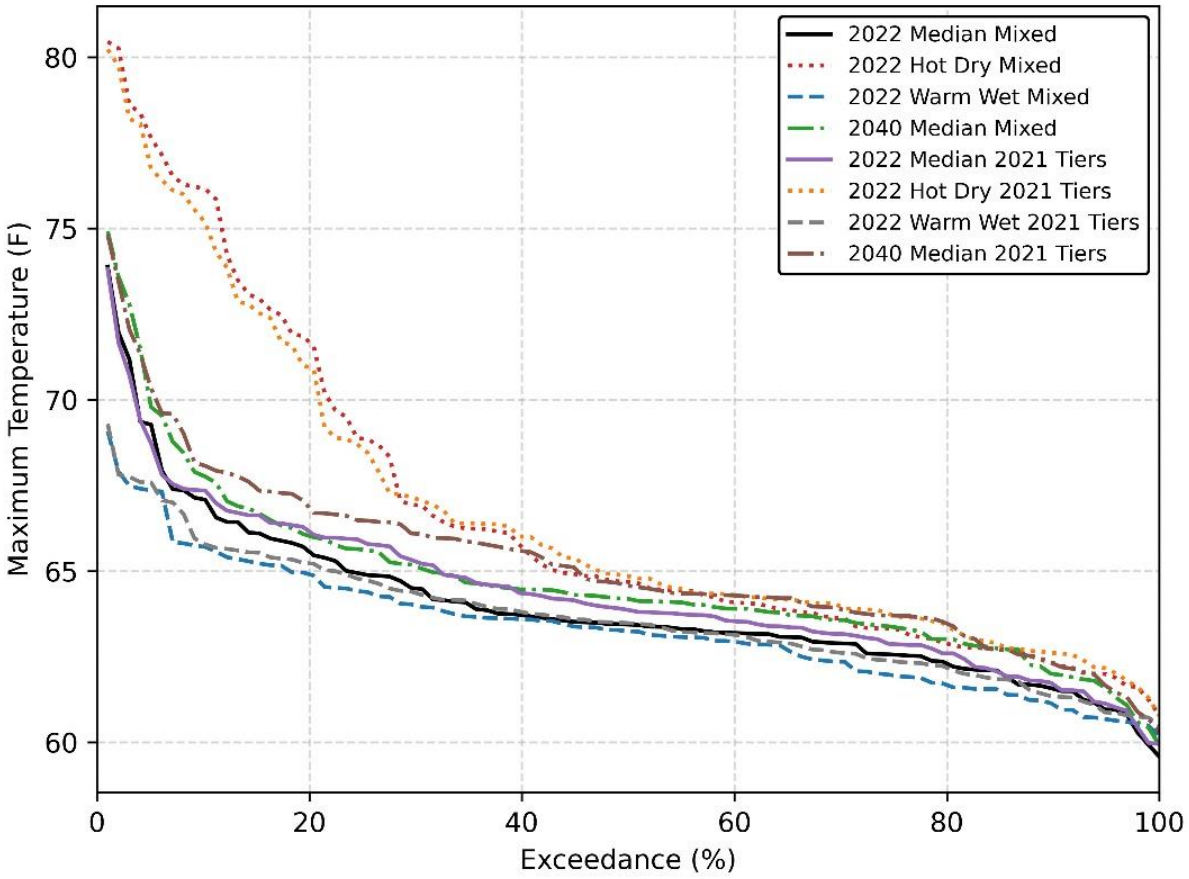

Figure F.2-5-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2020

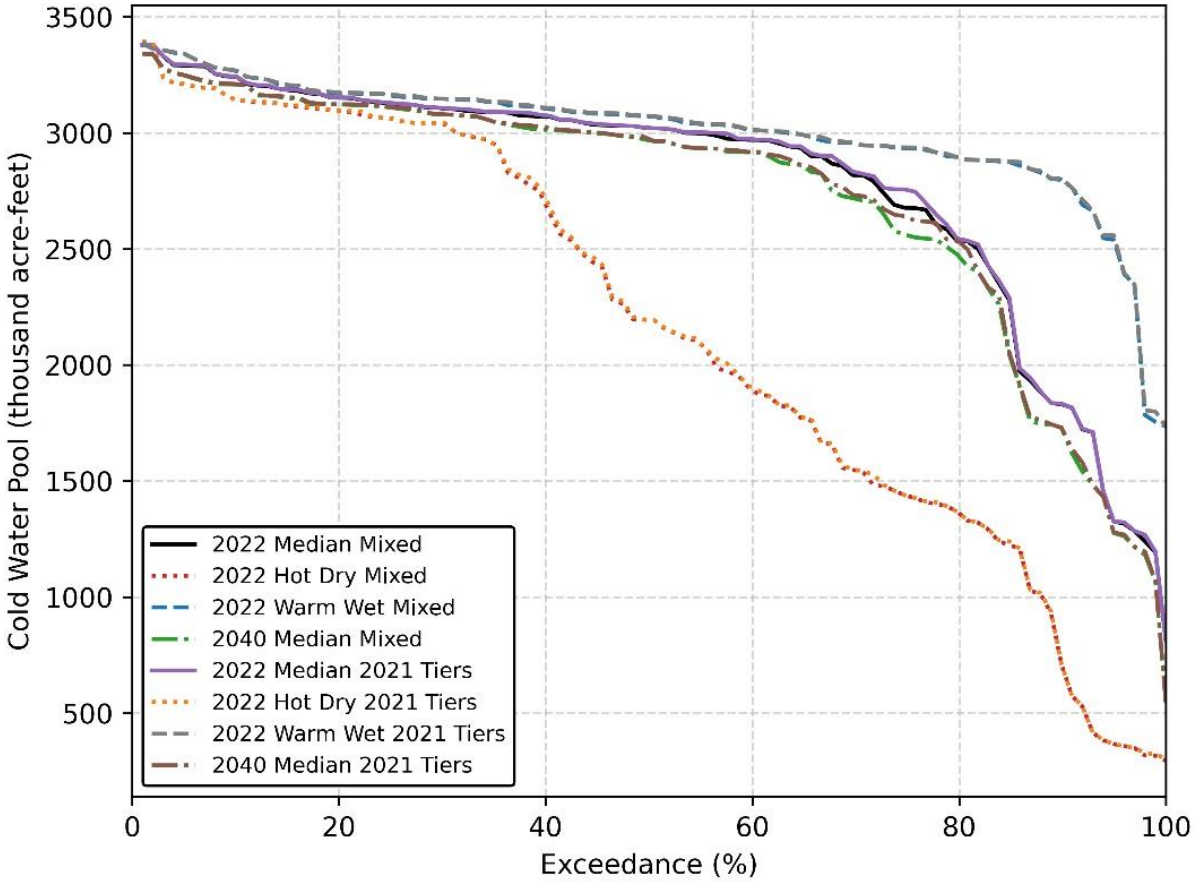

Figure F.2-5-27. Volume of water at the end of April less than 52 °F in Shasta Lake for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2021

F.2-5.2.2.2 American

Figure F.2-5-28 through Figure F.2-5-30 evaluate Alterative 2v3 without TUCPs on the American basin. Average May through end of October temperatures (Figure F.2-5-28) at the Watt Avenue compliance location are higher in the 2022 Hot Dry and 2040 Median scenarios as compared to the 2022 Median condition. Interestingly, although the 2022 Hot Dry scenario is hotter than the 2040 Median at the highest temperatures, the differences in the scenarios are minimal at the coolest temperatures. The 2022 Warm Wet scenario, with generally more water available in the system and cooler temperatures, has lower May through end of October temperatures than the 2022 Median scenario. This scaling is maintained through the maximum May through end of October temperatures as well.

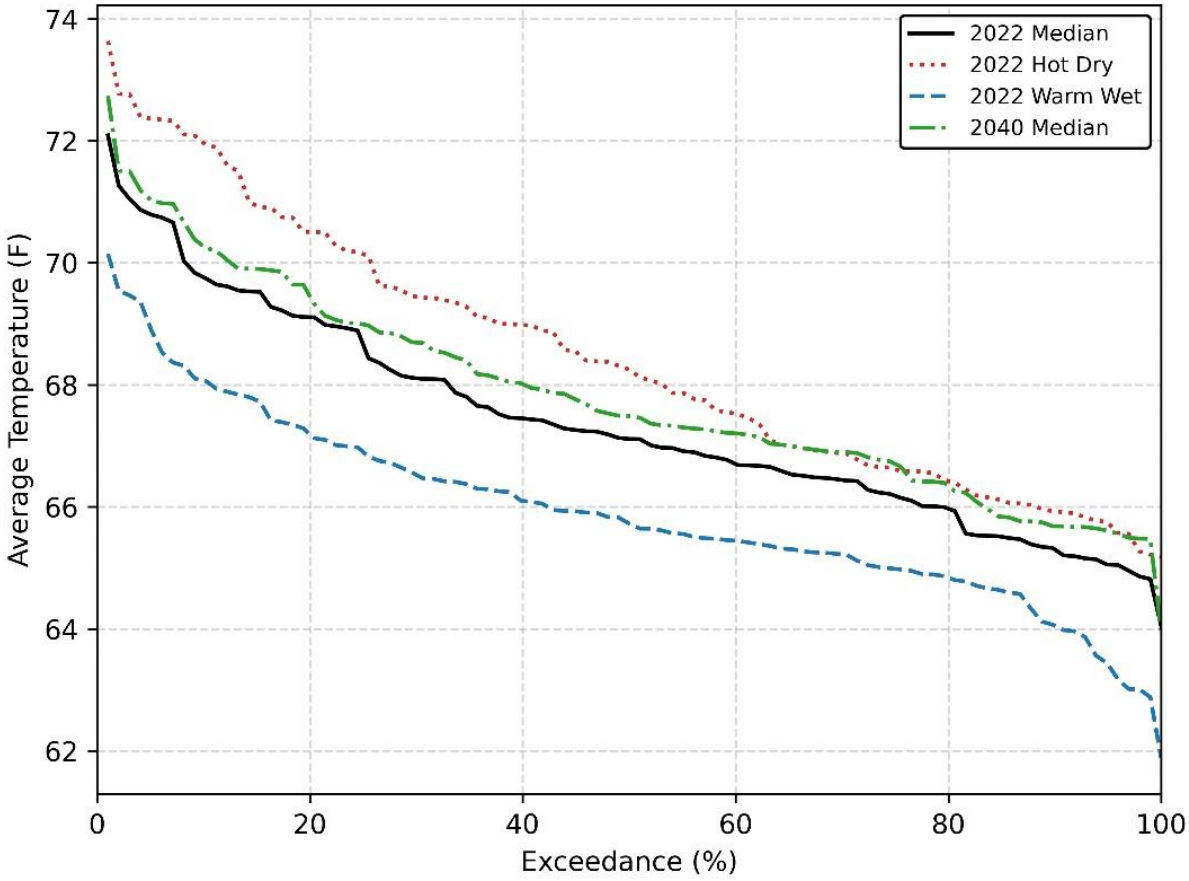

Figure F.2-5-28. Average May through end of October temperatures on the American River at Watt Avenue for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2020

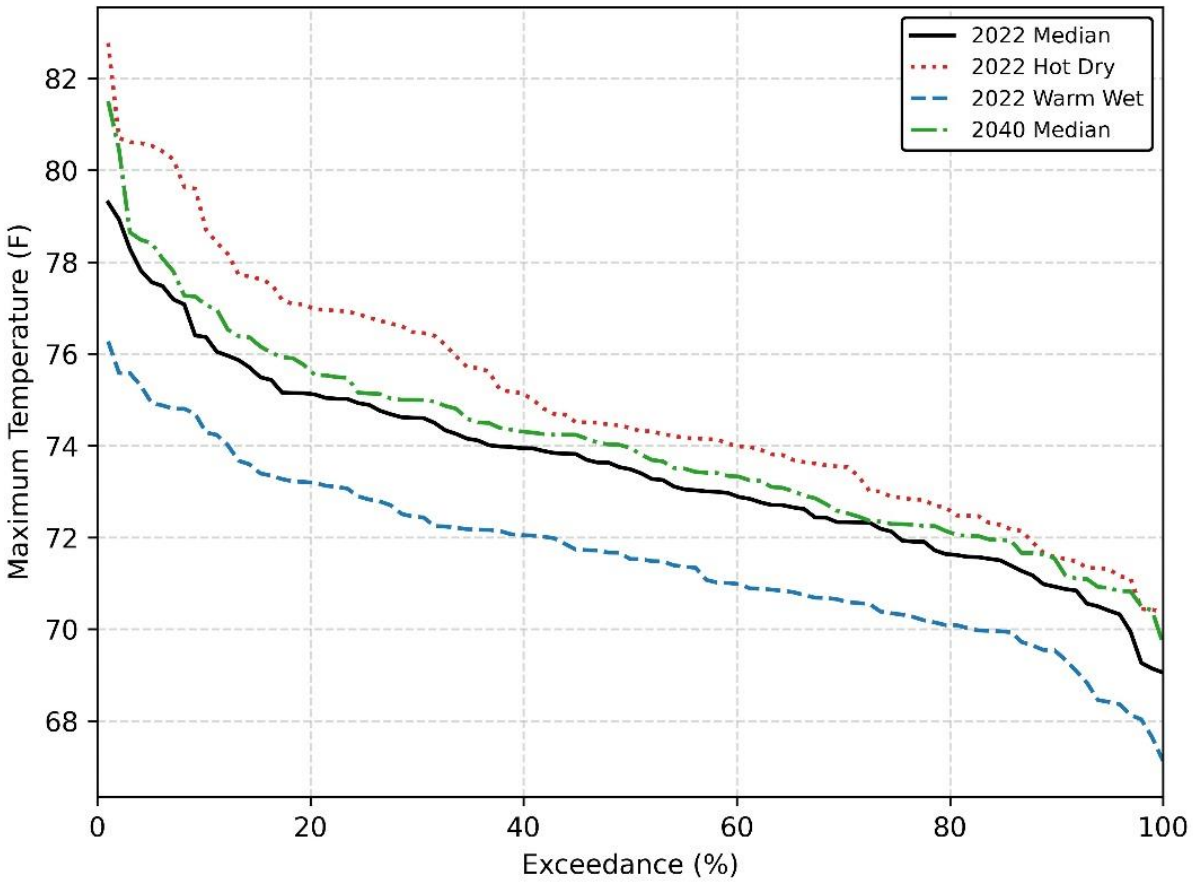

Figure F.2-5-29. Maximum May through end of October temperatures on the American River at Watt Avenue for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2020

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. The 2022 Warm Wet scenario has meaningfully larger end of April cold water pool (52 °F) as compared to the 2022 Median condition. Conversely, the 2022 Hot Dry scenario has meaningfully less cold water available than the 2022 Median. The availability of cold water is translated into temperature performance at Watt Avenue and compounded by the in-stream warming. The 2022 Median and 2040 Median scenarios have similar end of April cold-water pool resources; however, the 2040 Median condition performs about a degree warmer than the 2022 Median. This difference is due in part to the greater in-stream warming as well as greater warming in the reservoir reducing the cold water available in the temperature management season.

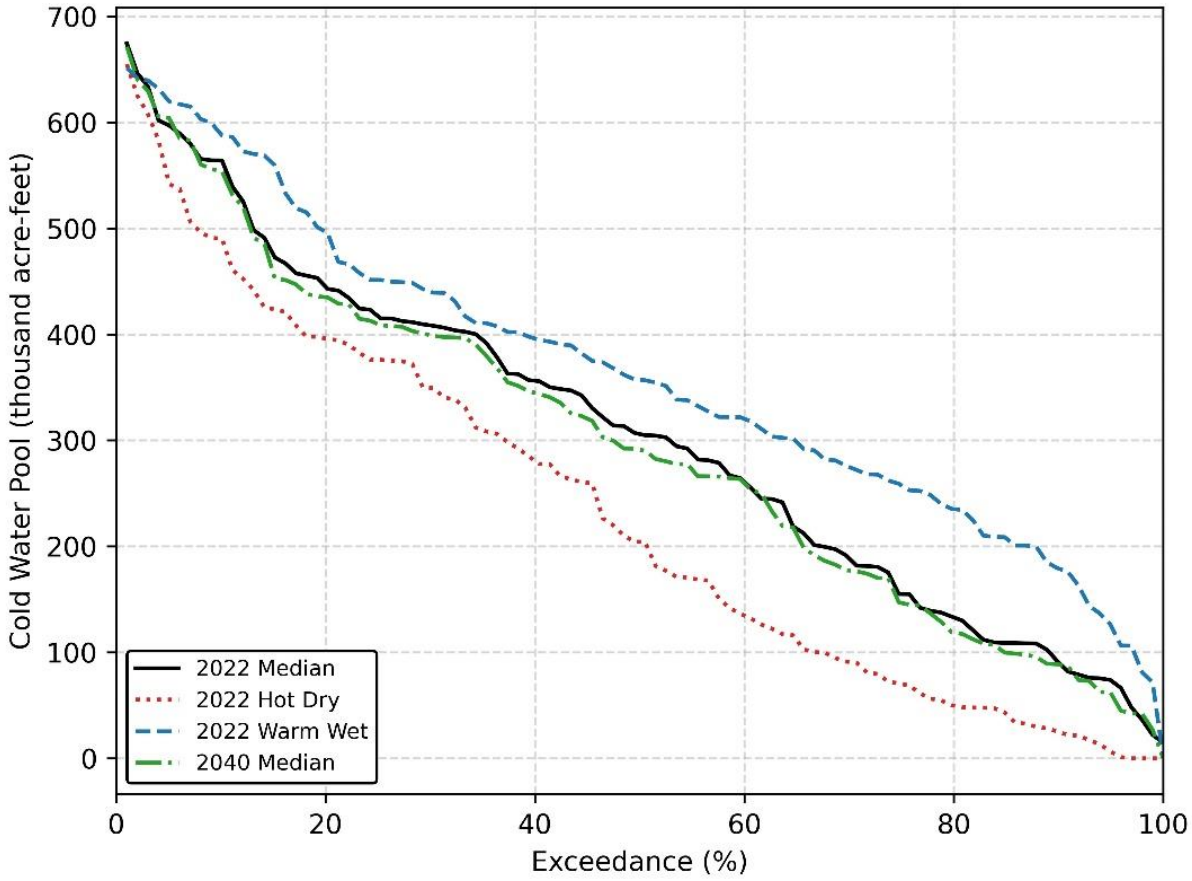

Figure F.2-5-30. Volume of water at the end of April less than 52 °F in Folsom Lake for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2021

F.2-5.2.2.3 Stanislaus

Figure F.2-5-31 and Figure F.2-5-32 summarize the temperature outcomes of Alternative 2v3 without TUCPs under the climate sensitivities in the Stanislaus basin. Average May through end of October temperatures at the Orange Blossom compliance location is hotter for the 2022 Hot Dry and 2040 Median scenarios when compared to the 2022 Median scenario. The 2022 Hot Dry scenario is hotter than the 2040 Median scenarios for all exceedances and the difference in temperatures between the two grows as the temperatures increase. The 2022 Warm Wet scenario average May through end of October temperatures at the Orange Blossom compliance location is cooler than the 2022 Median scenario due to generally more water available in the system and cooler temperatures. At high temperatures, the maximum May through October temperatures at the Orange Blossom compliance location follow a similar trend as the average May through October temperatures. At low temperatures, the 2022 Median, 2022 Hot Dry, and 2040 Median scenarios have similar maximum temperatures. The 2022 Warm Wet scenario has lower maximum temperatures at low temperatures when compared to the other scenarios.

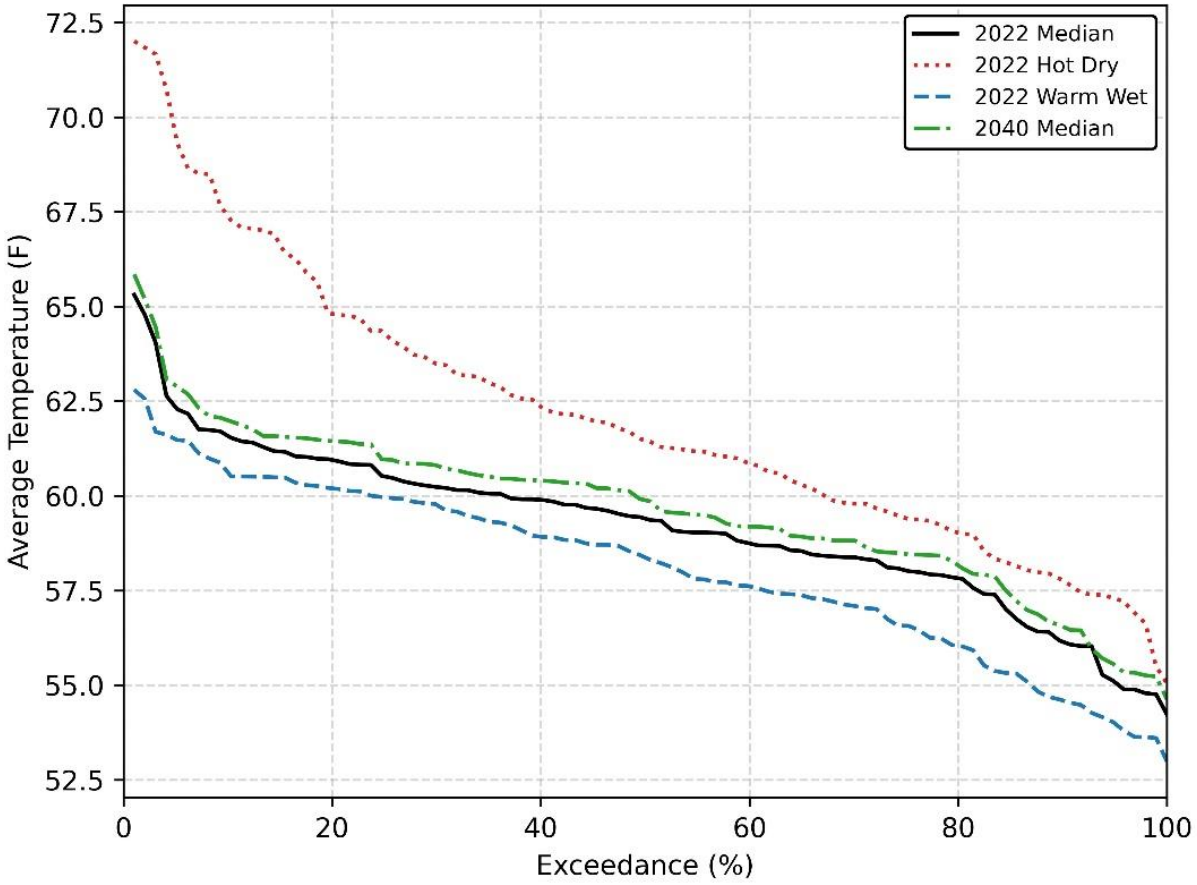

Figure F.2-5-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2019

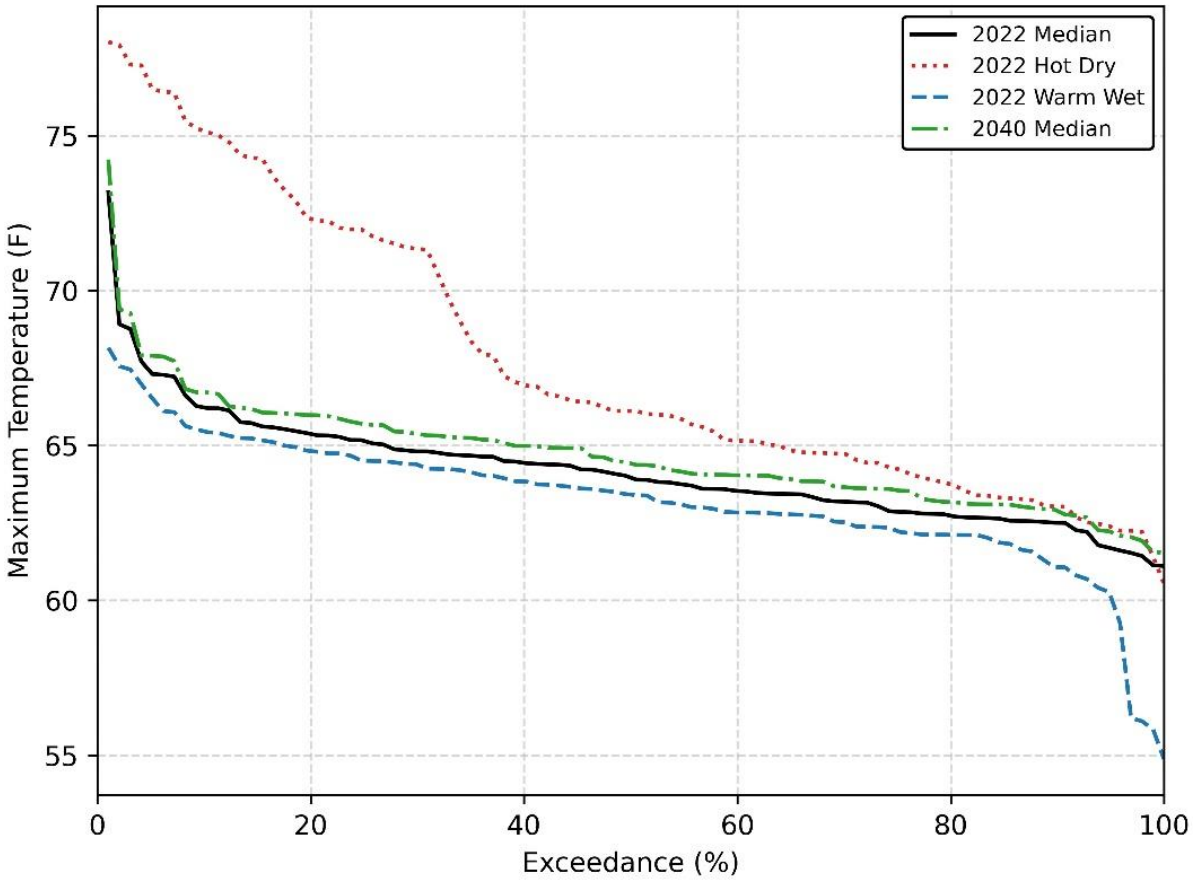

Figure F.2-5-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom for the Alternative 2v3 without TUCPs under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Section F.2-7 Climate Sensitivity Analysis, Alternative 3

F.2-7.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative 3 under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-7.2 Climate Change Comparison

F.2-7.2.1 CalSim 3

Figure F.2-7-1 through Figure F.2-7-21 show CalSim 3 simulation results for Alternative 3. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 3 were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough
- Sacramento River at Verona
- Sacramento River at Freeport
- Flow though Yolo Bypass

- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-7-1) and end of September (Figure F.2-7-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 10% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows (Figures 3 through 8), long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of reservoir management season, the differences are less notable. Summer months are commonly when river flows are due primarily to releases from storage instead of runoff events. Flows under 2040 Median climate are similar to flows under 2022 Median climate.

Clear Creek below Whiskeytown (Figure F.2-7-9) shows flow differences along the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. For Spring Creek inflow to Keswick Reservoir (Figure F.2-7-10), similar changes in long-term average flows are observed, except for June, when 2022 Hot and Dry and 2022 Warm and Wet conditions are similar. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-7-11) and end of September (Figure F.2-7-12) Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-7-13), in most months, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May

and June due to lower Folsom inflows in spring months, and is slightly lower than 2022 Hot Dry for the month of June. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. As compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in January of 2040 Median conditions due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-7-14), flow differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. Flows across all climate conditions are similar in June and July, months when releases consist of stored water.

For long-term monthly average San Joaquin River flows, differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. San Joaquin River at Gravelly Ford (Figure F.2-7-15) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam (Figure F.2-7-16) are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced (Figure F.2-7-17).

For long-term monthly average flows in the Delta (Figure F.2-7-18 through Figure F.2-7-21), flow differences follow the general trend, where 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in the fall, winter, and spring months. Flows across all climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure F.2-7-20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

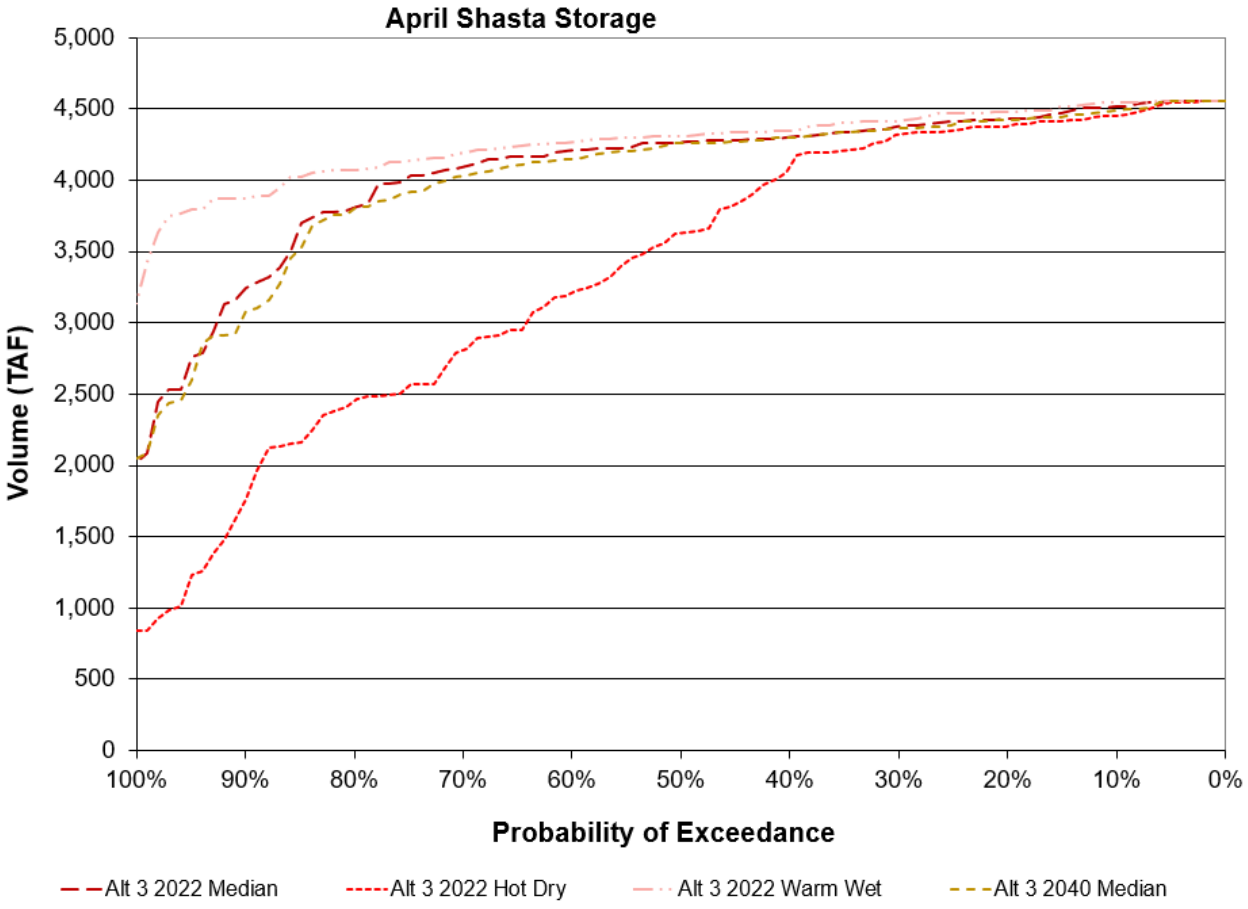

Figure F.2-7-1. End of April Shasta Storage

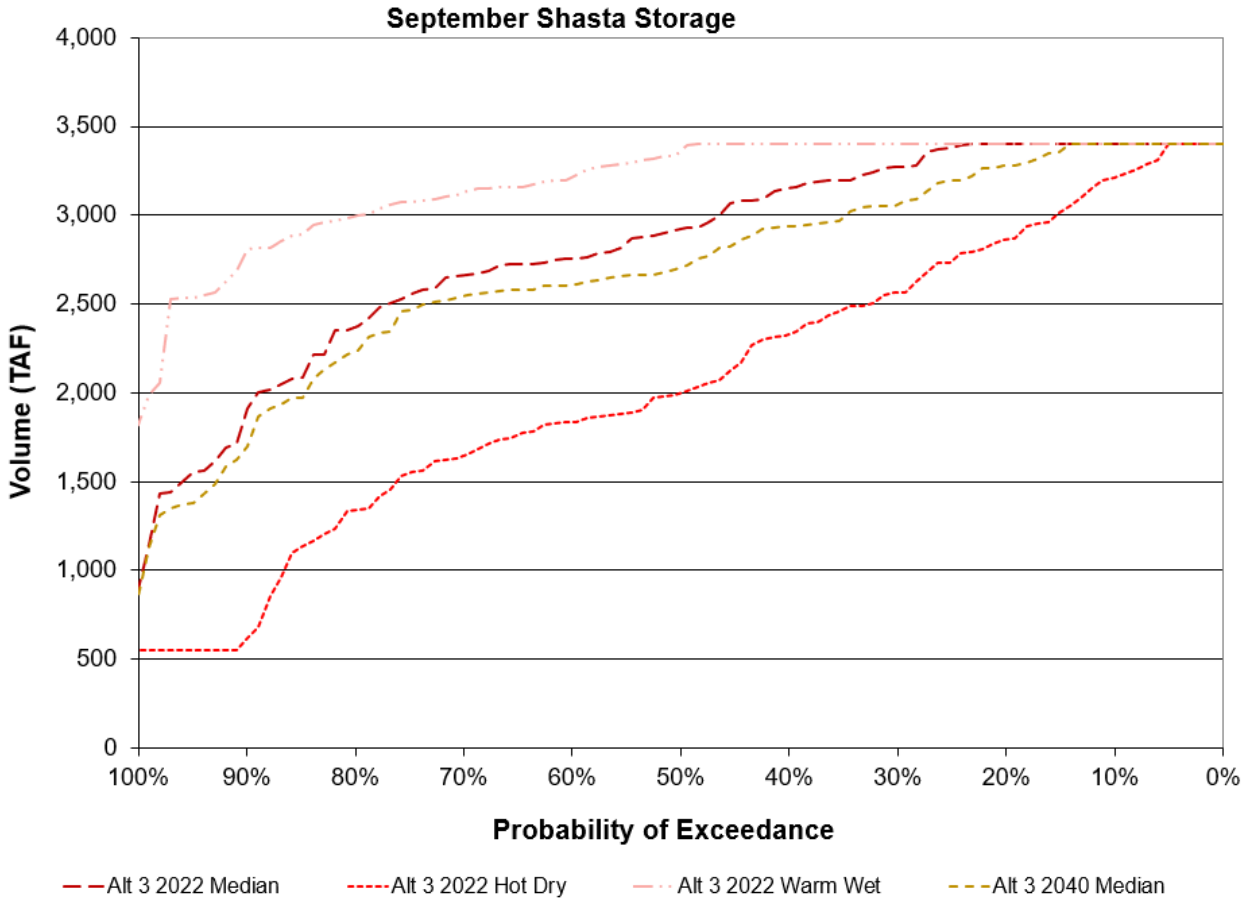

Figure F.2-7-2. End of September Shasta Storage

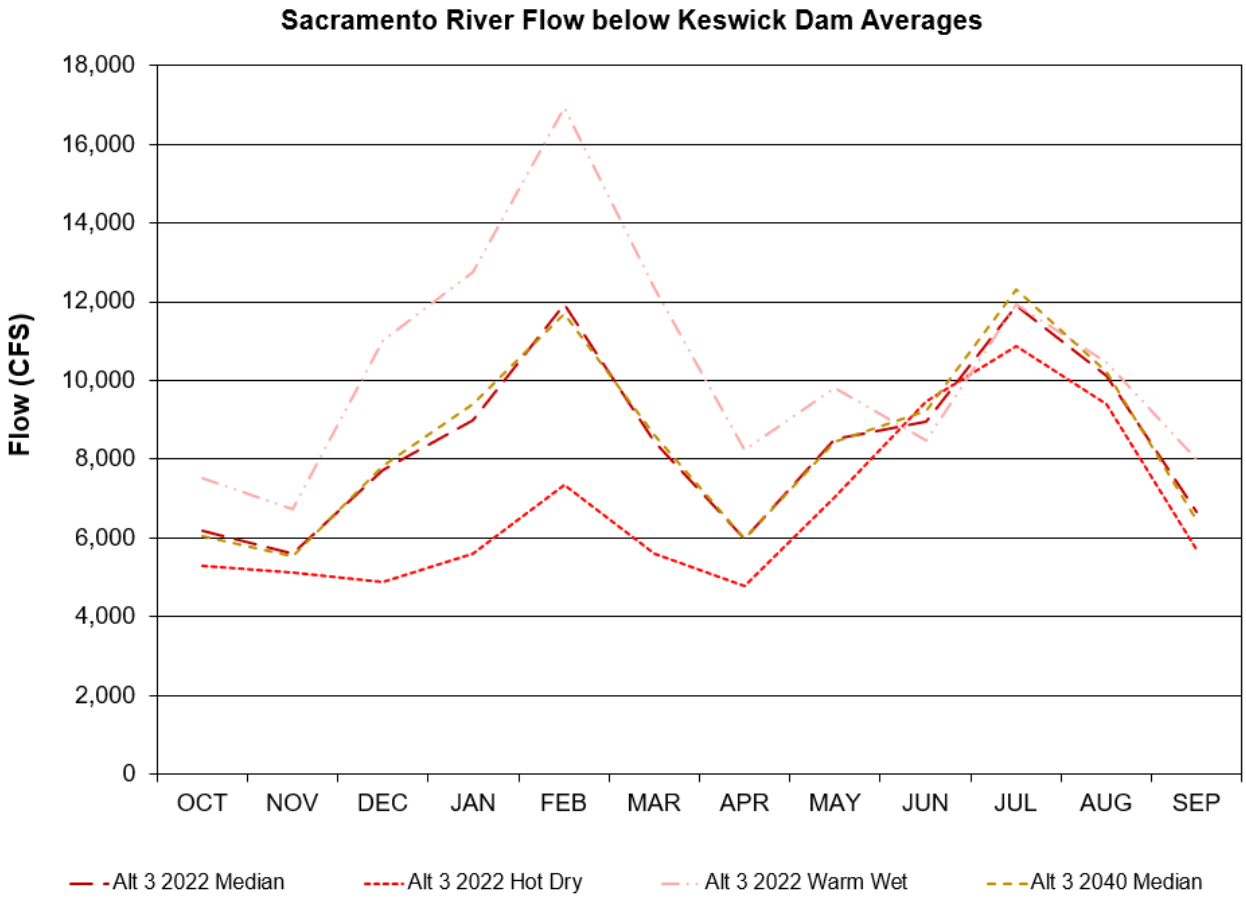

Figure F.2-7-3. Long-term Average Sacramento River flow below Keswick Dam

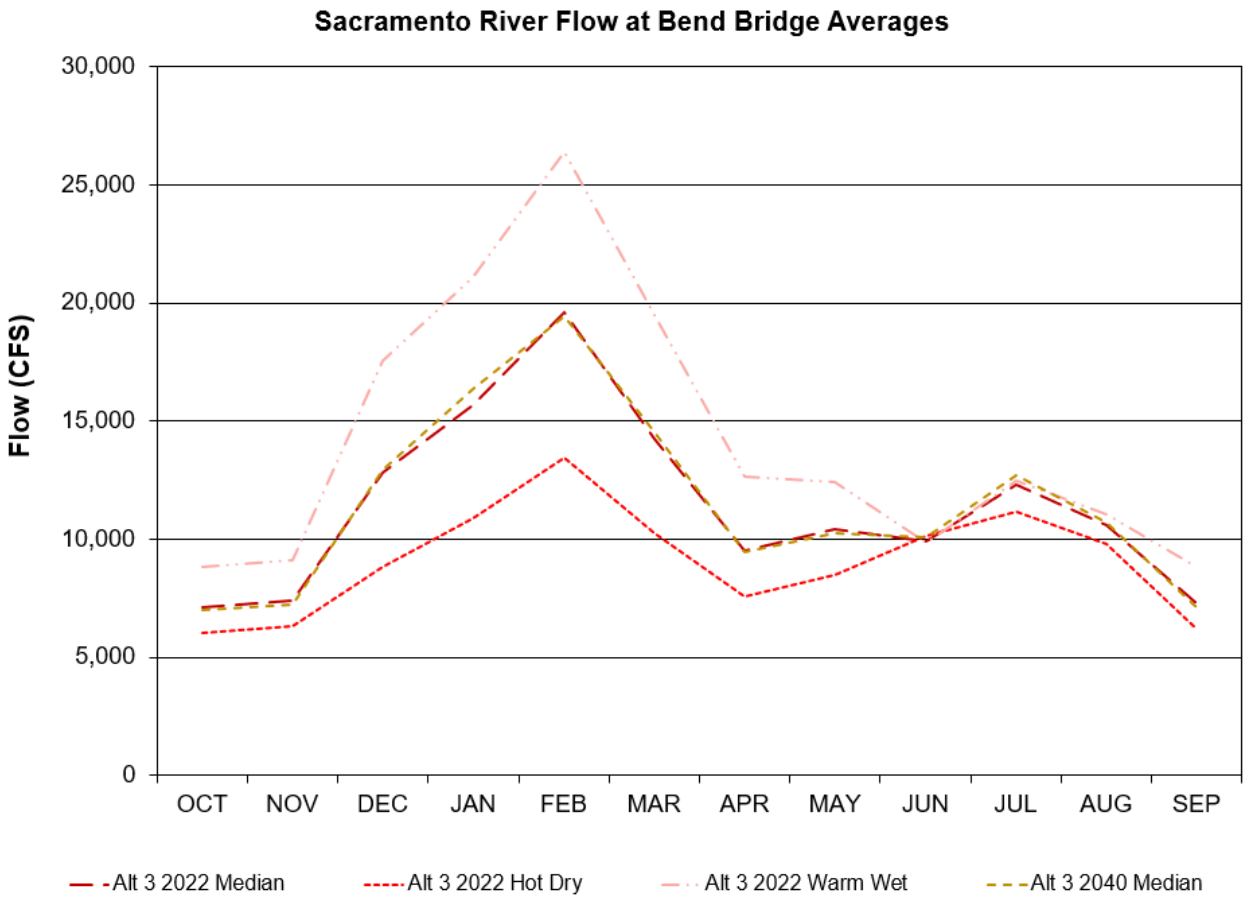

Figure F.2-7-4. Long-term Average Sacramento River flow at Bend Bridge

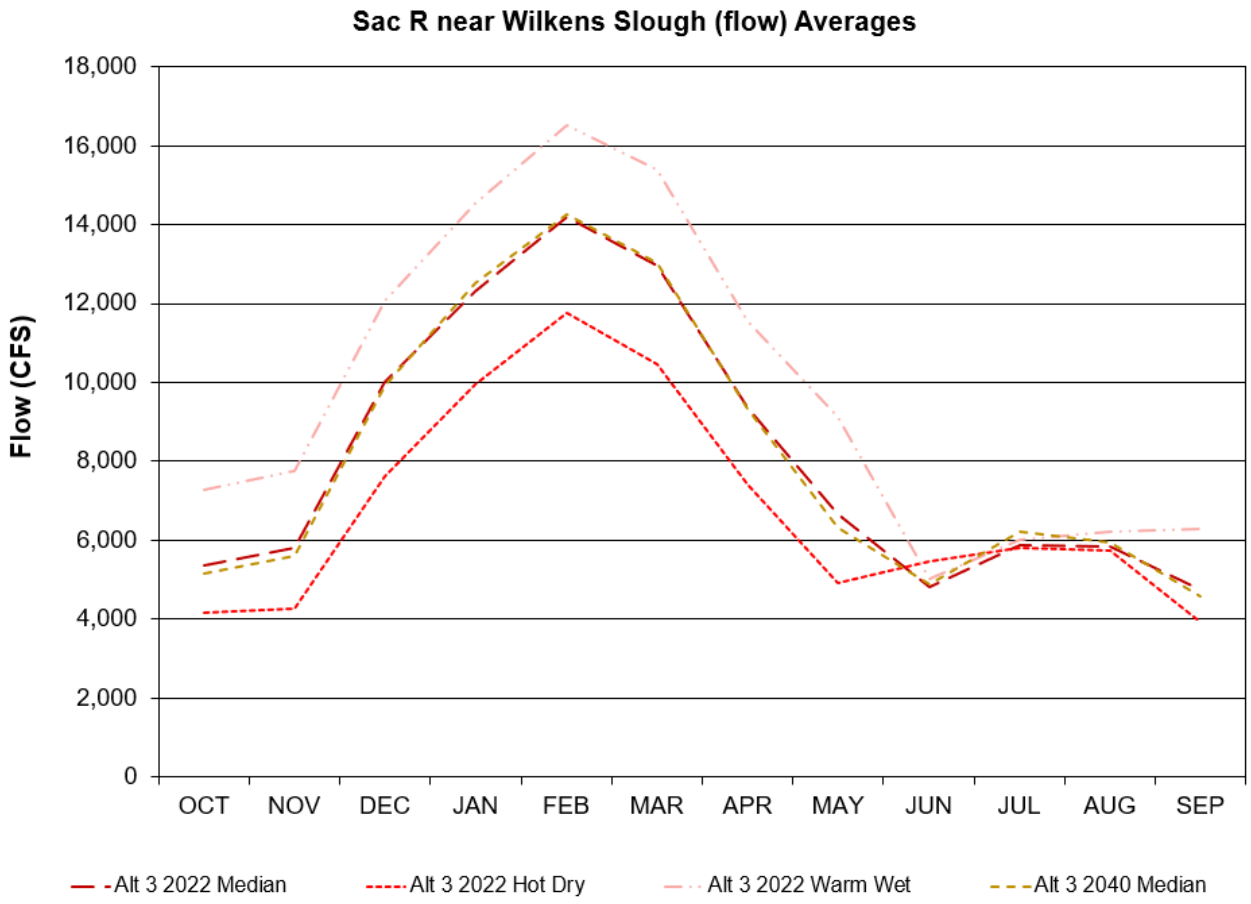

Figure F.2-7-5. Long-term Average Sacramento River flow near Wilkins Slough

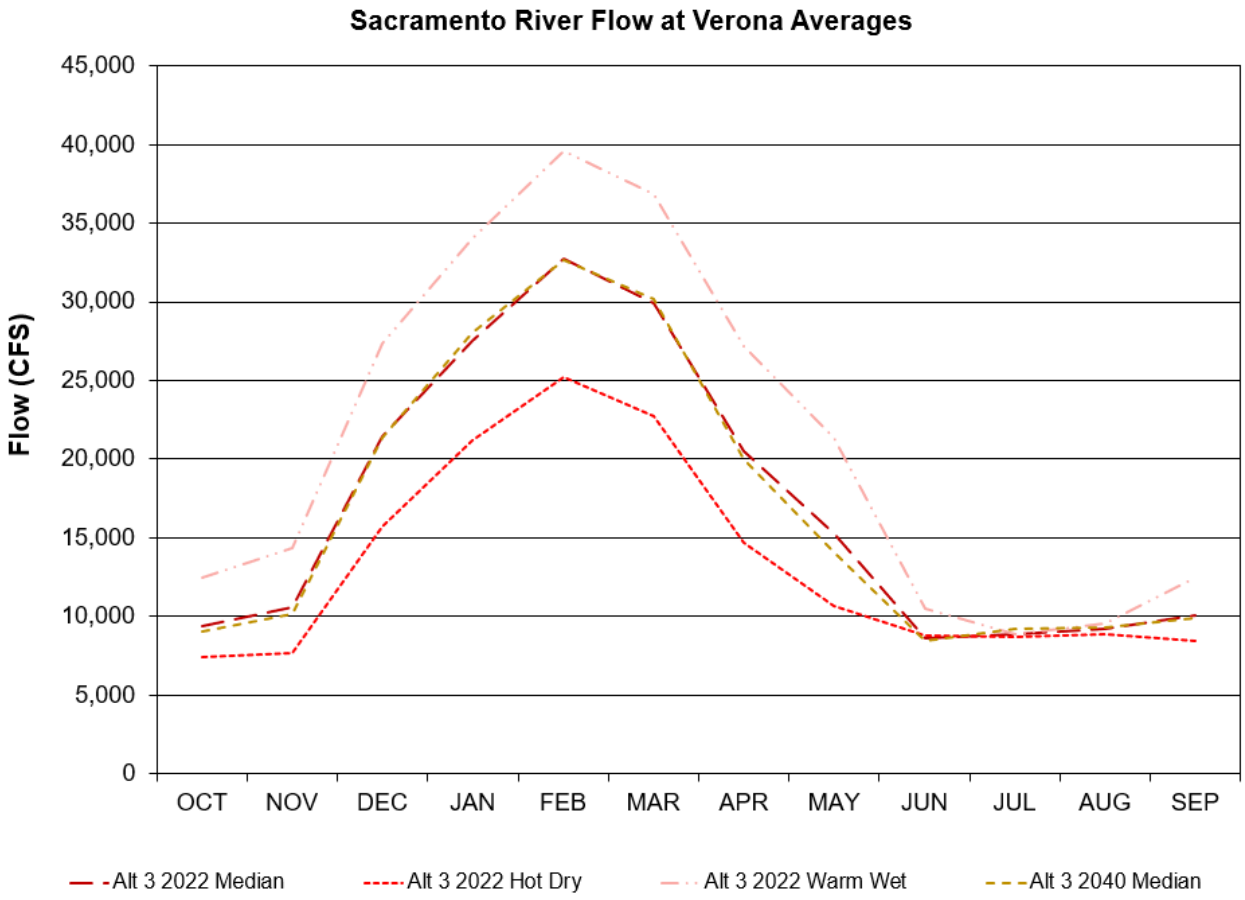

Figure F.2-7-6. Long-term Average Sacramento River flow at Verona

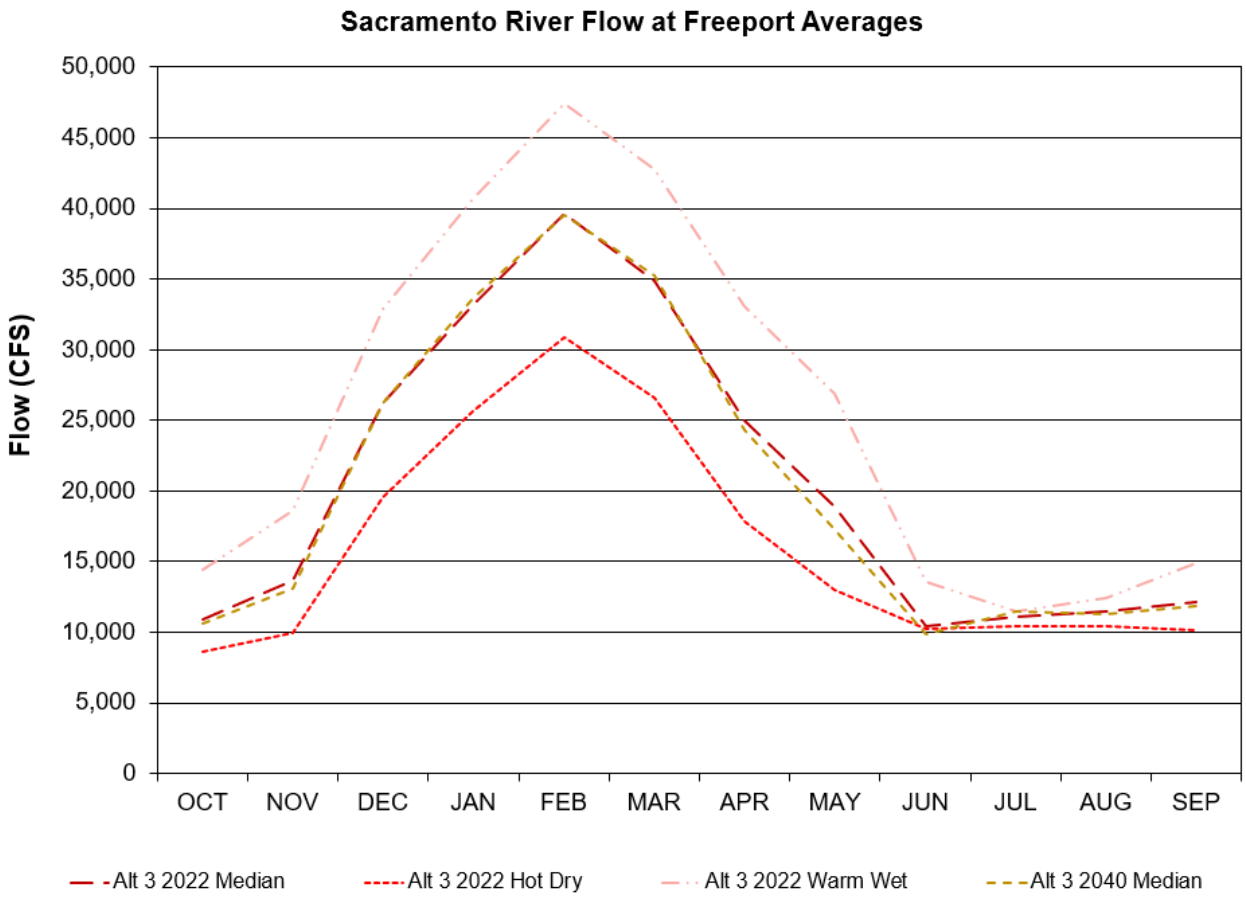

Figure F.2-7-7. Long-term Average Sacramento River flow at Freeport

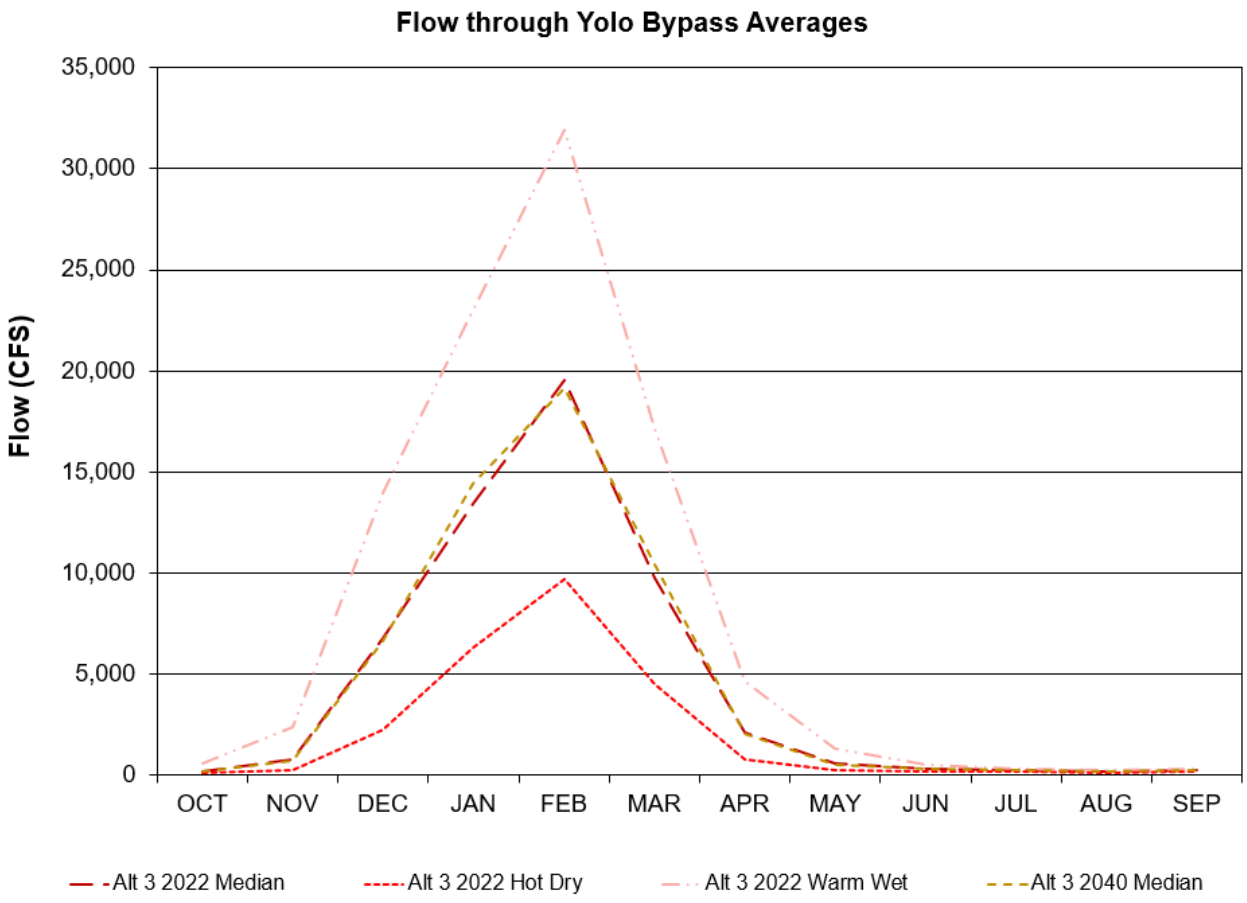

Figure F.2-7-8. Long-term Average Yolo Bypass Flow

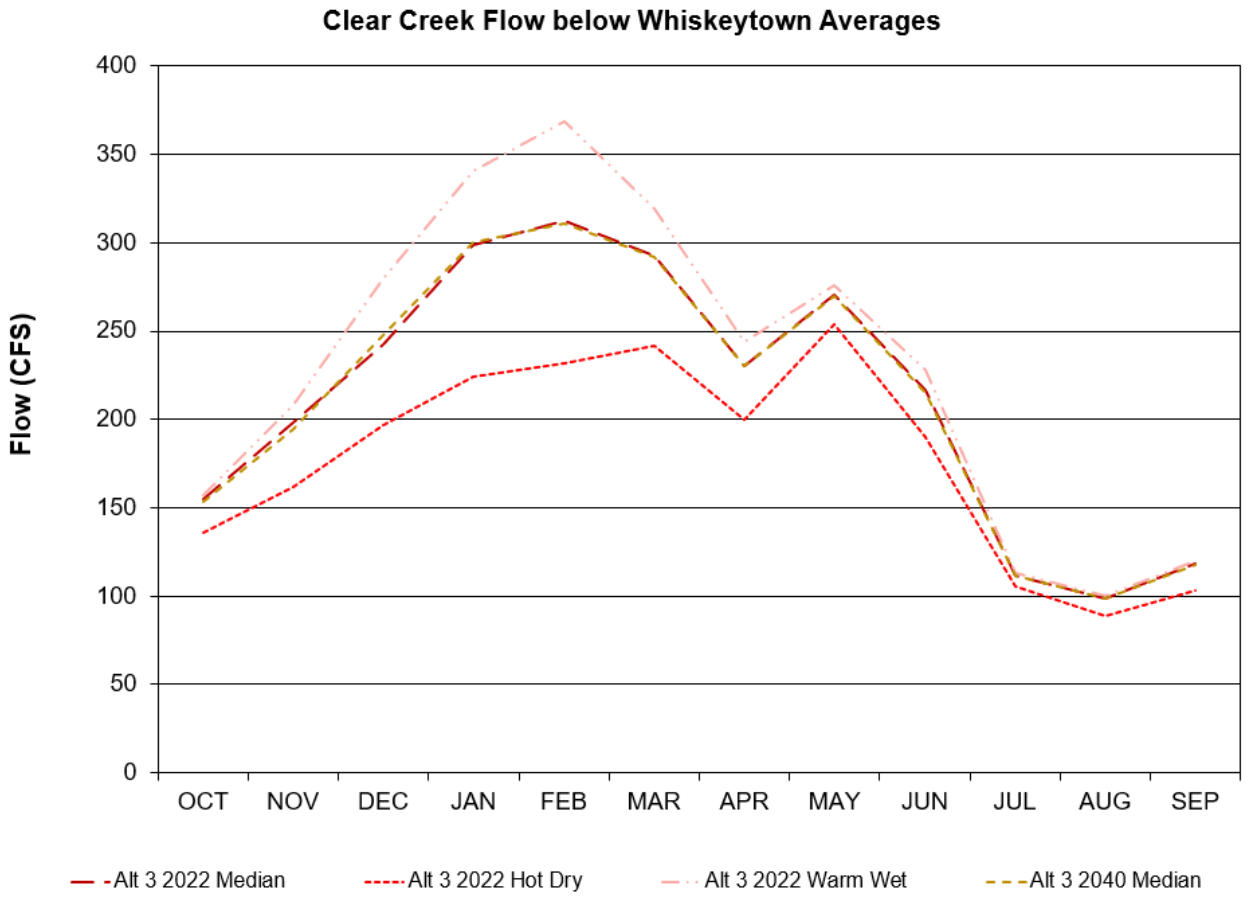

Figure F.2-7-9. Long-term Average Clear Creek flow below Whiskeytown

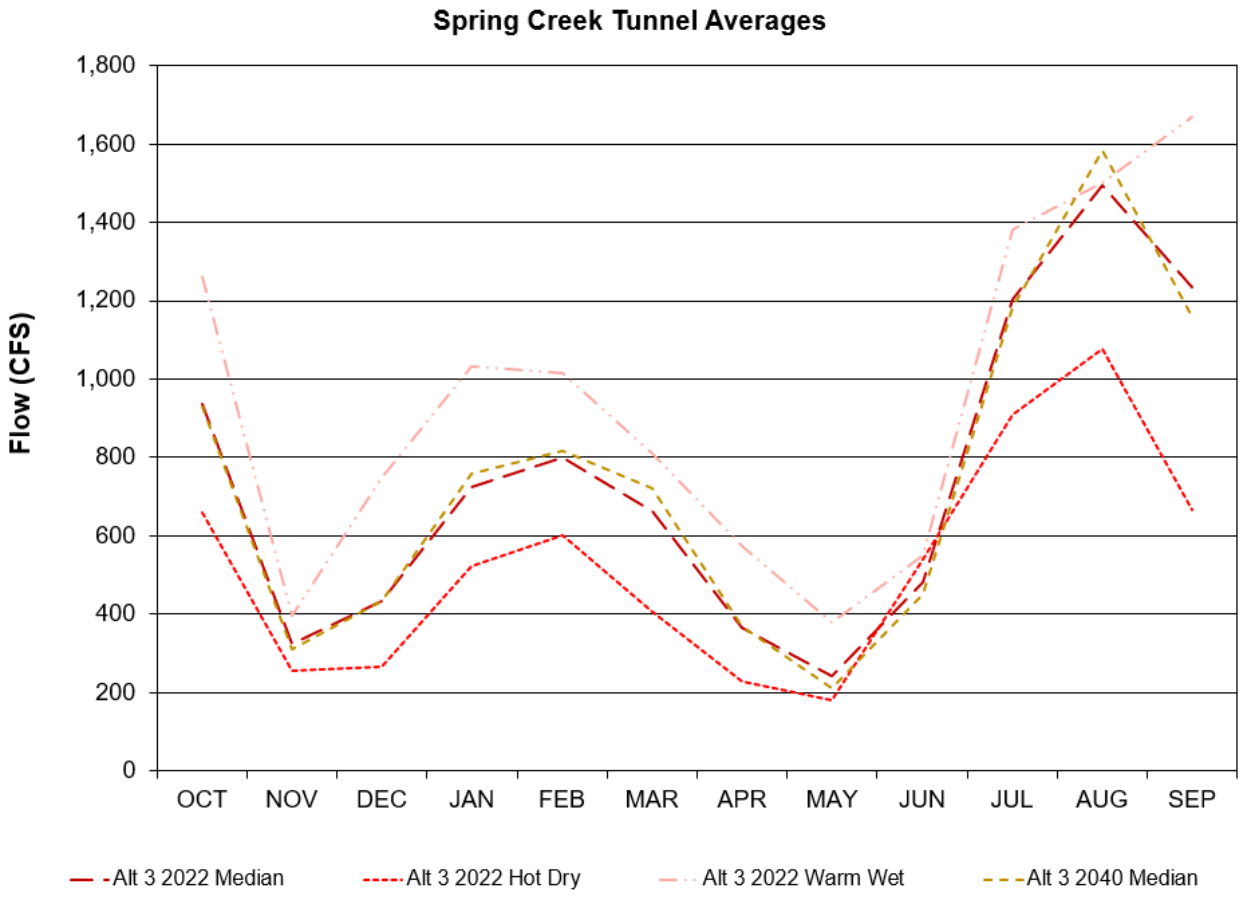

Figure F.2-7-10. Long-term Average Spring Creek Tunnel Flow

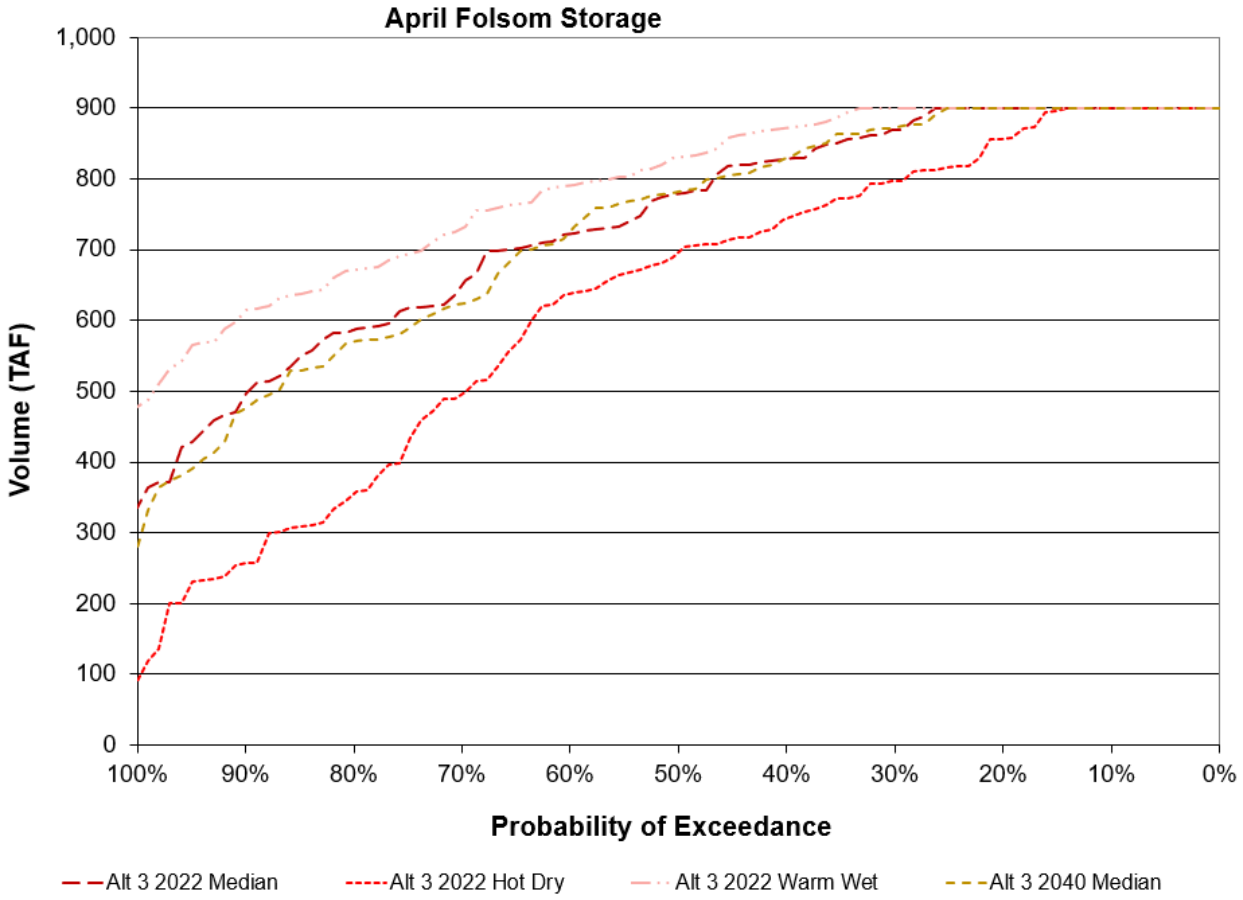

Figure F.2-7-11. End of April Folsom Storage

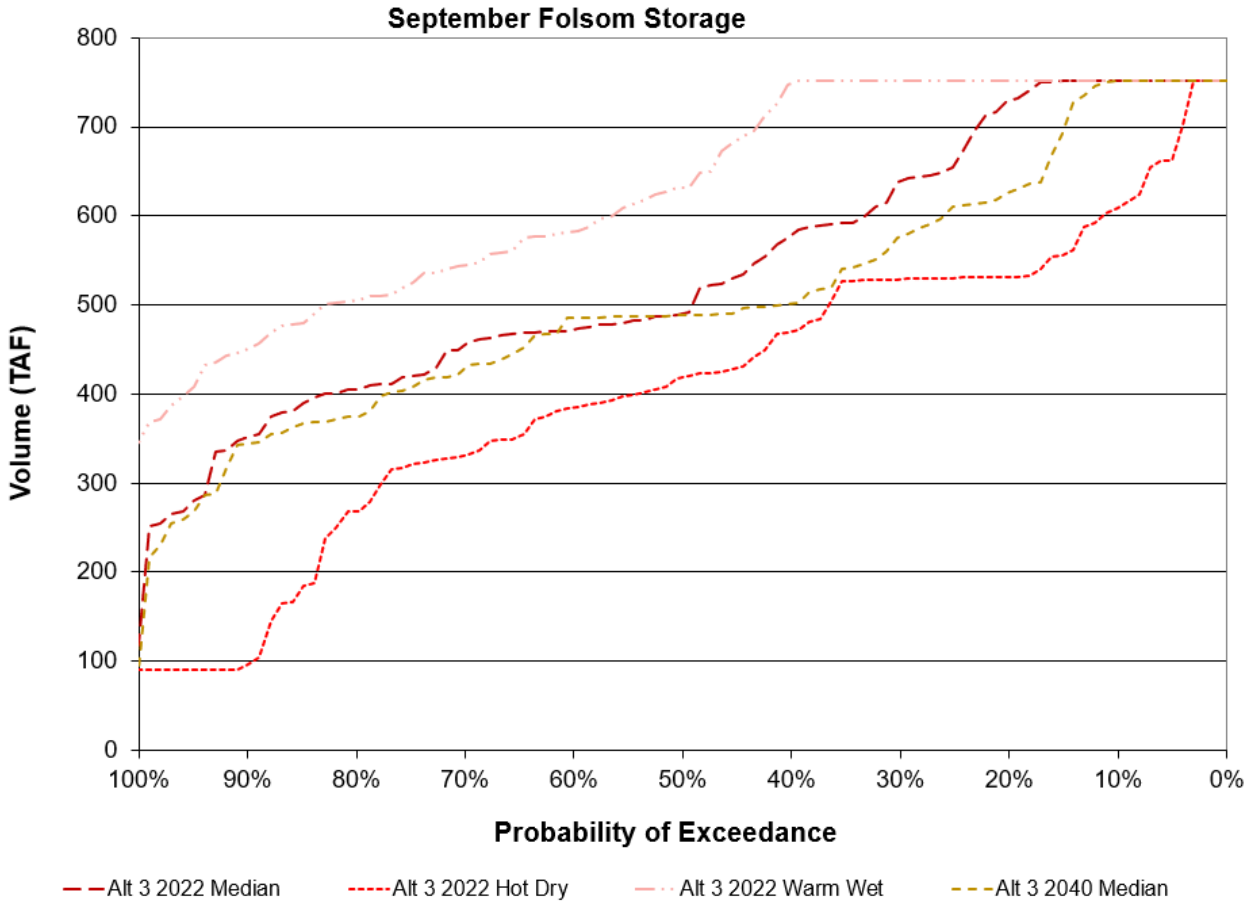

Figure F.2-7-12. End of September Folsom Storage

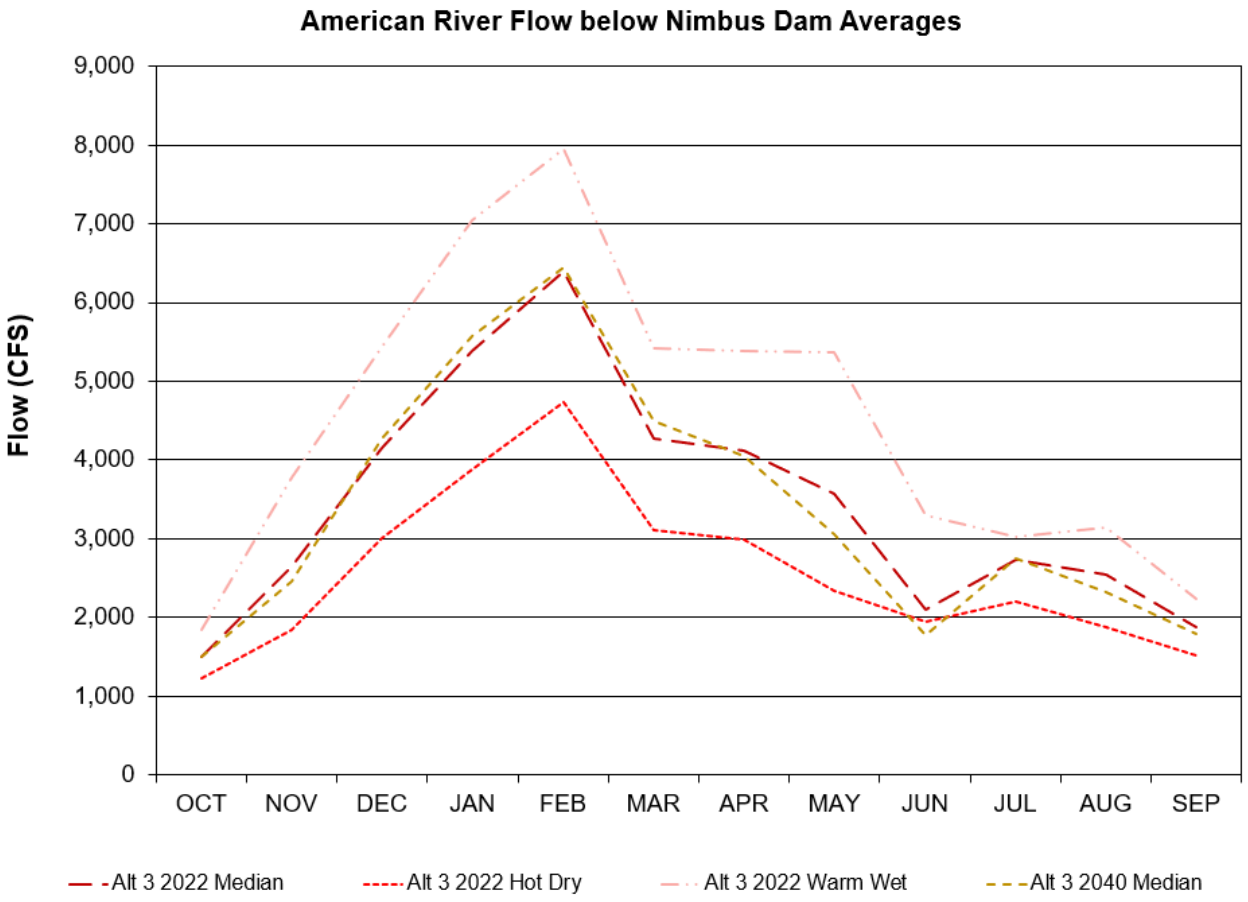

Figure F.2-7-13. Long-term Average American River flow below Nimbus Dam

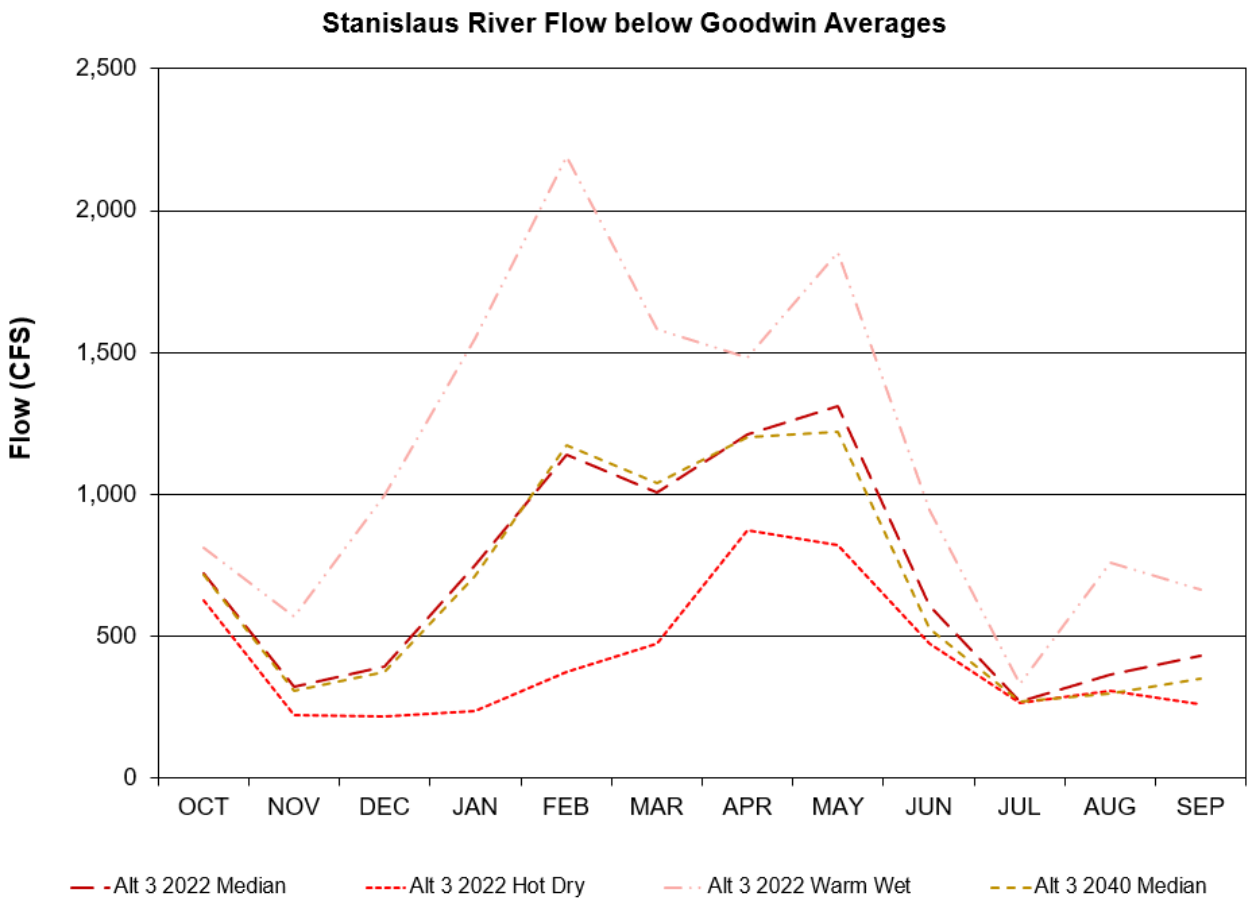

Figure F.2-7-14. Long-term Average Stanislaus River flow below Goodwin

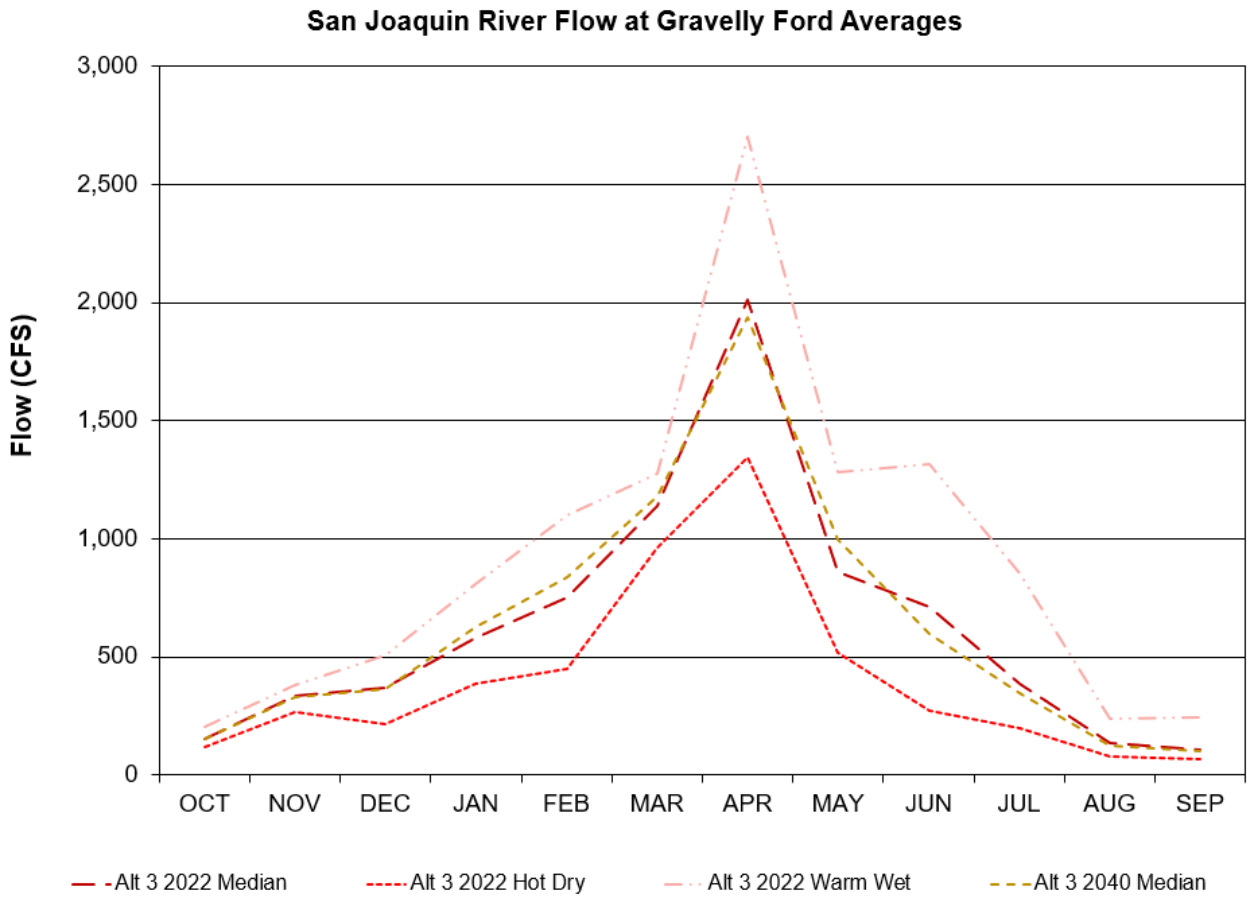

Figure F.2-7-15. Long-term Average San Joaquin River flow at Gravelly Ford

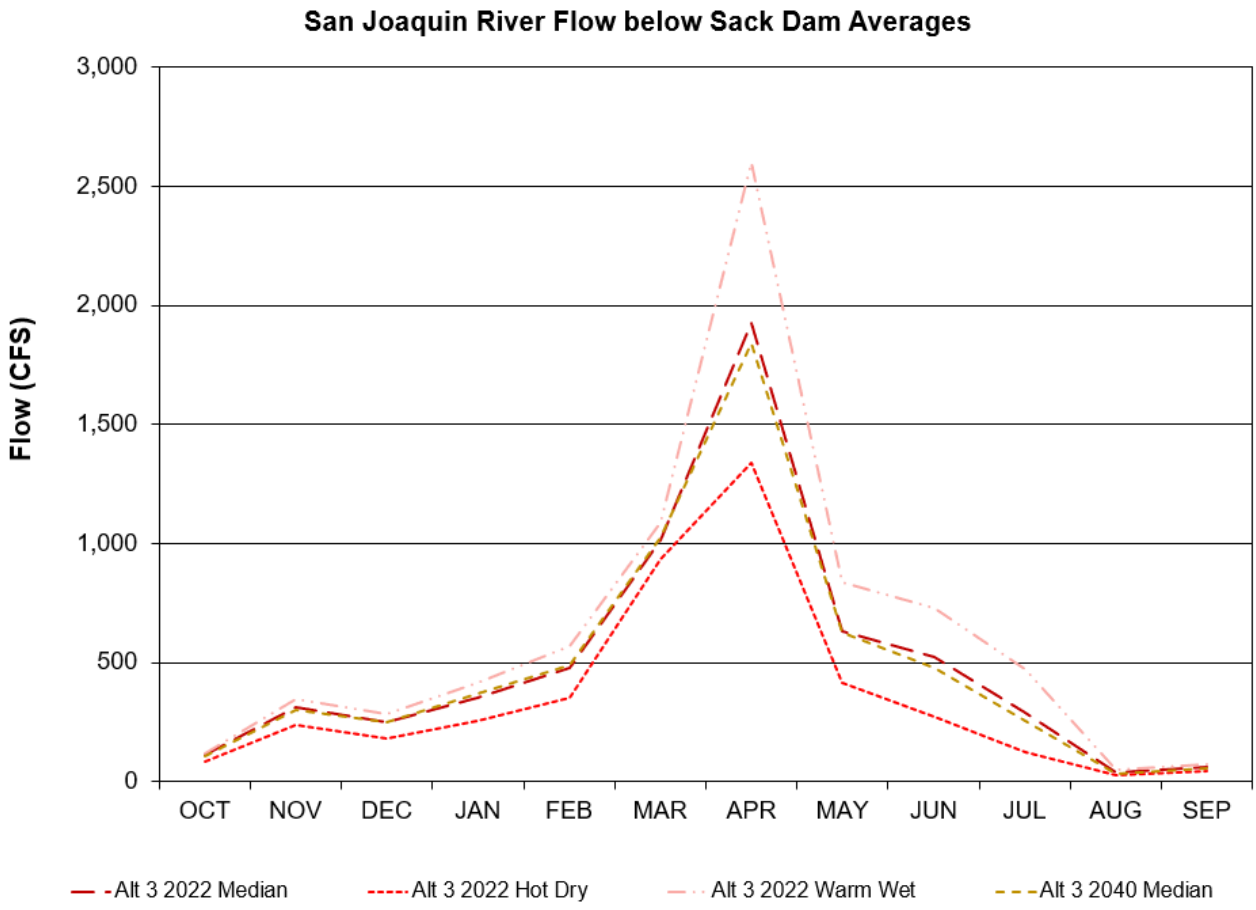

Figure F.2-7-16. Long-term Average San Joaquin River flow below Sack Dam

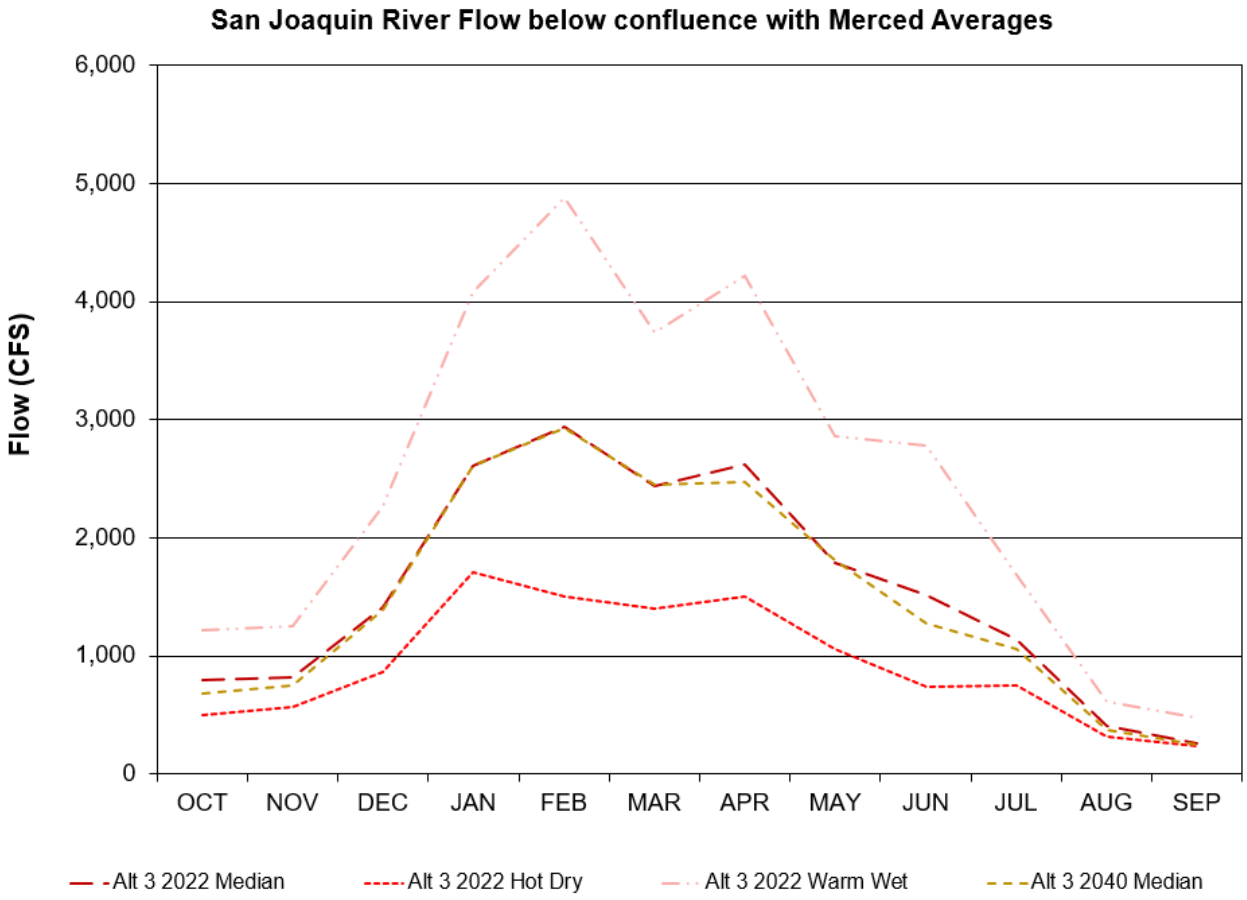

Figure F.2-7-17. Long-term Average San Joaquin River flow below Confluence with Merced River

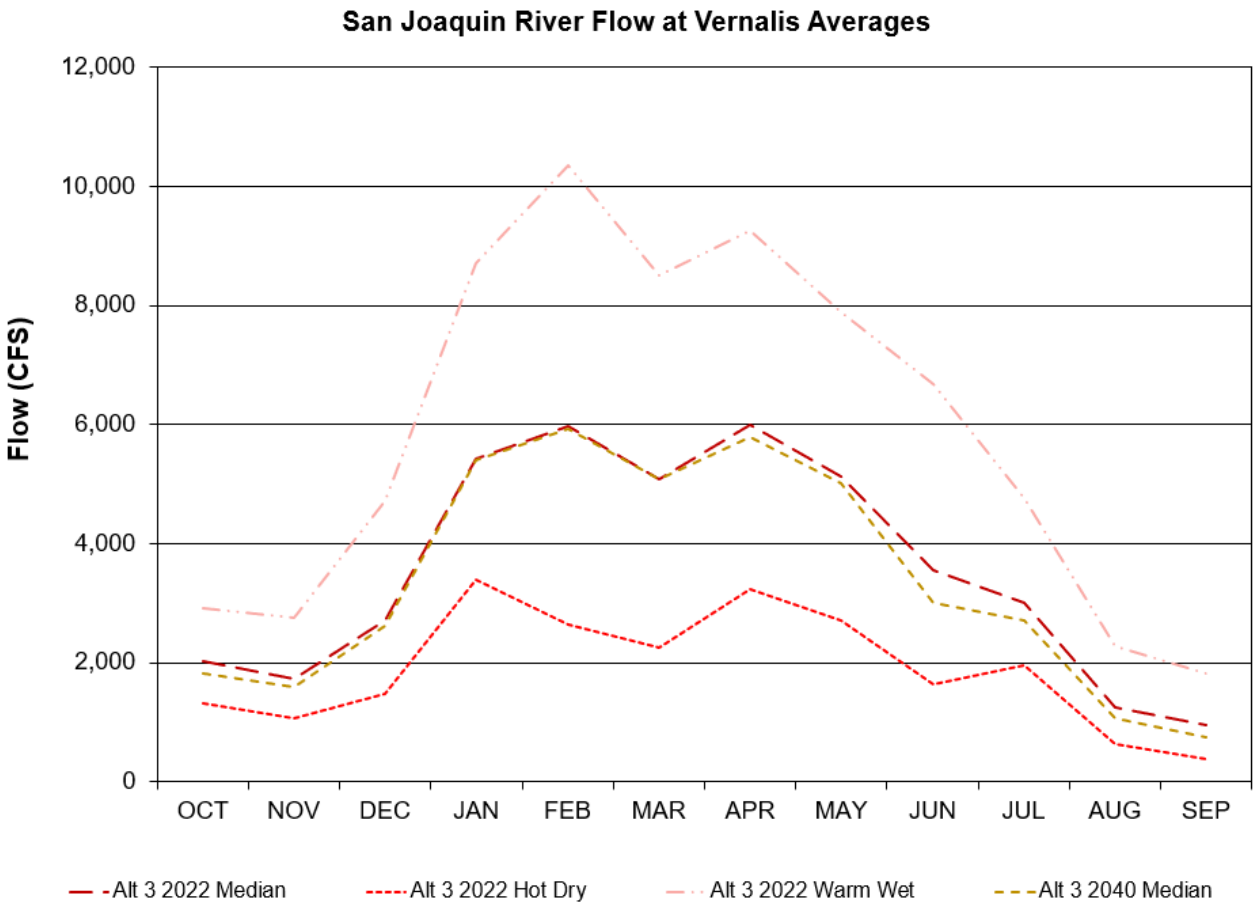

Figure F.2-7-18. Long-term Average San Joaquin River flow at Vernalis

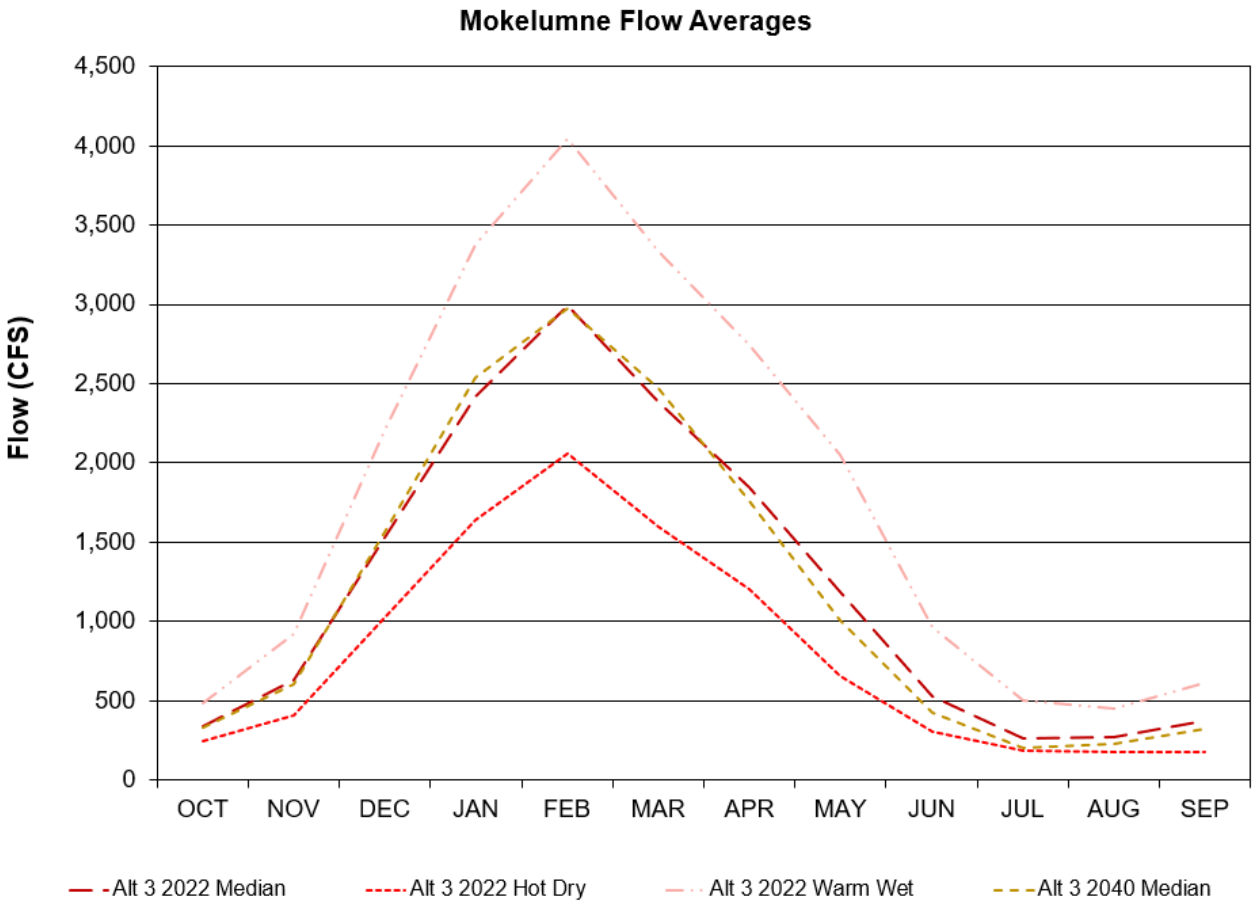

Figure F.2-7-19. Long-term Average Mokelumne River Flow

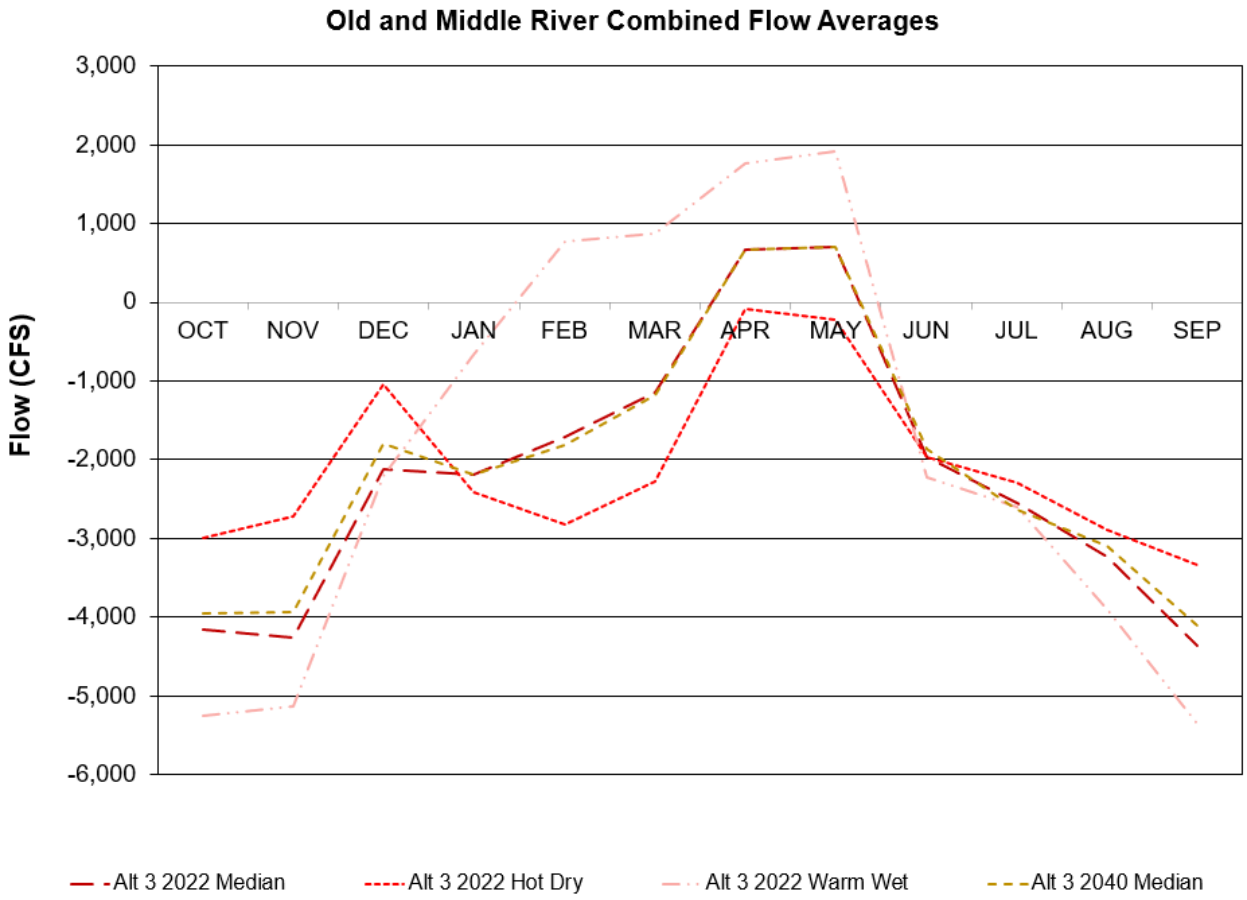

Figure F.2-7-20. Long-term Average Old and Middle River Combined Flow

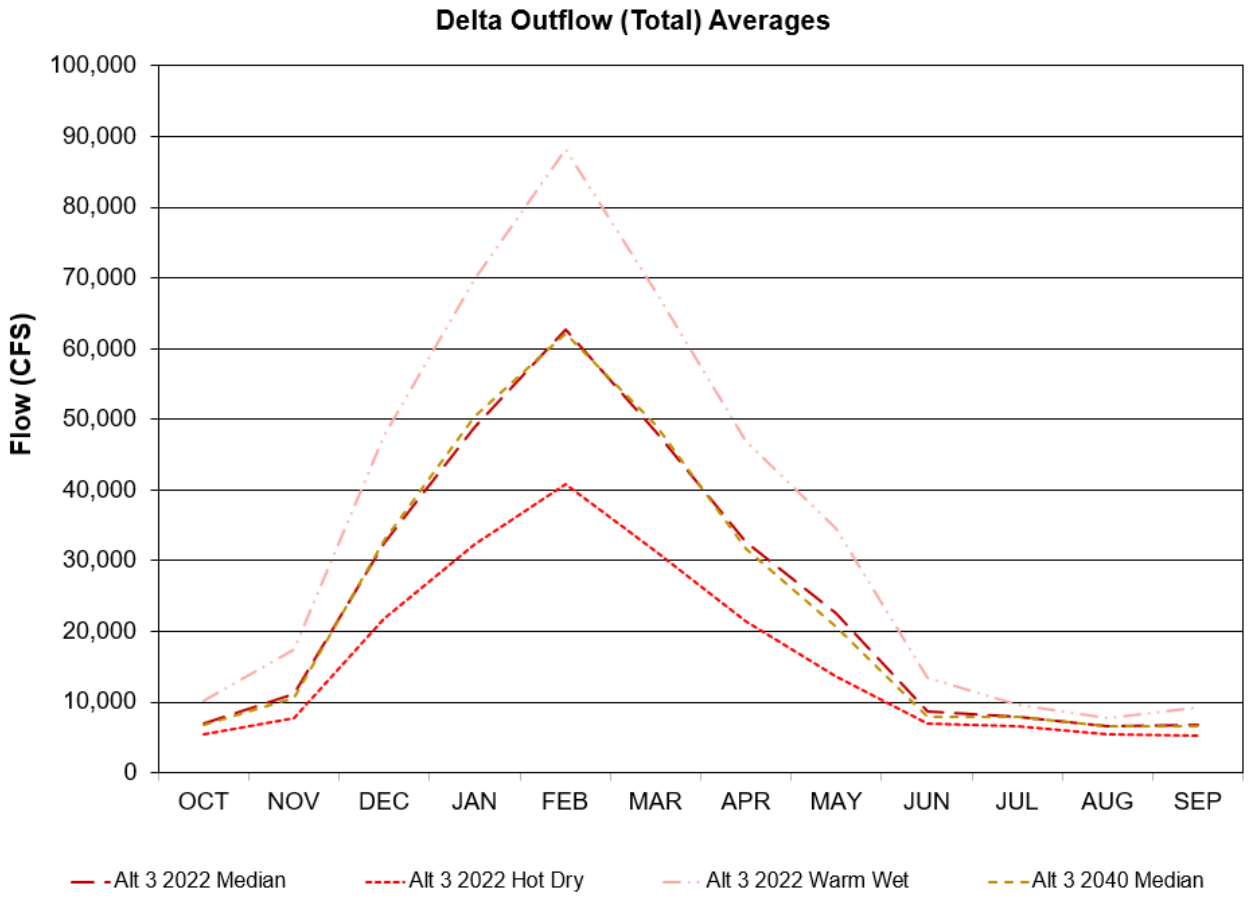

Figure F.2-7-21. Long-term Average Delta Outflow

F.2-7.2.2 HEC5Q

F.2-7.2.2.1 Sacramento

Figure F.2-7-22 through Figure F.2-7-27 evaluate the temperature outcomes in the Sacramento River under the climate sensitivities using the Alternative 3 logic. Temperature dependent mortality (TDM) was calculated using the standard LTO parameterization from the converged daily modeled temperatures prior to converging and calculating the six hour temperature metrics.

The Alternative 3 TDM estimate shown in Figure F.2-7-22 demonstrates substantial climate variability. Under the 2022 Median climate scenario, TDM exceeds 60% in less than 10% of the simulated years. Under the 2022 Warm Wet climate scenario which is cooler and wetter than the 2022 Median climate scenario, TDM exceeds 60% in approximately 5% of the simulated years. Conversely, the 2022 Hot Dry climate scenario which is warmer and drier than the 2022 Median scenario has large TDM values occur more frequently with 60% TDM occurring in approximately 25% of the simulated years. The 2040 Median scenario performs similarly to the 2022 Median scenario, albeit with an approximately 20% upward exceedance shift surrounding the 20% exceedance threshold.

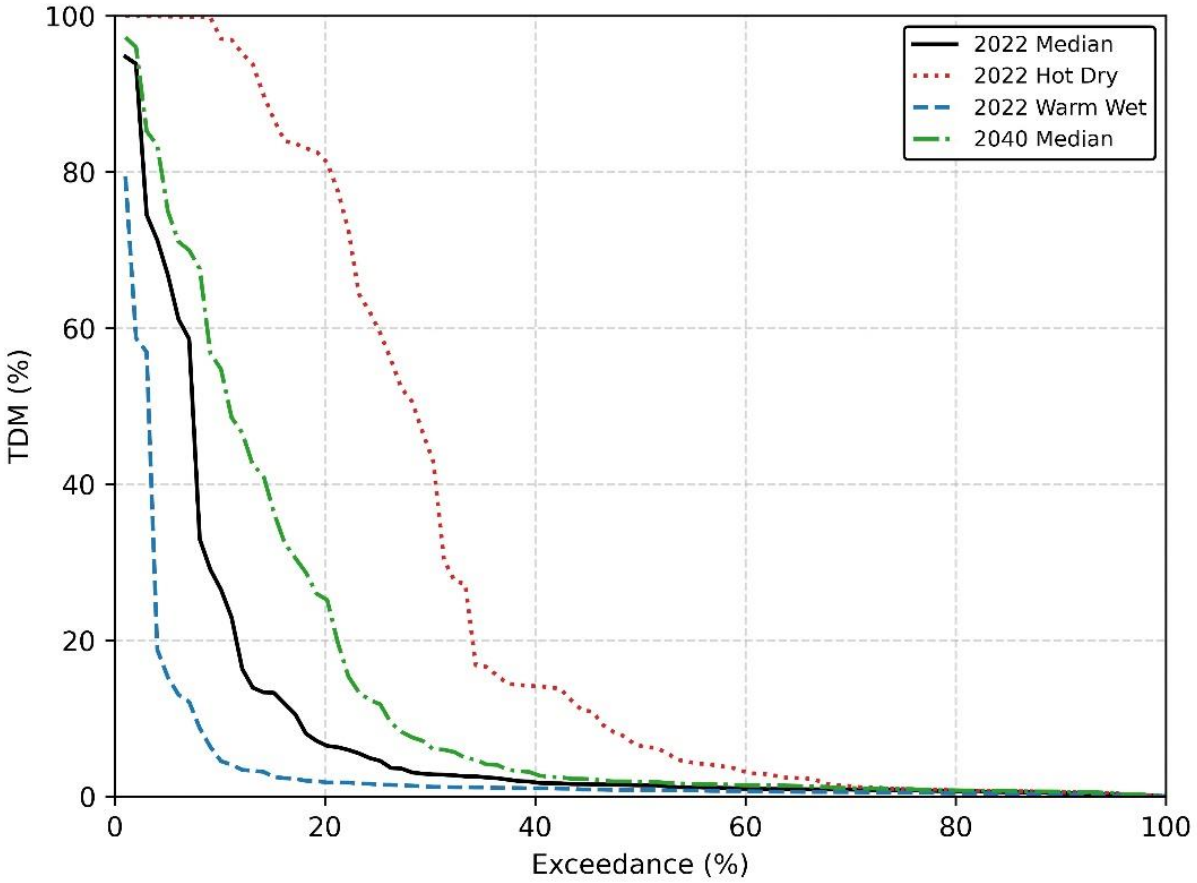

Figure F.2-7-22. Martin model TDM exceedance plot for Alternative 3 under various climate assumptions for water years 1922 through 2021

The Alternative 3 TDM values are driven by the Sacramento River temperature from Clear Creek down to Red Bluff. Figure F.2-7-23 and Figure F.2-7-24 show the average and maximum May through end of October temperature in the Sacramento River below Clear Creek with Figure F.2-7-25 and Figure F.2-7-26 providing the same information from Red Bluff.

The scaling of TDM follows temperature outcomes with the 2022 Hot Dry scenario having the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest temperatures of the scenarios. While the scenarios have a clear incremental increase in average temperature, temperatures above the 60% exceedance threshold are largely similar. An analogous trend is visible in Figure F.2-7-27 with the volume of water less than 52 degrees Fahrenheit (°F) at the end of April. More cold water correlates with lower TDMs across the climate scenarios. However, despite having generally similar cold-water volumes, the 2040 Median condition exhibits worse TDM outcomes than the 2022 Median, likely due to the roughly degree higher average temperatures under the 2040 Median scenario. The higher average temperatures under the 2040 Median scenario are likely due in part to the greater in-stream and reservoir warming.

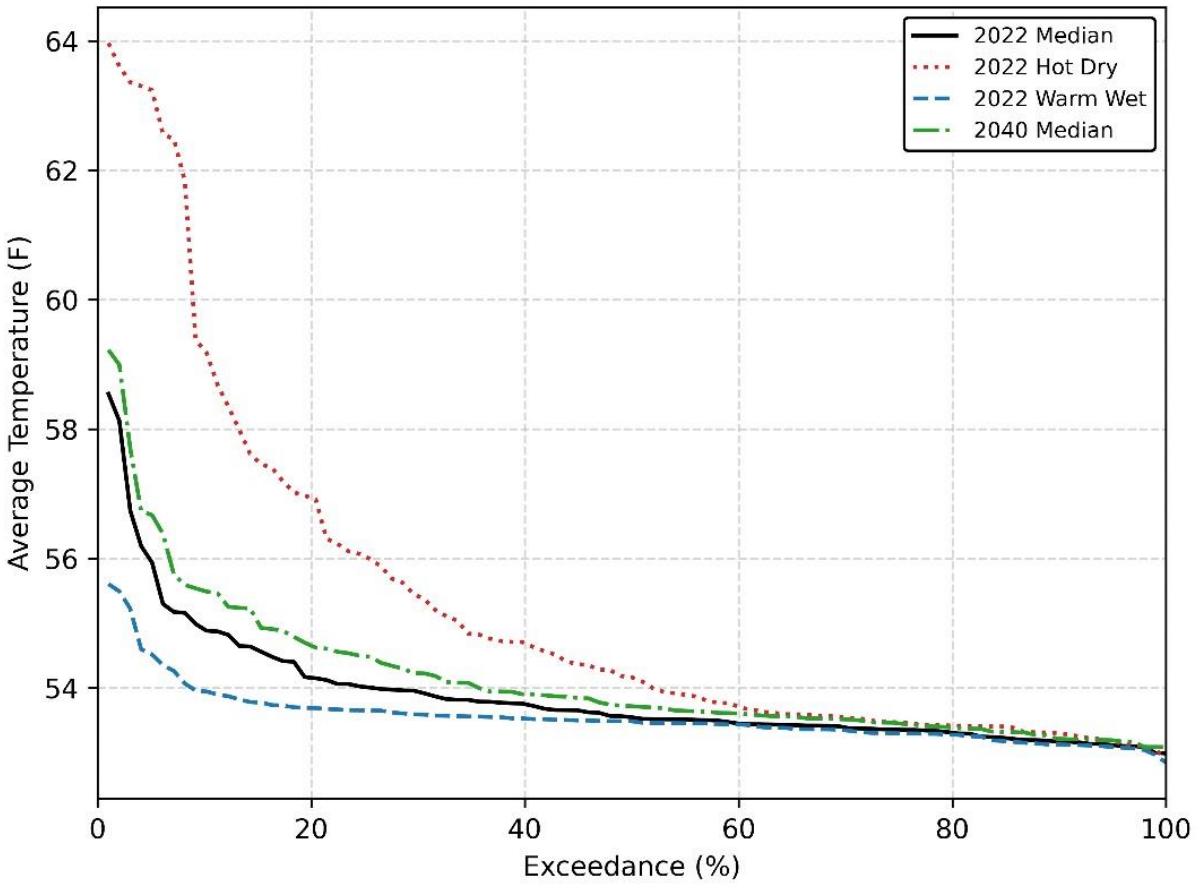

Figure F.2-7-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 3 under various climate assumptions for water years 1923 through 2020

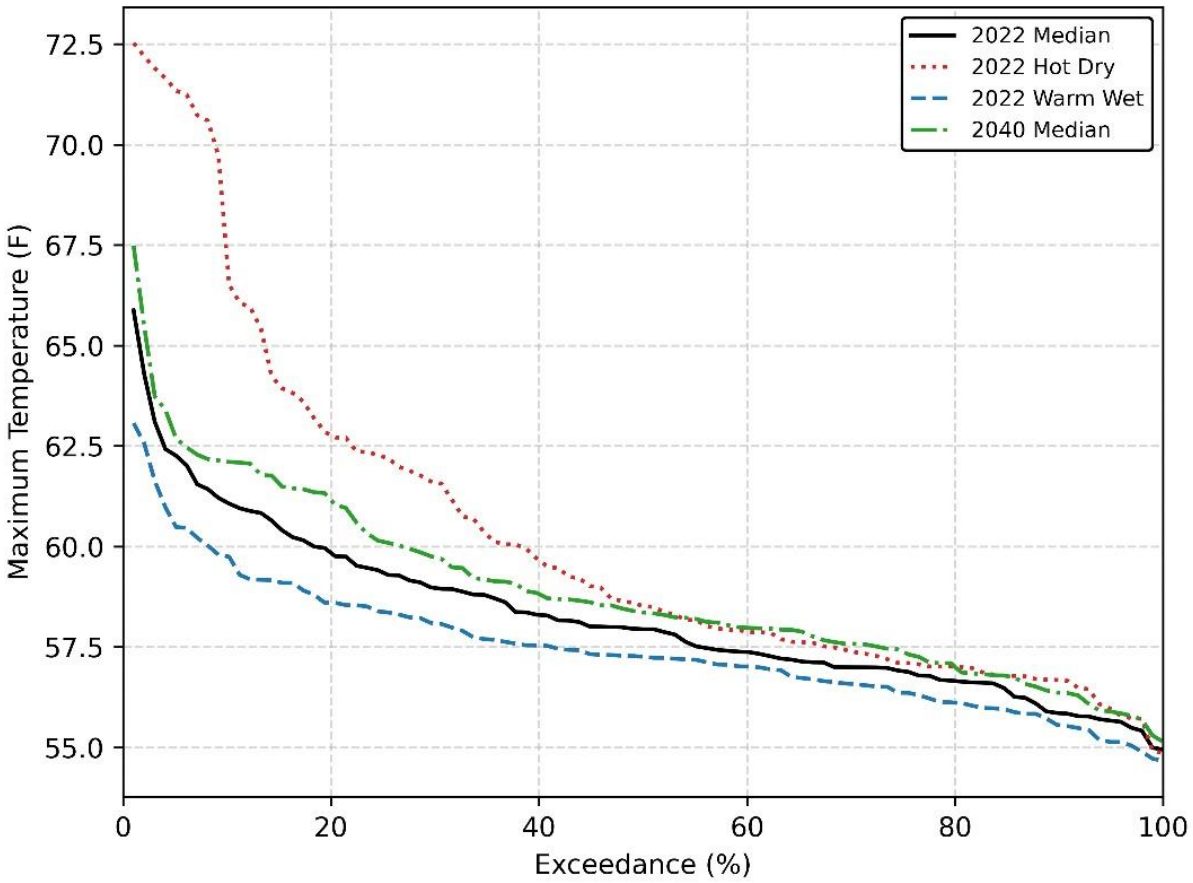

Figure F.2-7-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 3 under various climate assumptions for water years 1923 through 2020

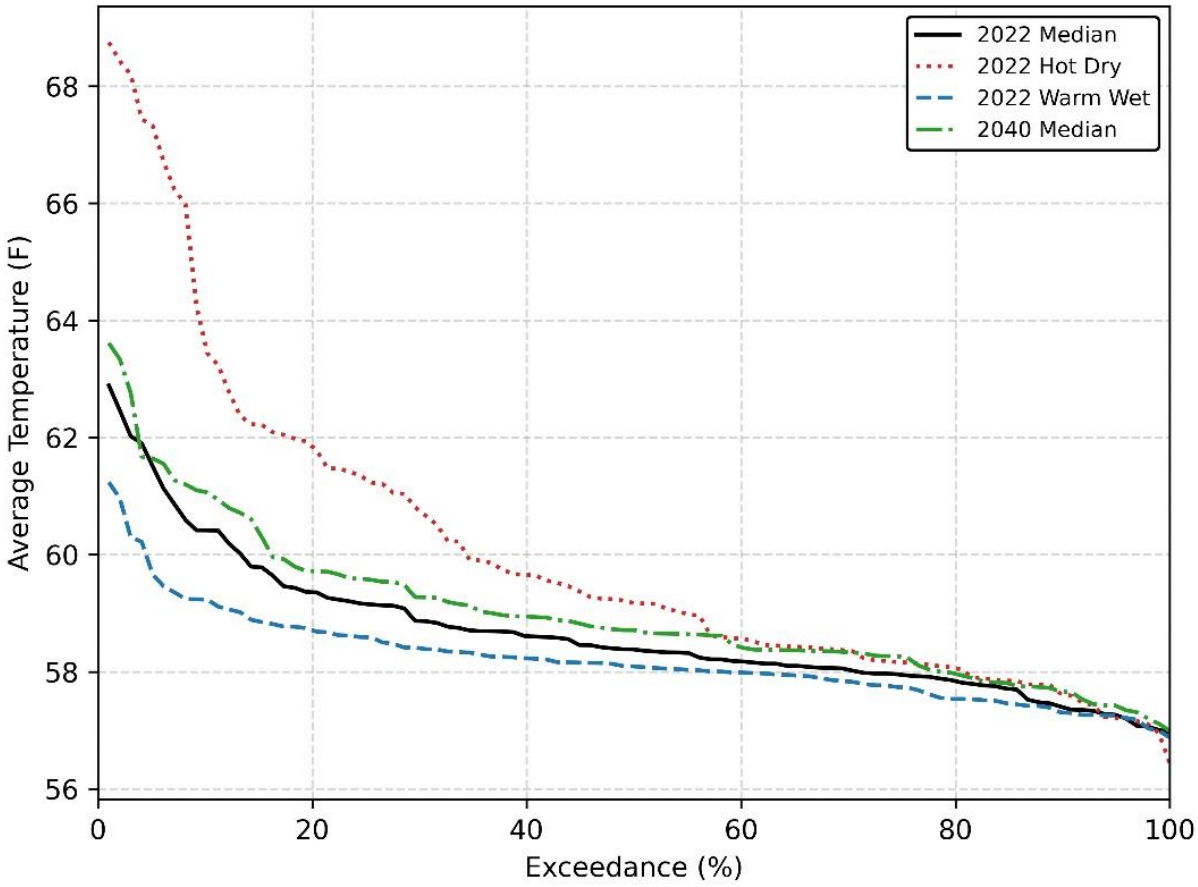

Figure F.2-7-25. Average May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 3 under various climate assumptions for water years 1923 through 2020

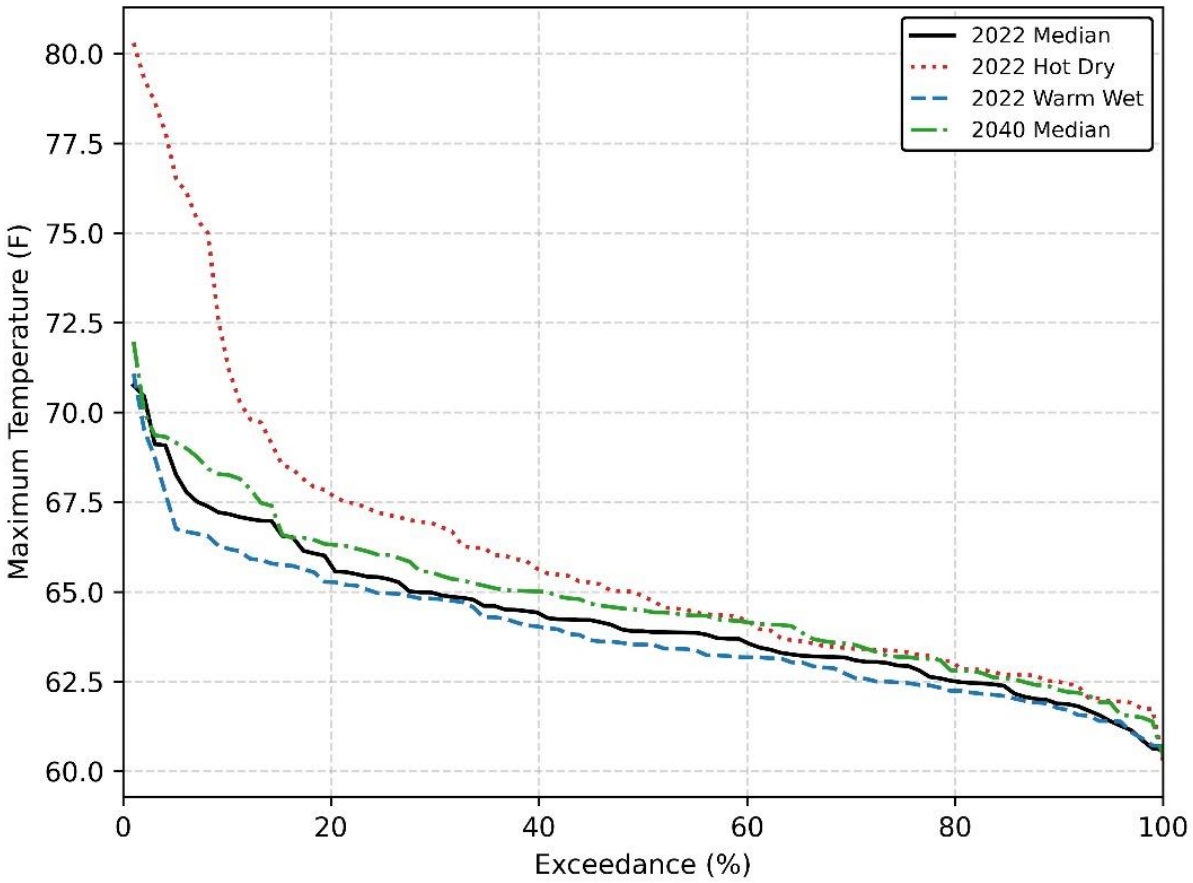

Figure F.2-7-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 3 under various climate assumptions for water years 1923 through 2020

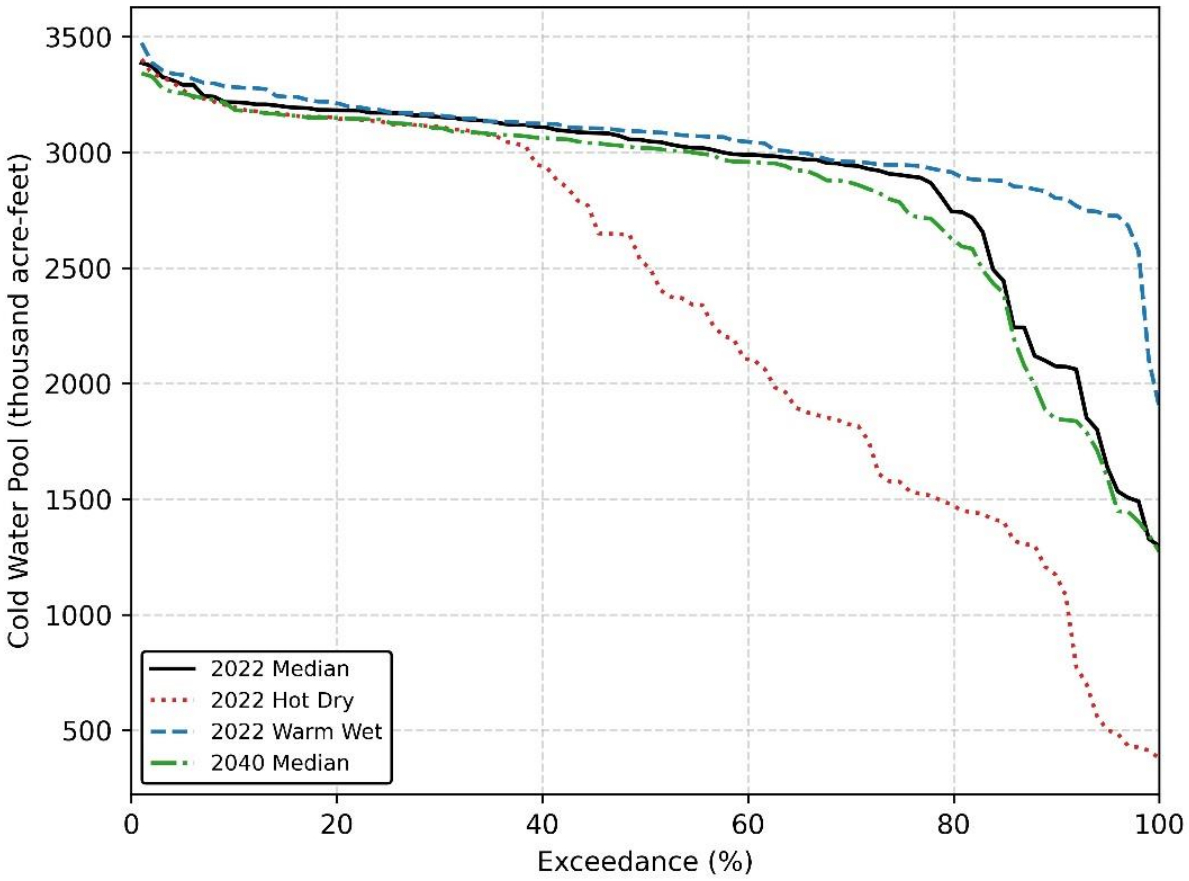

Figure F.2-7-27. Volume of water at the end of April less than 52°F in Shasta Lake for Alternative 3 under various climate assumptions for water years 1923 through 2021

American

Figure F.2-7-28 through Figure F.2-7-30 evaluate the temperature outcomes in the American River under the climate sensitivities using the Alternative 3 logic. The 2022 Hot Dry scenario has the highest average and maximum temperatures at low exceedances. At high exceedances, both the 2022 Hot Dry and 2040 Median scenarios perform similarly and have the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. Figure F.2-7-30 shows the volume of water less than 52 °F at the end of April in Folsom Lake. The 2022 Hot Dry scenario has the lowest volumes of cold-water and the 2022 Warm Wet scenario has the highest volumes of cold-water. Despite the 2022 Median and 2040 Median having similar volumes of cold-water, the 2040 scenario exhibits higher average and maximum temperatures likely due in part to the greater in-stream and reservoir warming.

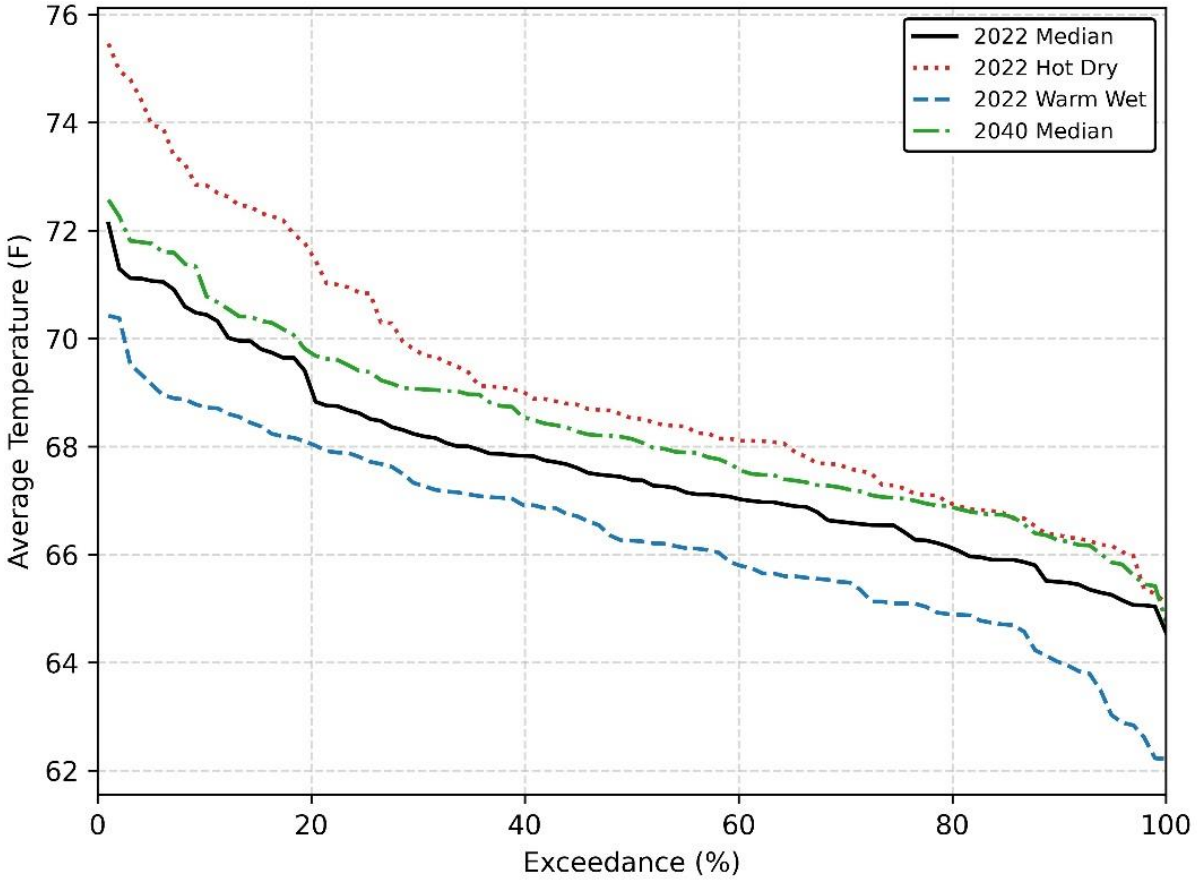

Figure F.2-7-28. Average May through end of October temperatures on the American River at Watt Avenue for Alternative 3 under various climate assumptions for water years 1923 through 2020

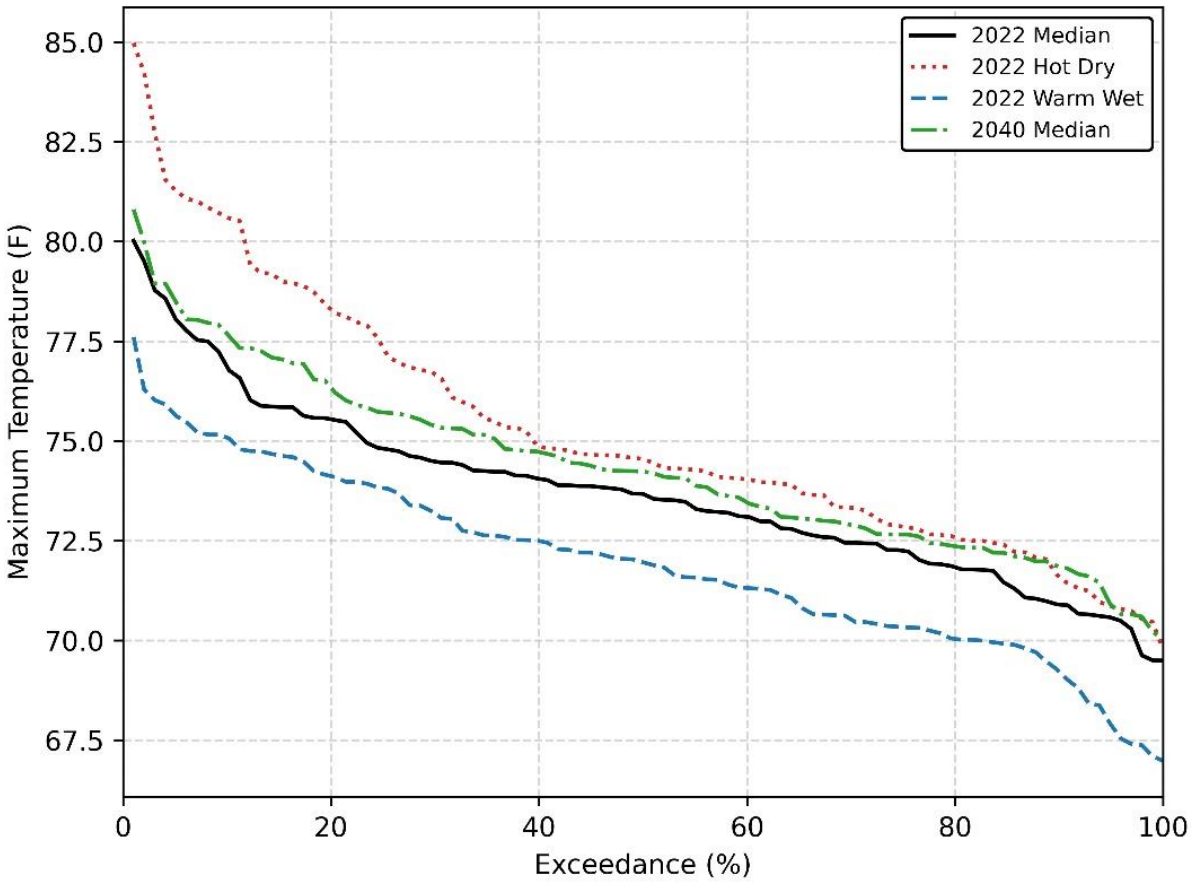

Figure F.2-7-29. Maximum May through end of October temperatures on the American River at Watt Avenue for Alternative 3 under various climate assumptions for water years 1923 through 2020

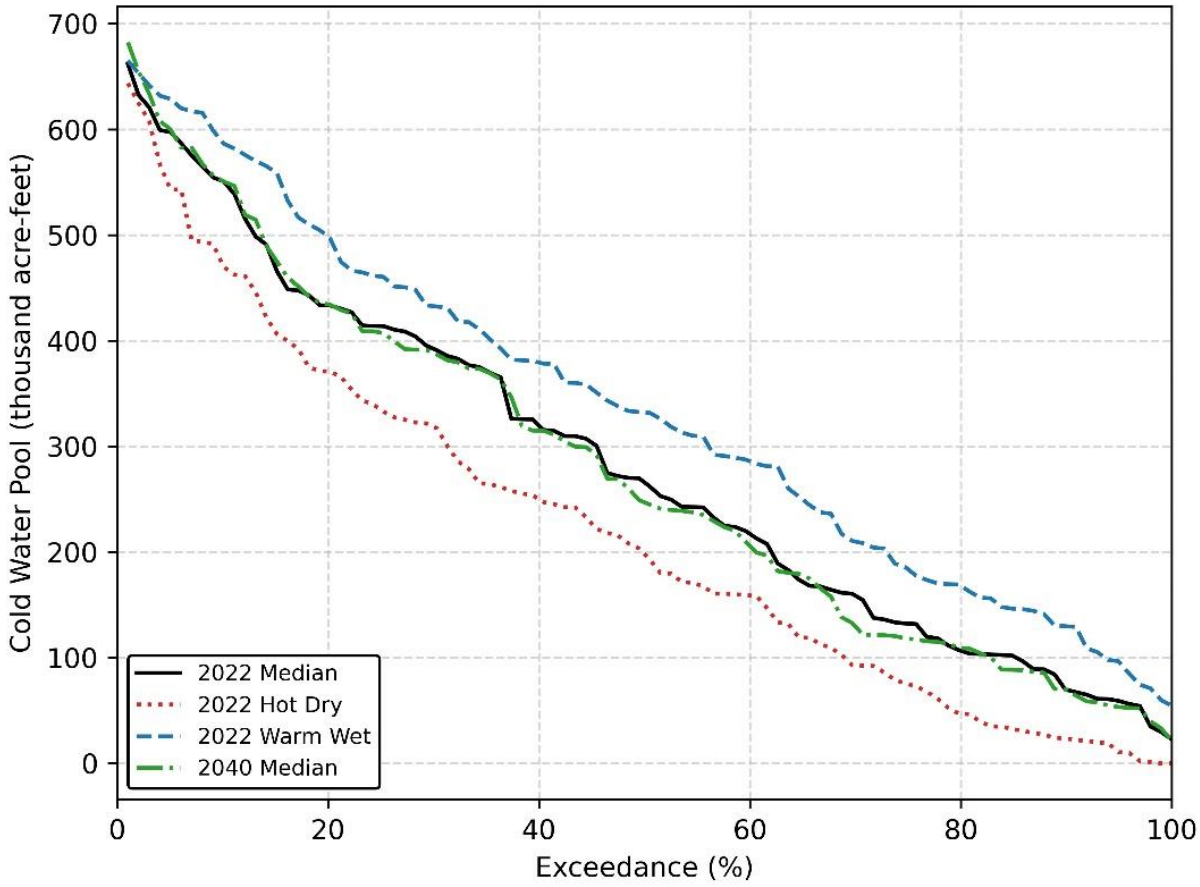

Figure F.2-7-30. Volume of water at the end of April less than 52 °F in Folsom Lake for Alternative 3 under various climate assumptions for water years 1923 through 2021

F.2-7.2.2.2 Stanislaus

Figure F.2-7-31 and Figure F.2-7-32 evaluate the temperature outcomes in the Stanislaus River under the climate sensitivities using the Alternative 3 logic. The 2022 Hot Dry scenario has the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures. The 2040 Median temperatures are slightly higher than the 2022 Median due to instream warming.

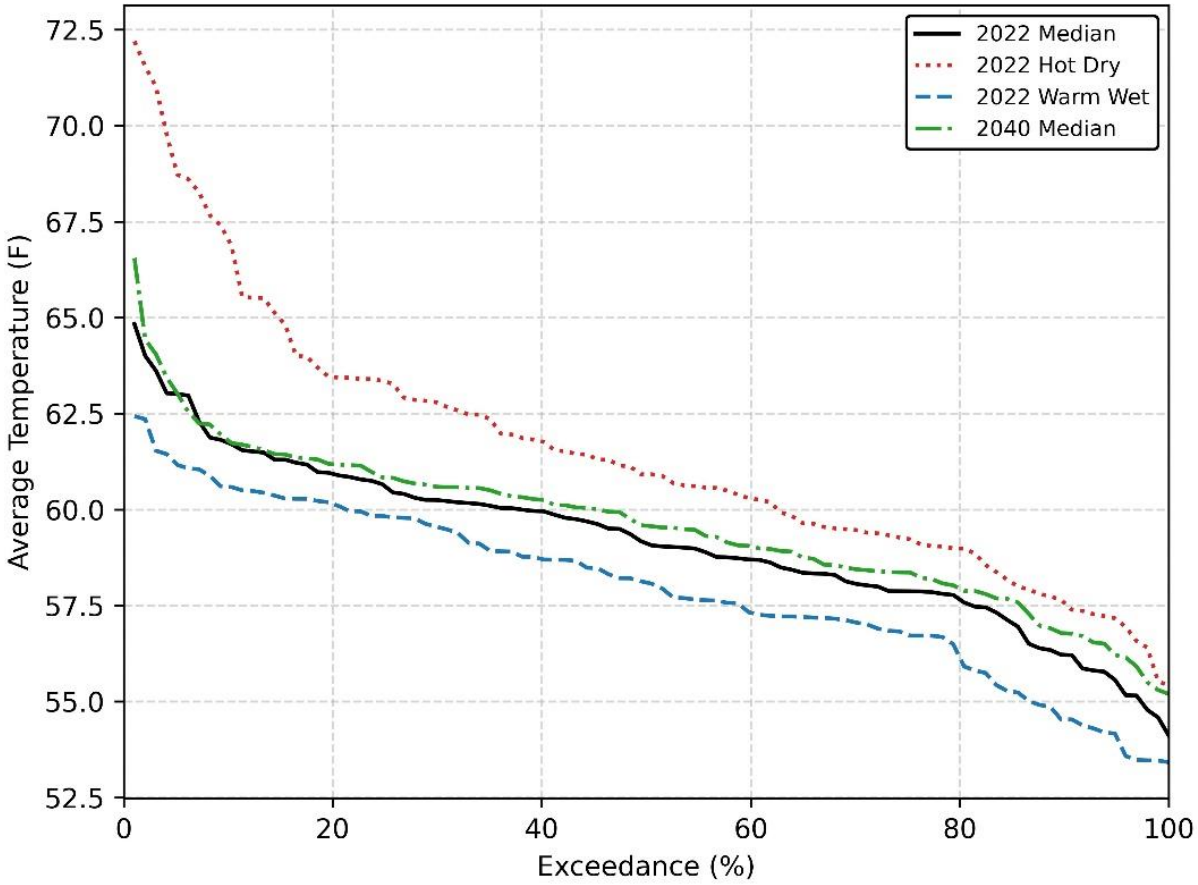

Figure F.2-7-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 3 under various climate assumptions for water years 1923 through 2019

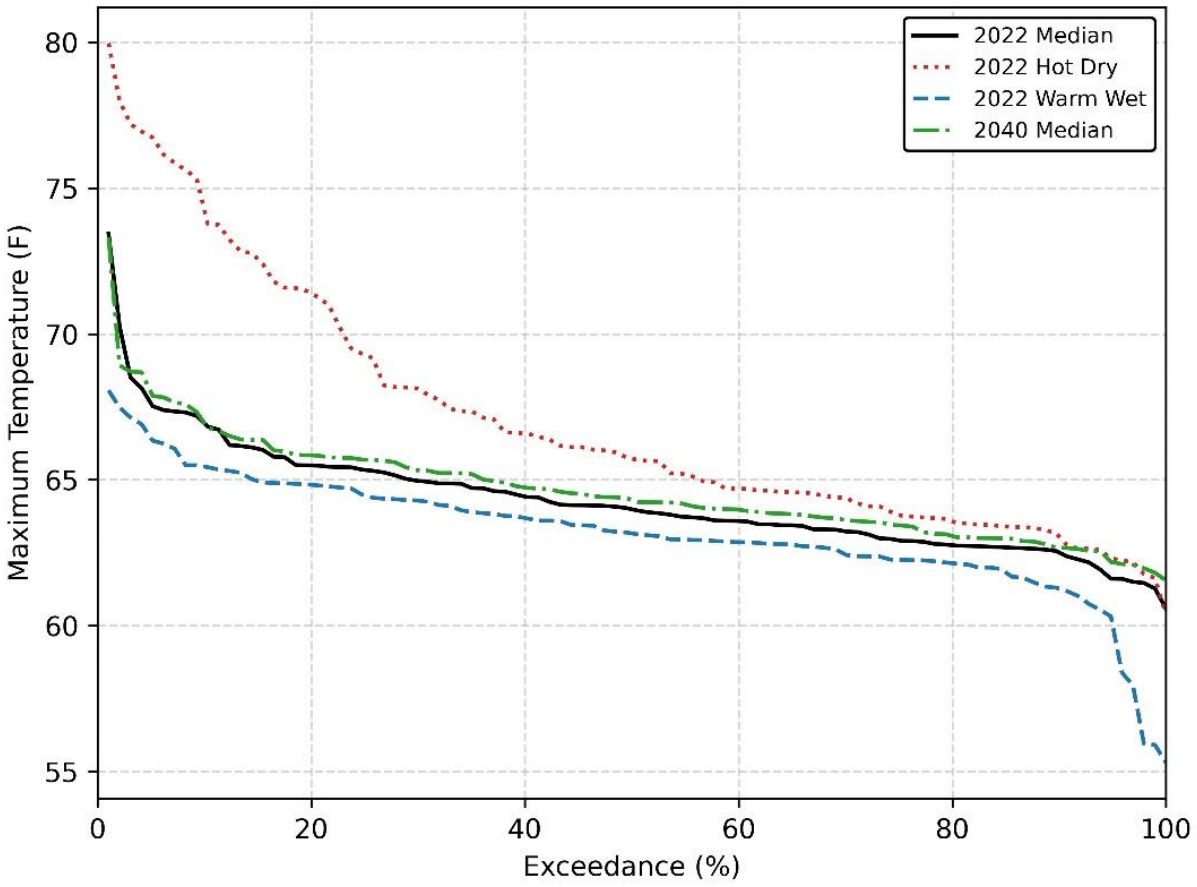

Figure F.2-7-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 3 under various climate assumptions for water years 1923 through 2019

Appendix F, Modeling

Section F.2-8 Climate Sensitivity Analysis, Alternative 4

F.2-8.1 Introduction

This document summarizes key findings from a sensitivity analysis of climate change scenarios to Alternative 4 under 2022 Median, 2022 Hot Dry, 2022 Warm Wet, and 2040 Median climates. Operations results from these simulations were analyzed to understand how these changes to climate affect operations as compared to 2022 Median climate. The CalSim 3 model was used for quantifying the changes in storage and flows at various compliance locations noted below. The HEC5Q and Anderson/Martin Mortality models were used quantifying changes in river water temperature and temperature-dependent mortality (TDM). The following sections summarize key CalSim 3 and HEC5Q output parameters for these scenarios.

Methodology and resulting changes to CalSim 3 hydrology inputs are detailed in 2021 LTO Climate Sensitivity Analysis – Future Climate Data Development and Methodology for CalSim 3.

F.2-8.2 Climate Change Comparison

F.2-8.2.1 CalSim 3

Figure F.2-8-1 through Figure F.2-8-13 show CalSim 3 simulation results for Alternative 4. The changes analyzed in this document are relevant to assessing the potential range of future climate conditions. It should be noted that the range of climate conditions explored in this sensitivity analysis cover an extreme range of hydrology. Although it's possible that regulations would change under more extreme conditions, assumed changes would be pre-decisional. Therefore, no changes to operational rules were incorporated into these sensitivities. Simulation results for Alternative 4 were assessed at the following locations:

- Shasta Storage (end of April and end of September)
- Sacramento River below Keswick
- Sacramento River at Bend Bridge
- Sacramento River near Wilkins Slough
- Sacramento River at Verona
- Sacramento River at Freeport
- Flow though Yolo Bypass

- Clear Creek below Whiskeytown
- Spring Creek inflow to Keswick Reservoir
- Folsom Storage (end of April and end of September)
- American River below Nimbus Dam
- Stanislaus River below Goodwin Dam
- San Joaquin River at Gravelly Ford
- San Joaquin River below Sack Dam
- San Joaquin River at Merced Confluence
- San Joaquin River at Vernalis
- Mokelumne River
- Old and Middle River Combined
- Delta Outflow

Relative to 2022 Median climate conditions, end of April (Figure F.2-8-1) and end of September (Figure F.2-8-2) Shasta storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. 2022 Hot and Dry conditions are severe from a water supply perspective. End of September Shasta storage is at deadpool in about 10% of years. Under this scenario, it's likely that an adjustment to operations would be considered to prevent the frequency of deadpool conditions. For Sacramento River watershed flows, long-term monthly averages under 2022 Warm and Wet climate are consistently higher and 2022 Hot and Dry climate are consistently lower in the fall, winter and spring months. In summer months, or the main months of reservoir management season, the differences are less notable. Summer months are commonly when river flows are due primarily to releases from storage instead of runoff events. Flows under 2040 Median climate are similar to flows under 2022 Median climate.

Clear Creek below Whiskeytown (Figure F.2-8-9) flow changes are similar to the changes observed in the Sacramento River watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows in fall and winter months. For Spring Creek inflow to Keswick Reservoir (Figure F.2-8-10), similar changes in long-term average flows are observed, except for June. Higher Spring Creek inflows are observed in June of 2022 Hot and Dry and lower inflows are observed in 2022 Warm and Wet. These differences in Spring Creek Inflow reflect an earlier uptick in demand under 2022 Hot and Dry and decreased demand under 2022 Warm and Wet.

Relative to 2022 Median climate conditions, end of April (Figure F.2-8-11) and end of September (Figure F.2-8-12) Folsom storage is higher under 2022 Warm and Wet and lower under 2022 Hot and Dry, and 2040 Median climates. For long-term monthly average American River flows below Nimbus Dam (Figure F.2-8-13), changes to flow are similar to the changes in the Sacramento watershed. In all months, 2022 Warm and Wet flows are higher, 2022 Hot and

Dry flows are lower, and 2040 Median flows are similar as compared to 2022 Median flows. Relative to 2022 Median conditions, 2040 Median flow is lower in May and June due to lower Folsom inflows in spring months. More of the snowmelt, which would runoff in spring, is either evaporated or runs off and is spilled from Folsom earlier in the water year. As compared to 2022 Median conditions, American River flow below Nimbus Dam is slightly higher in January of 2040 Median conditions due to spills in wetter years.

For long-term monthly average Stanislaus River flows below Goodwin (Figure F.2-8-14), changes are similar to the changes in the Sacramento watershed. Flows across all climate conditions are mostly in June and July, months when releases consist of stored water. Otherwise, 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows.

For long-term monthly average San Joaquin River flows, changes to flow are similar to the changes in the Sacramento watershed. San Joaquin River at Gravelly Ford (Figure F.2-8-15) flows, due to snowmelt, increase in the Spring months and peak in April. As expected, the high flow period under the 2022 Warm and Wet conditions extends longer than the other climate conditions. Conditions in the San Joaquin River below Sack Dam (Figure F.2-8-16) are similar those at Gravelly Ford. The increase and decrease in San Joaquin River flows under 2022 Warm and Wet and 2022 Hot and Dry, respectively, are even more notable below the confluence with the Merced (Figure F.2-8-17).

For long-term monthly average flows in the Delta (Figure F.2-8-18 through Figure F.2-8-21), changes are generally similar to the changes in the Sacramento watershed. 2022 Warm and Wet flows are higher, 2022 Hot and Dry flows are lower, and 2040 Median flows are similar to 2022 Median flows. Flows across all climate conditions are most similar from April through November, when flows are largely influenced by releases from storage. The Old and Middle River combined long-term flow averages (Figure F.2-8-20) for the 2022 Warm and Wet climate are notably higher (less negative) in January through March compared to the other climate conditions, mainly due to an increase in San Joaquin River at Vernalis flow in these months.

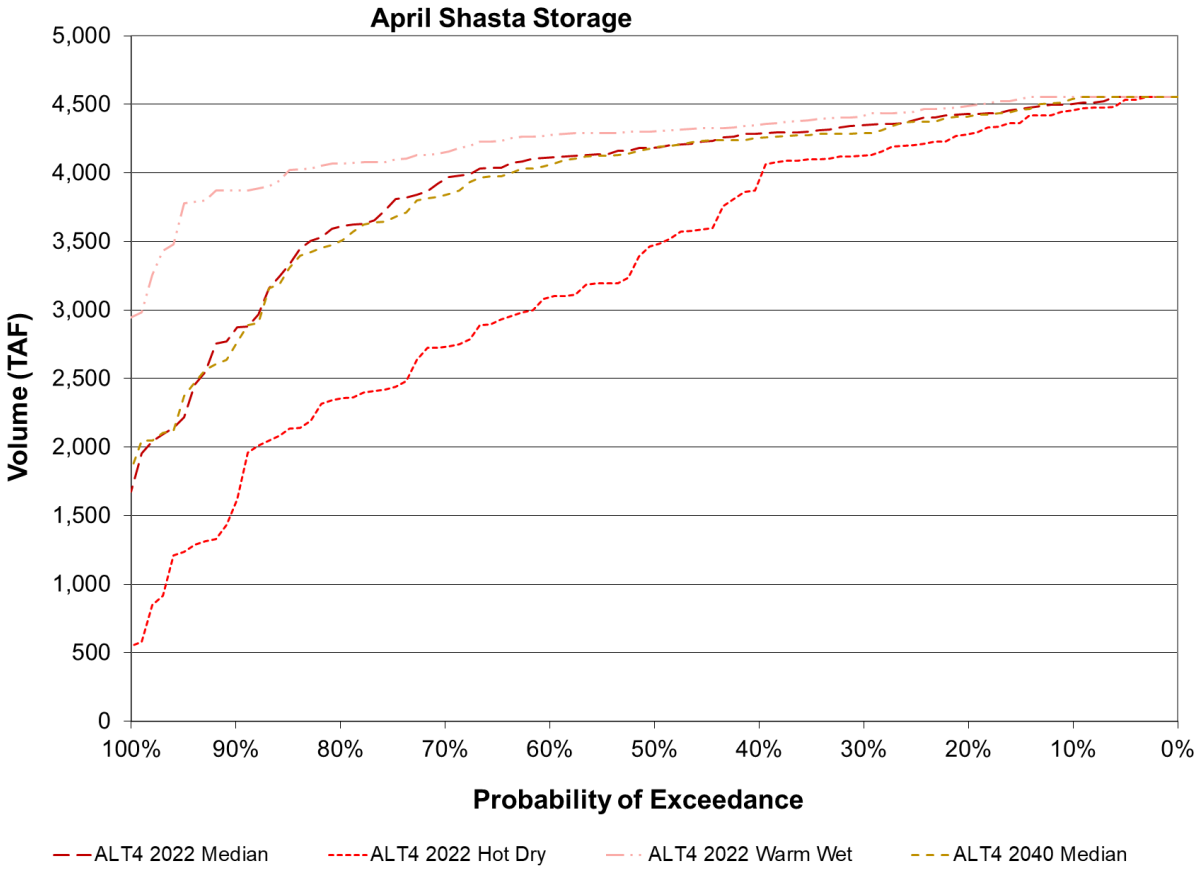

Figure F.2-8-1. End of April Shasta Storage

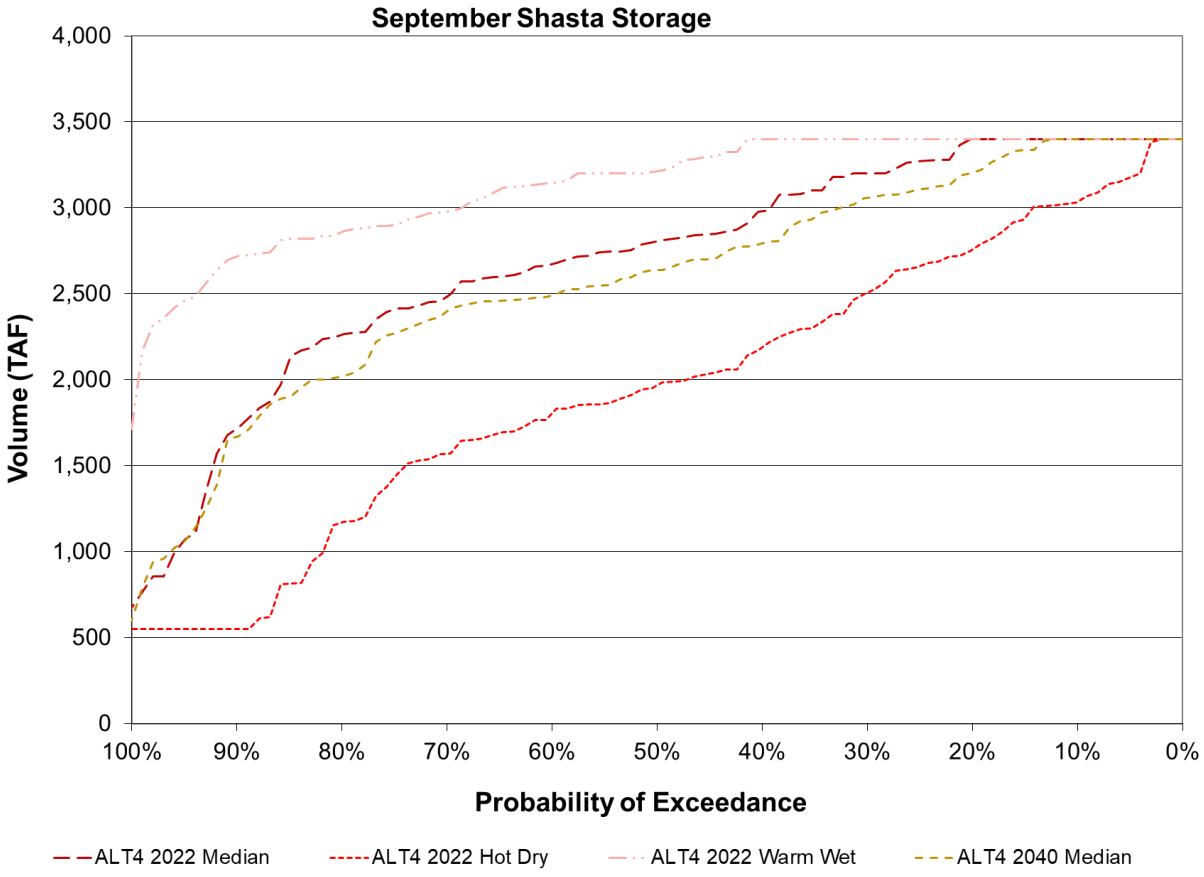

Figure F.2-8-2. End of September Shasta Storage

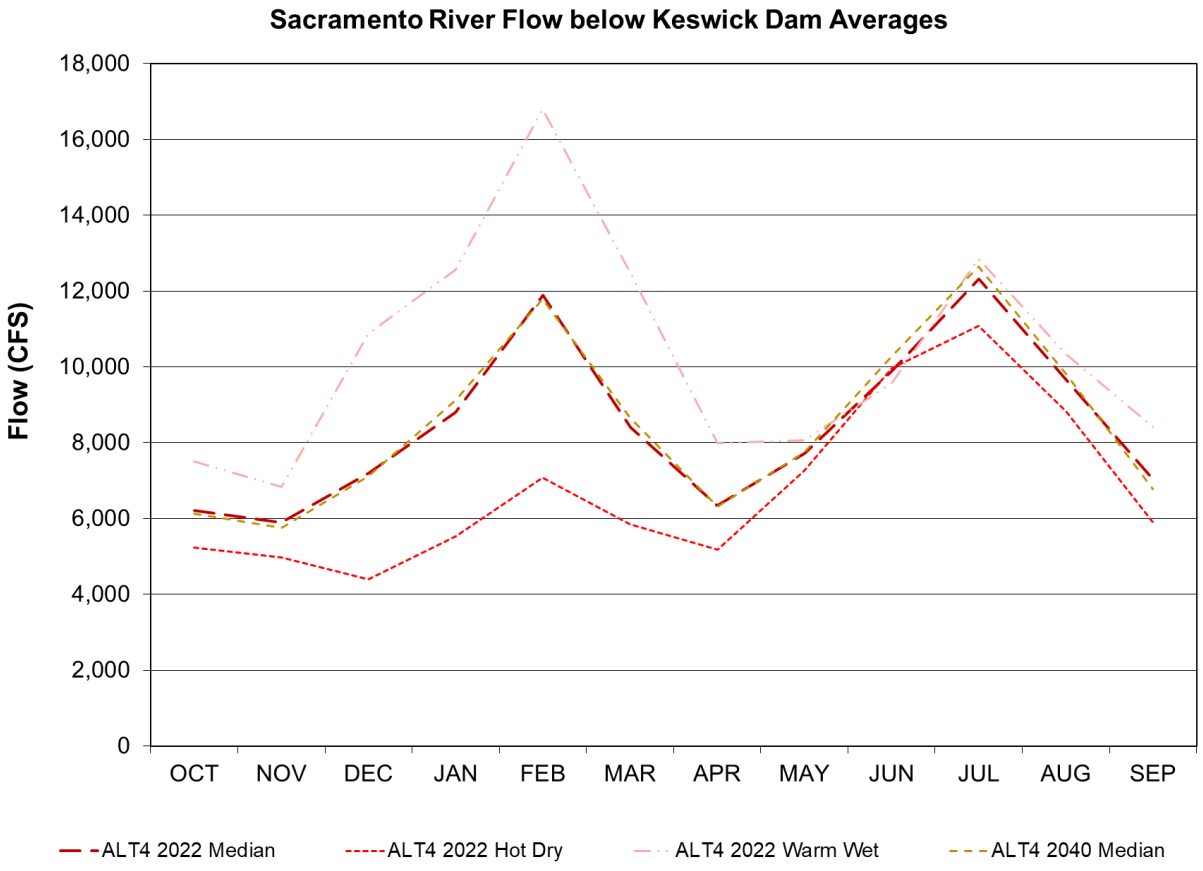

Figure F.2-8-3. Long-term Average Sacramento River flow below Keswick Dam

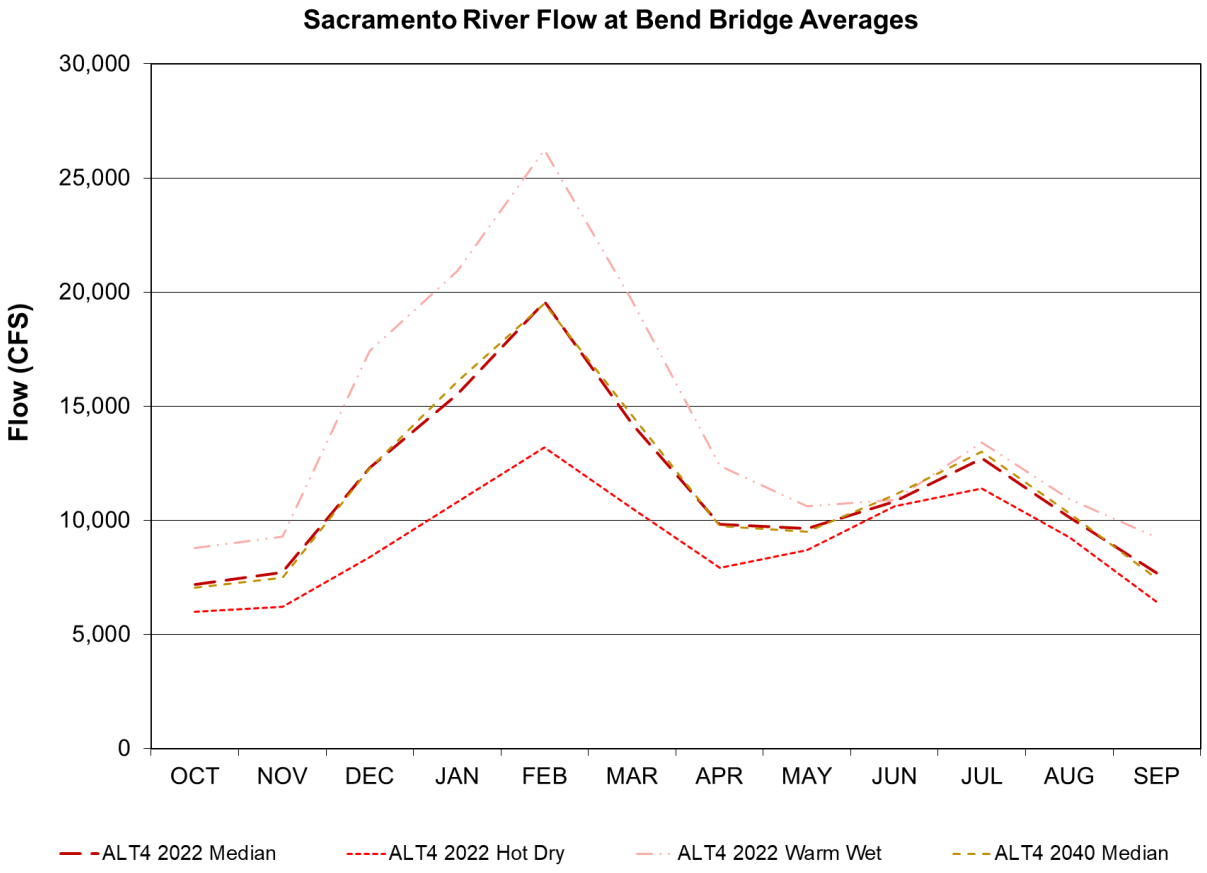

Figure F.2-8-4. Long-term Average Sacramento River flow at Bend Bridge

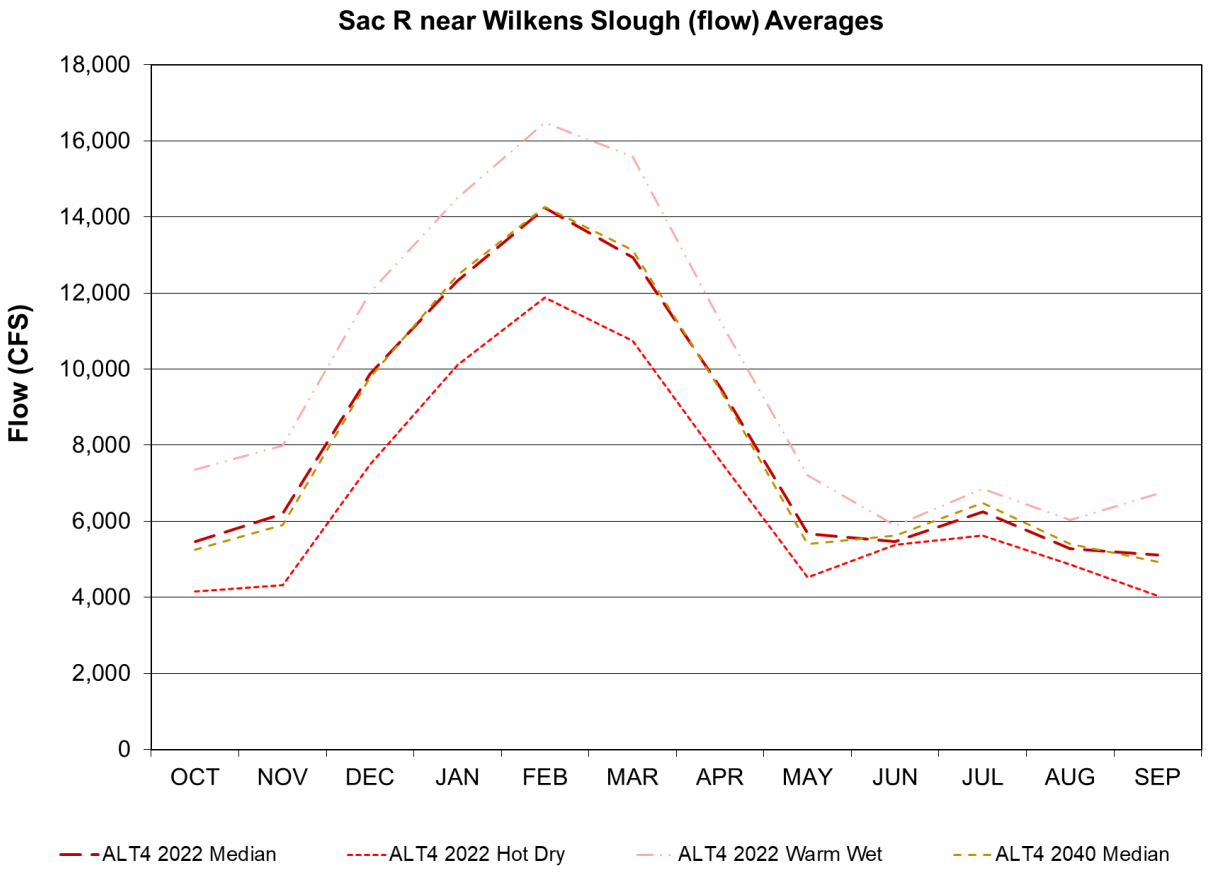

Figure F.2-8-5. Long-term Average Sacramento River flow near Wilkins Slough

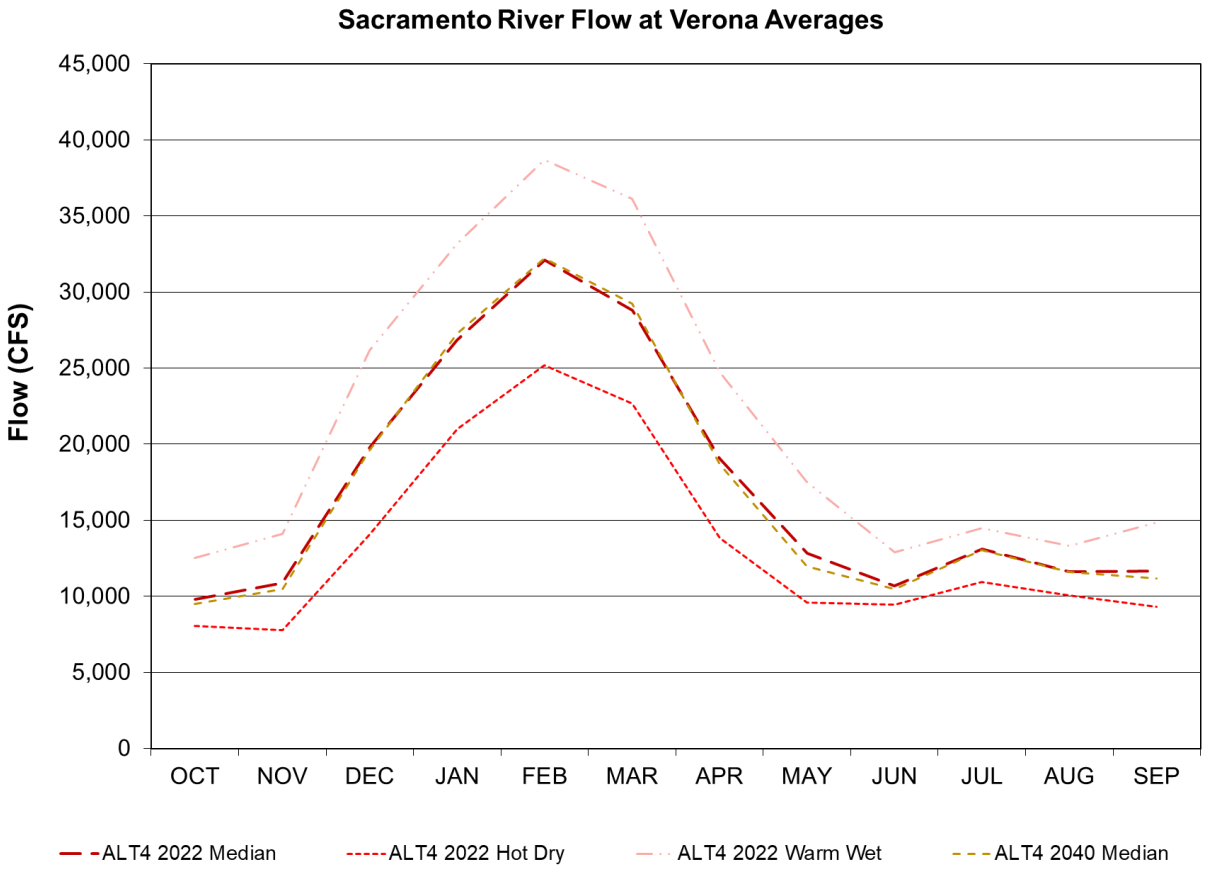

Figure F.2-8-6. Long-term Average Sacramento River flow at Verona

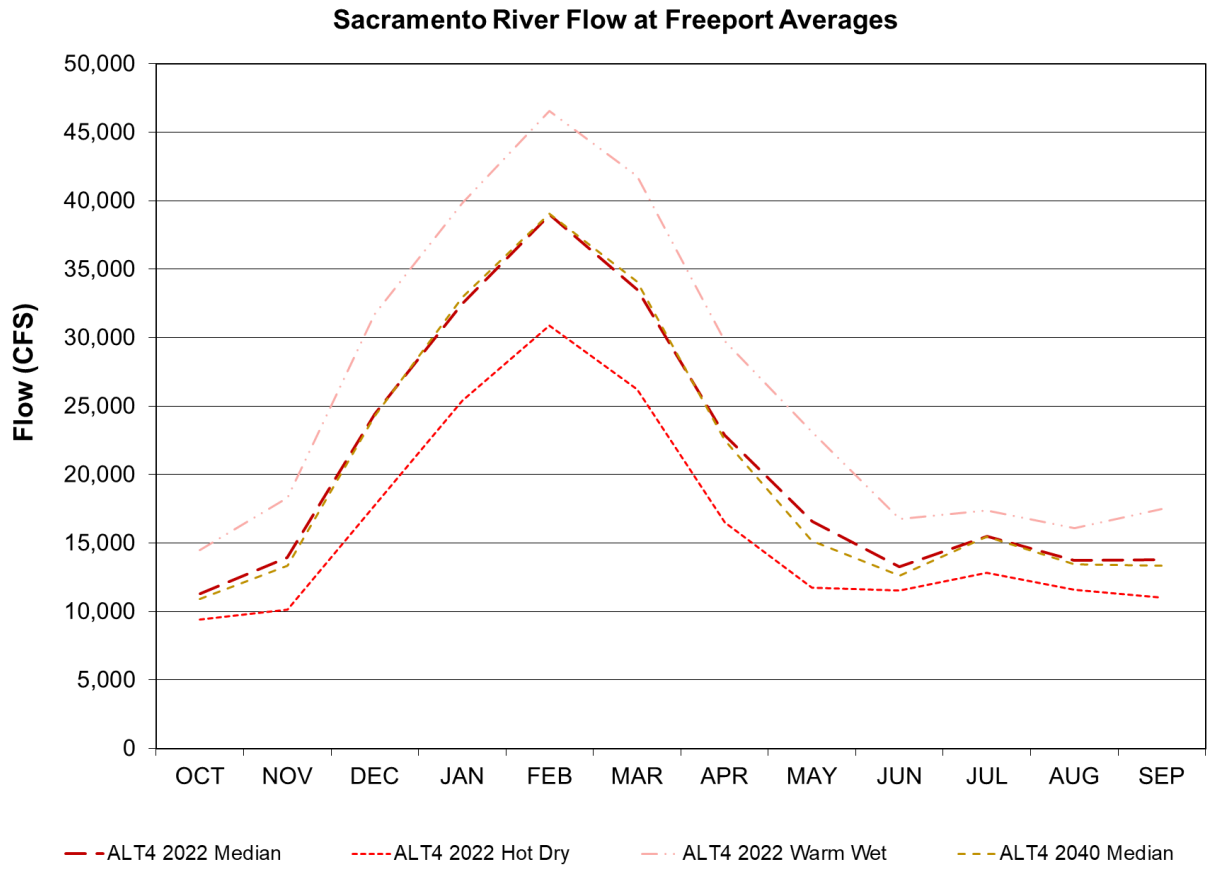

Figure F.2-8-7. Long-term Average Sacramento River flow at Freeport

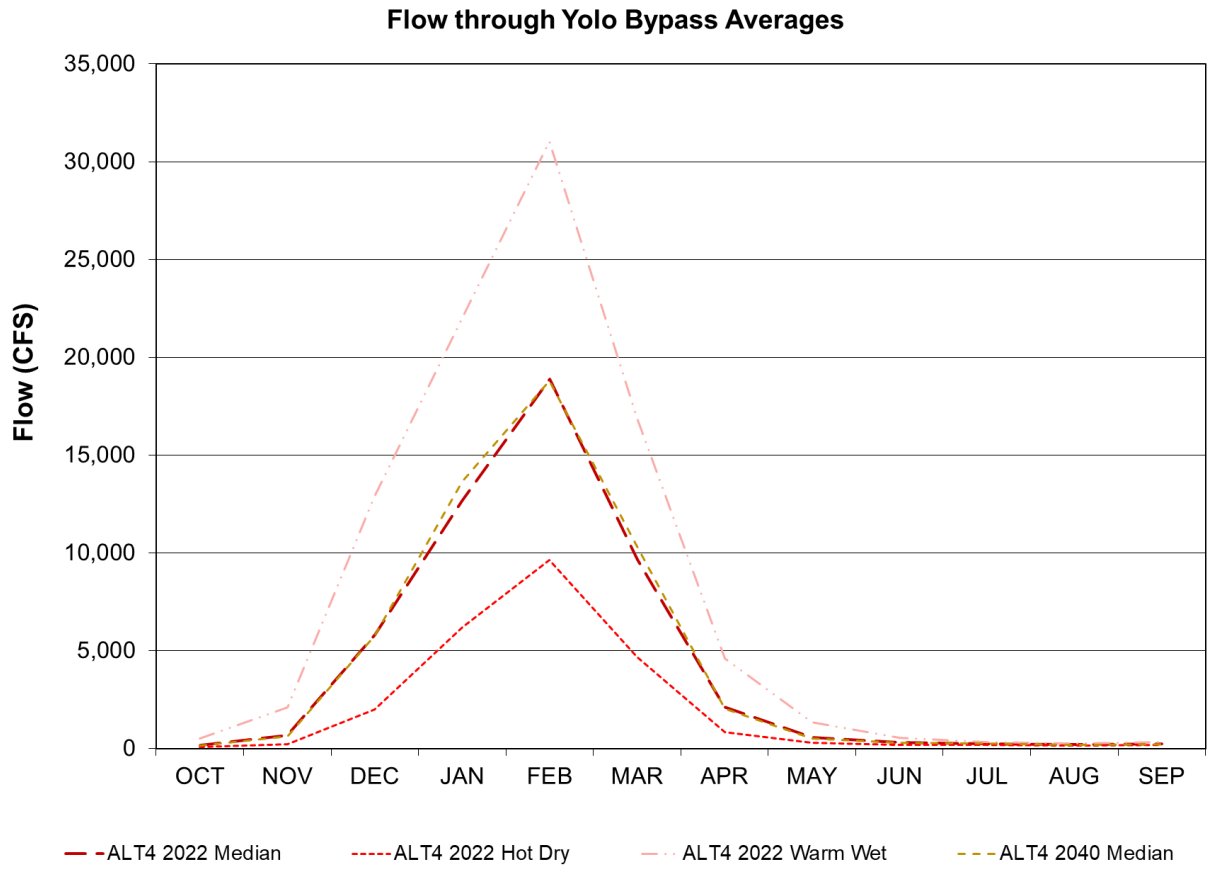

Figure F.2-8-8. Long-term Average Yolo Bypass Flow

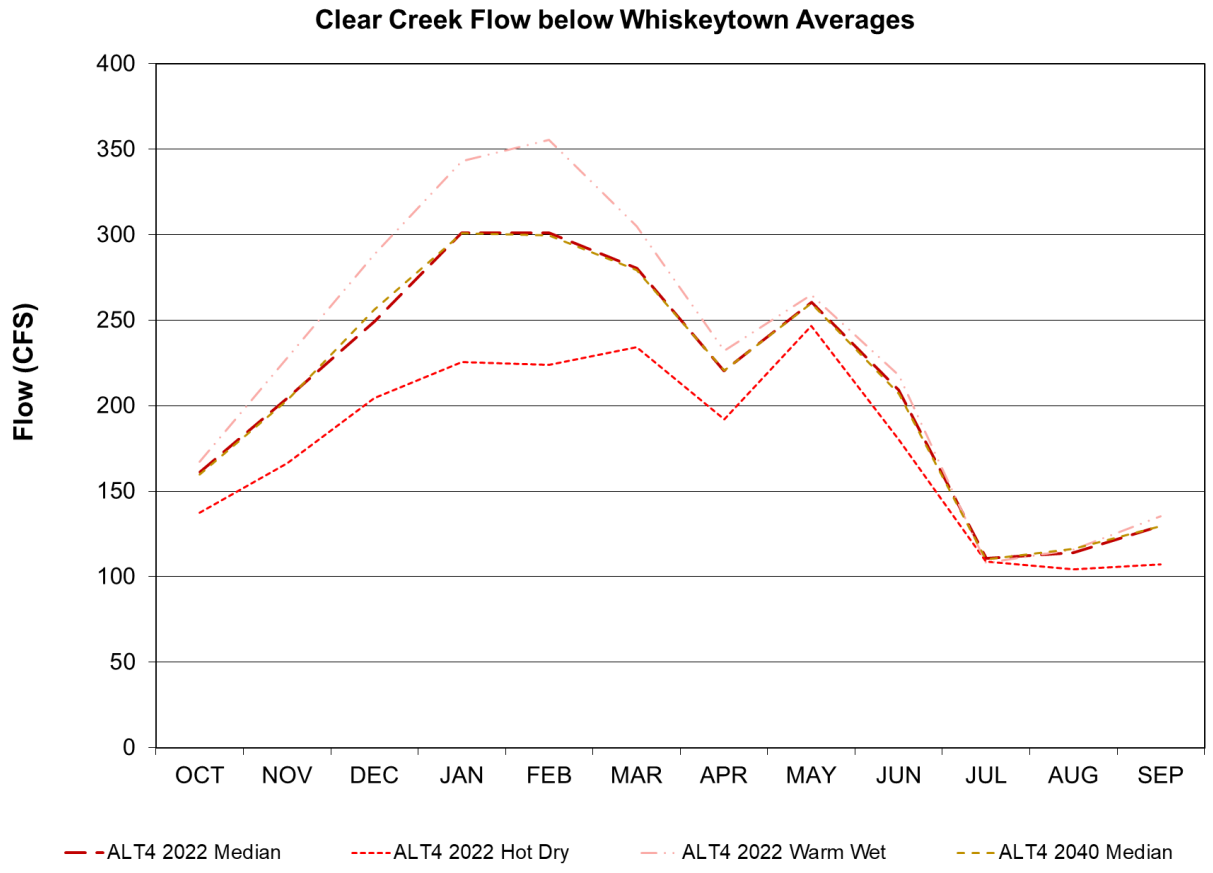

Figure F.2-8-9. Long-term Average Clear Creek flow below Whiskeytown

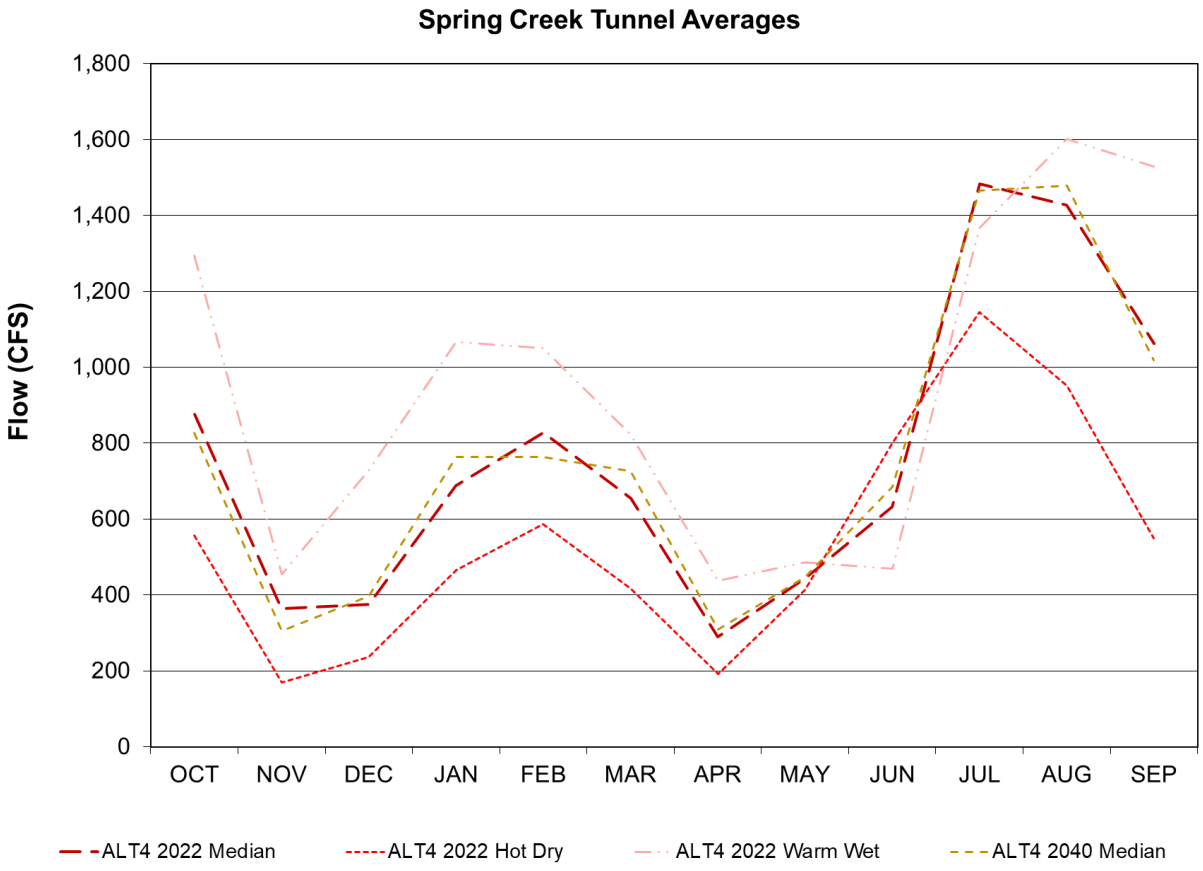

Figure F.2-8-10. Long-term Average Spring Creek Tunnel Flow

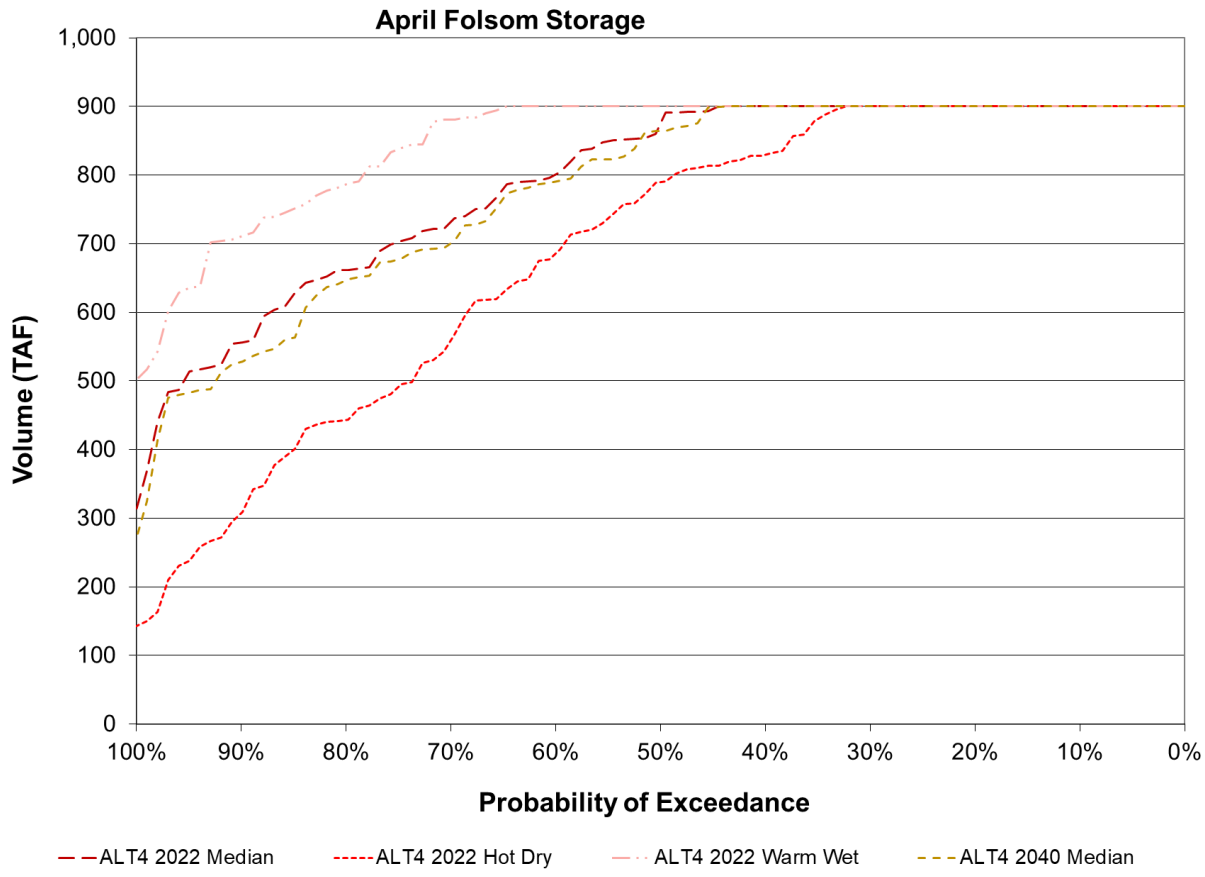

Figure F.2-8-11. End of April Folsom Storage

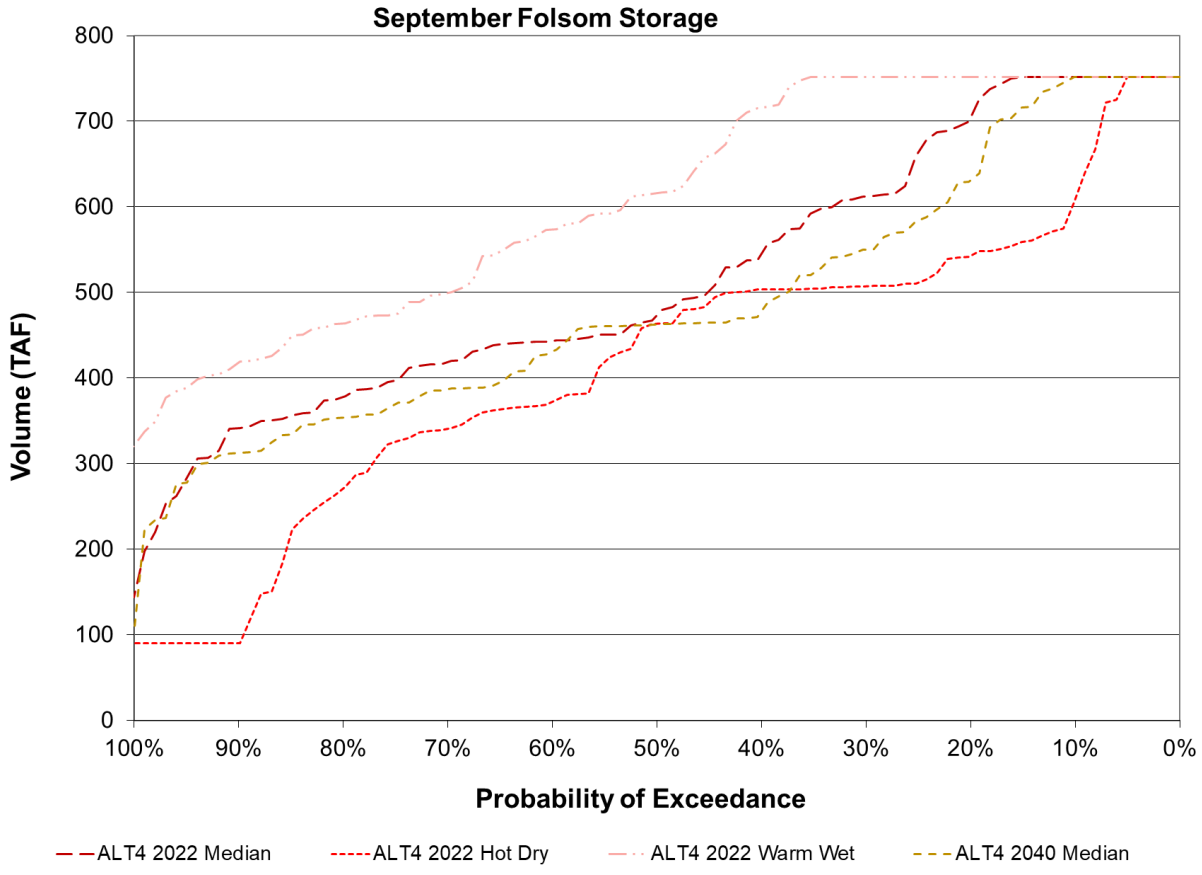

Figure F.2-8-12. End of September Folsom Storage

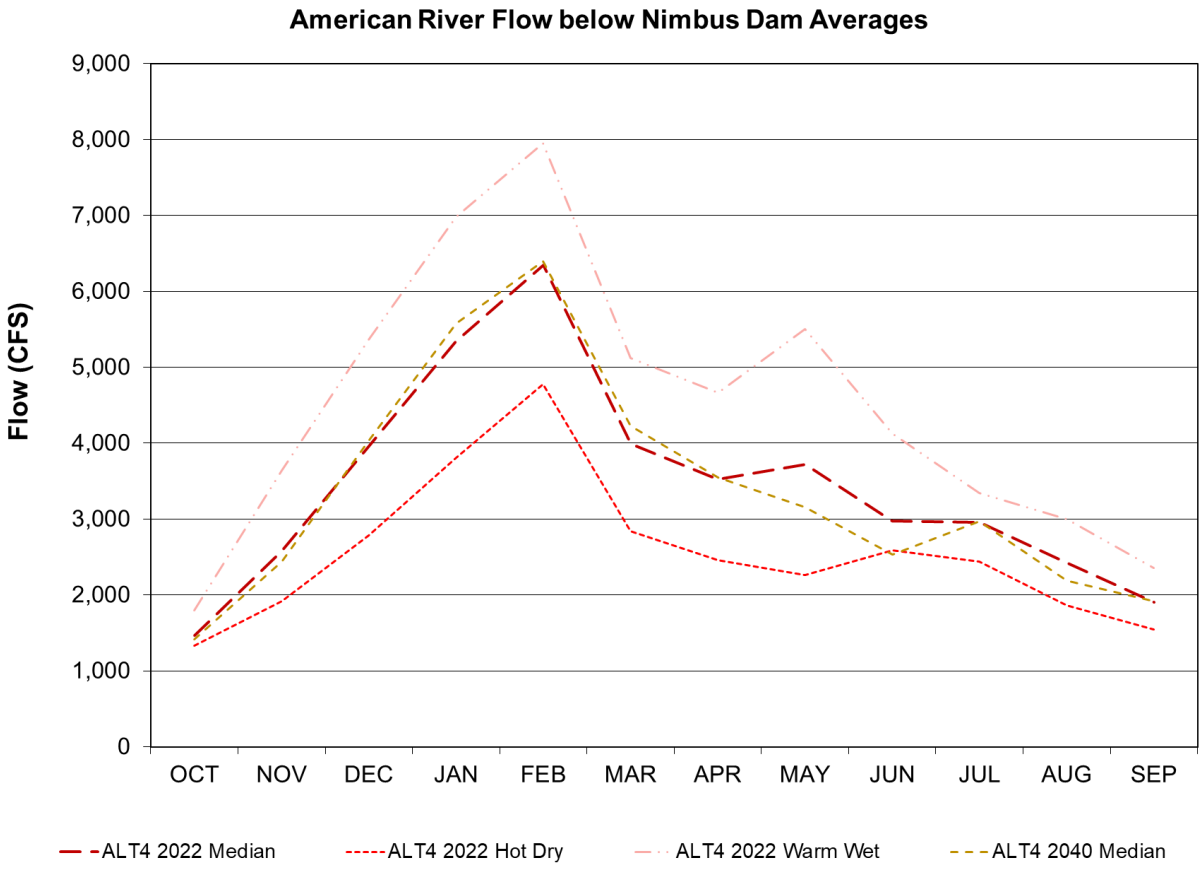

Figure F.2-8-13. Long-term Average American River flow below Nimbus Dam

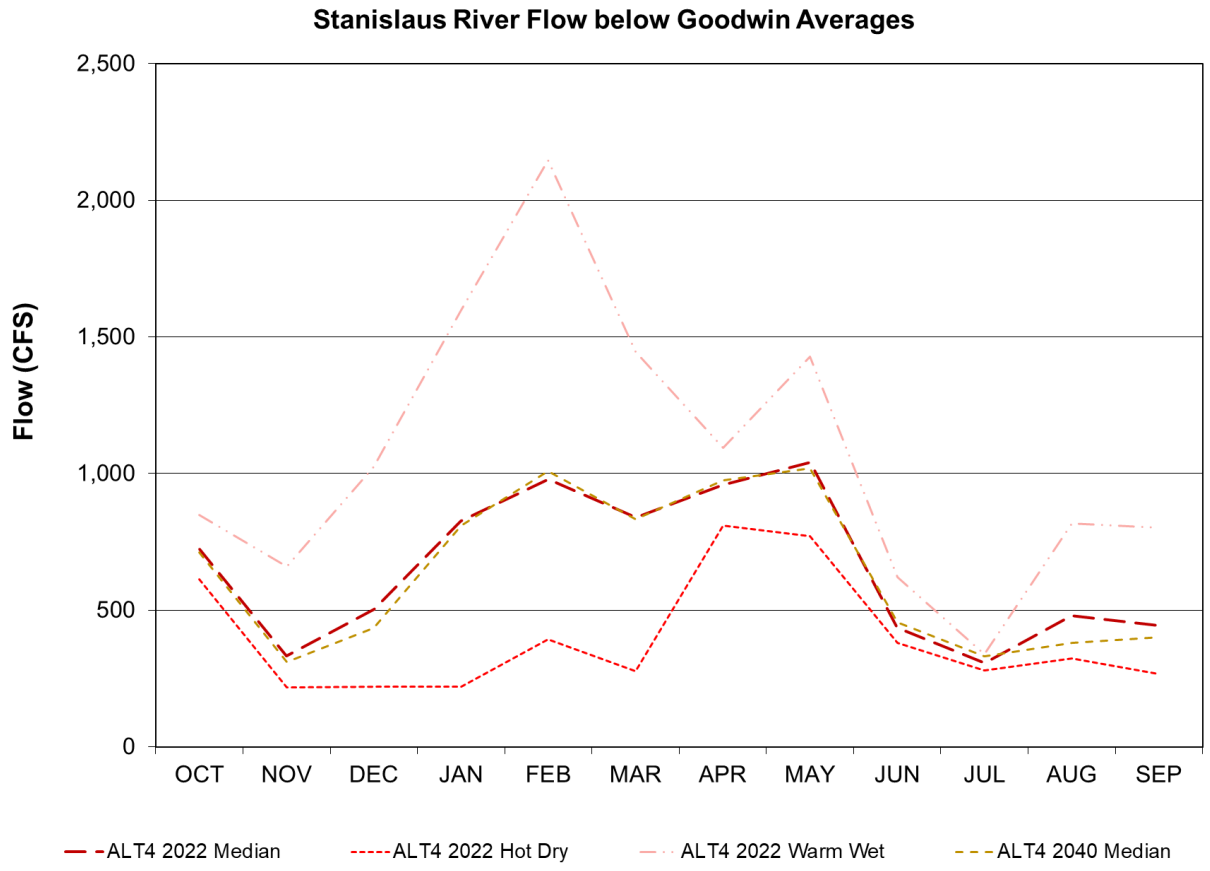

Figure F.2-8-14. Long-term Average Stanislaus River flow below Goodwin

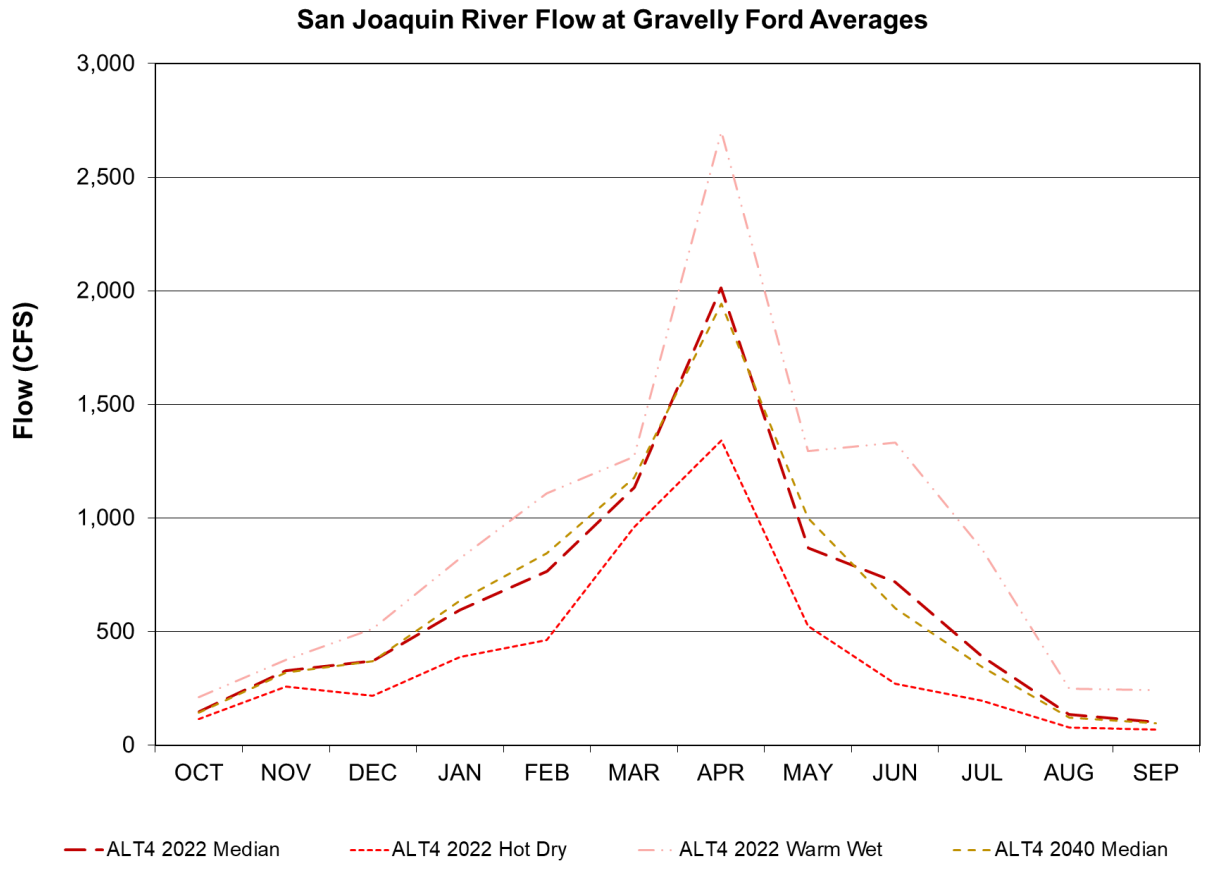

Figure F.2-8-15. Long-term Average San Joaquin River flow at Gravelly Ford

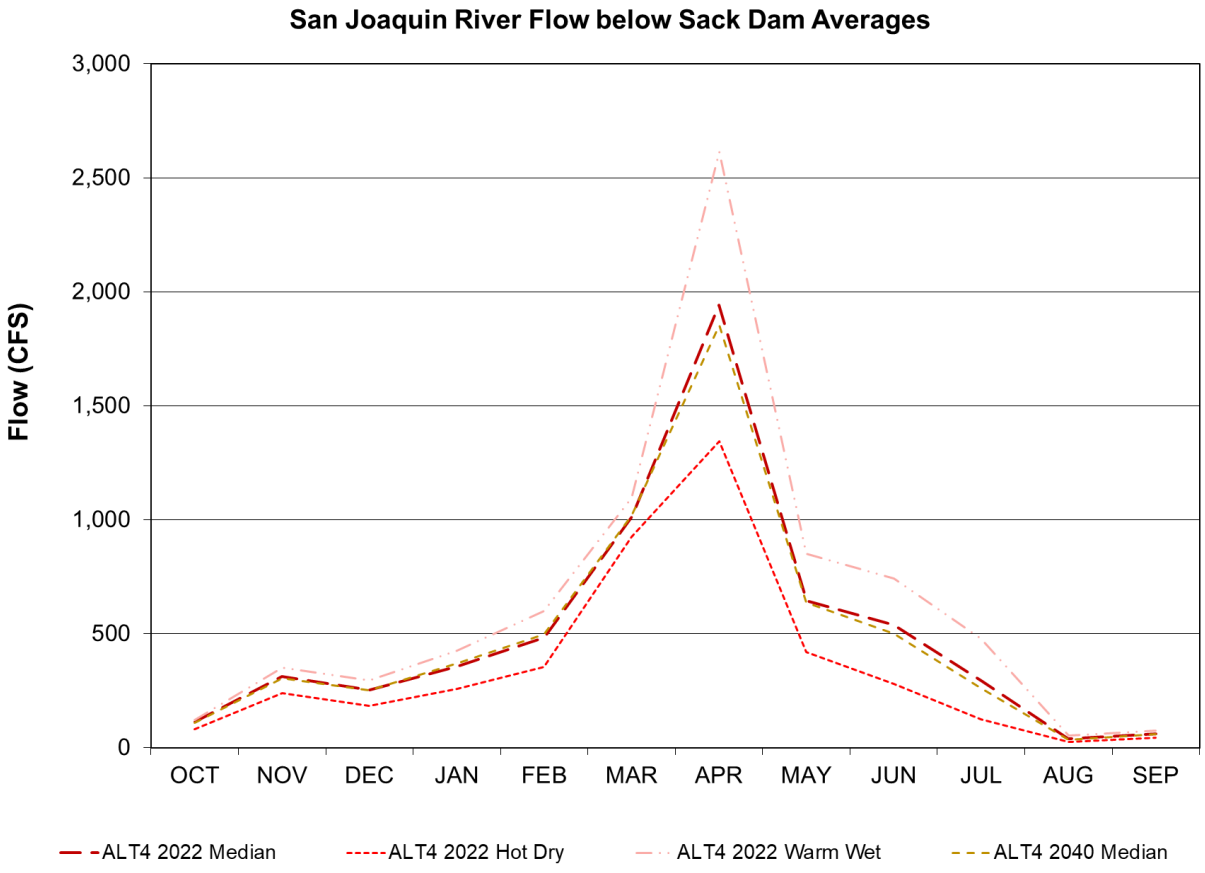

Figure F.2-8-16. Long-term Average San Joaquin River flow below Sack Dam

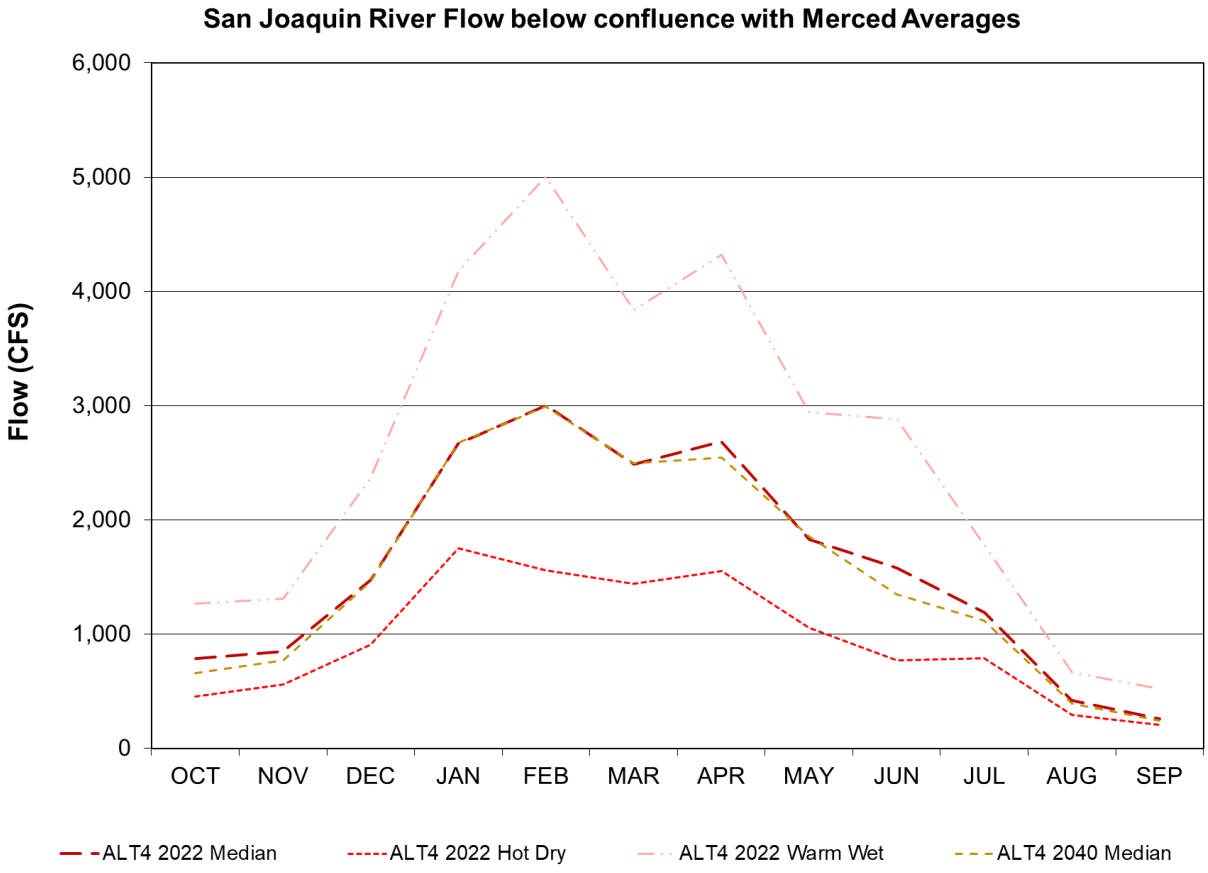

Figure F.2-8-17. Long-term Average San Joaquin River flow below Confluence with Merced River

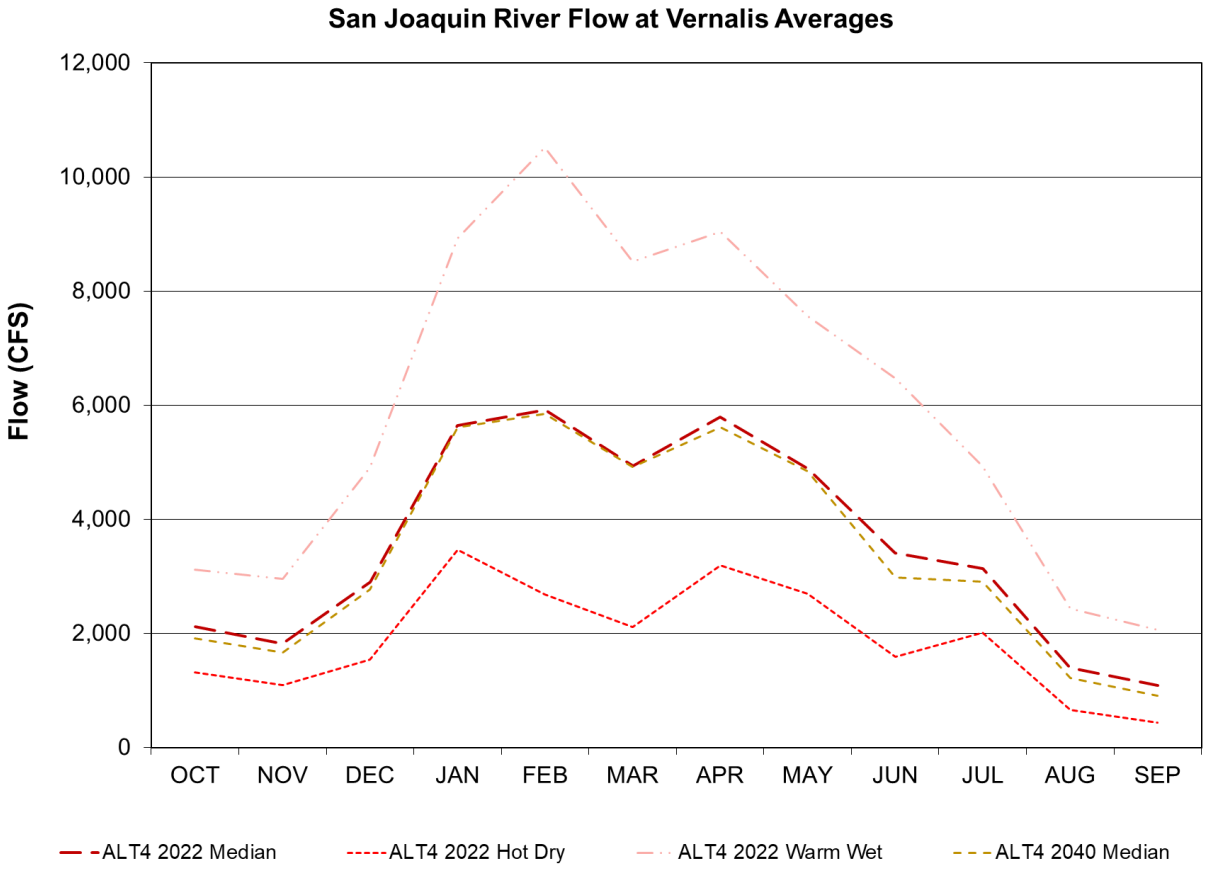

Figure F.2-8-18. Long-term Average San Joaquin River flow at Vernalis

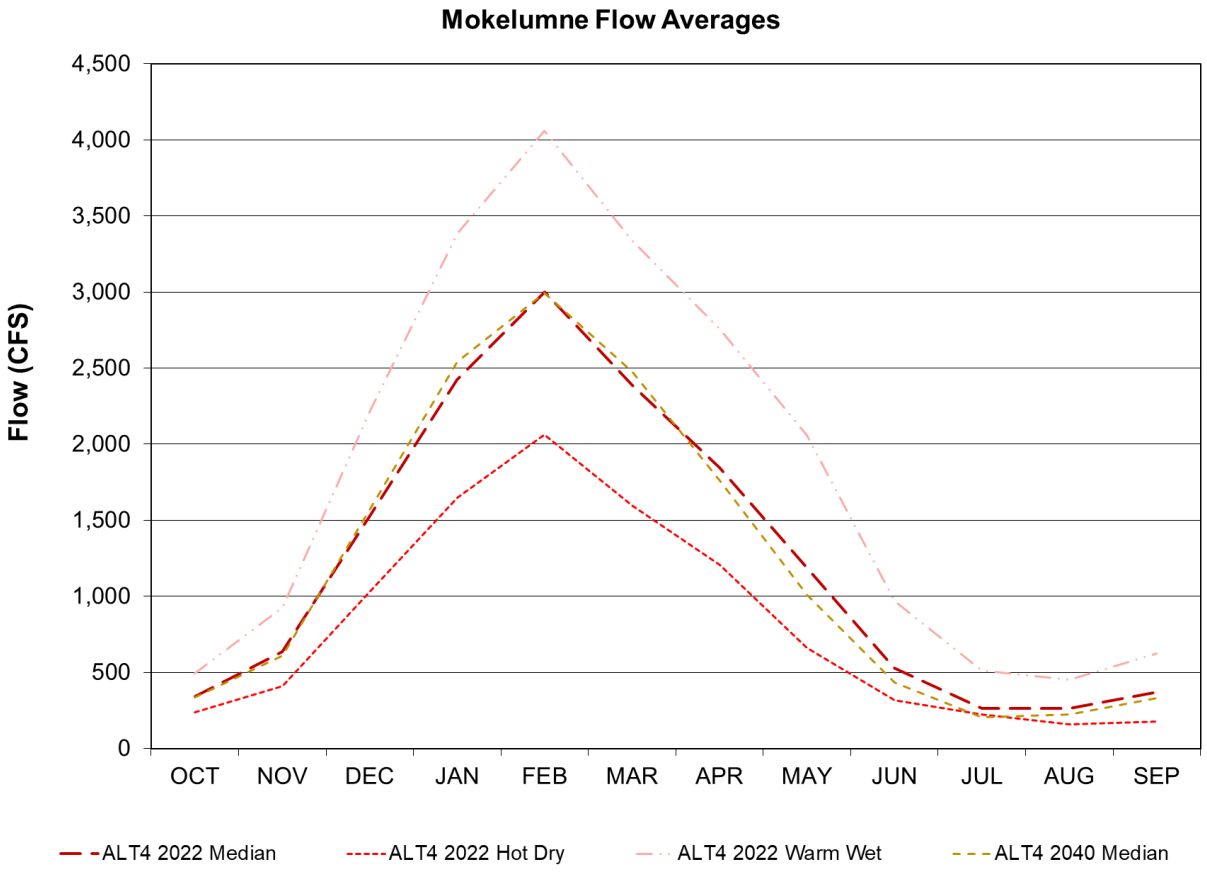

Figure F.2-8-19. Long-term Average Mokelumne River Flow

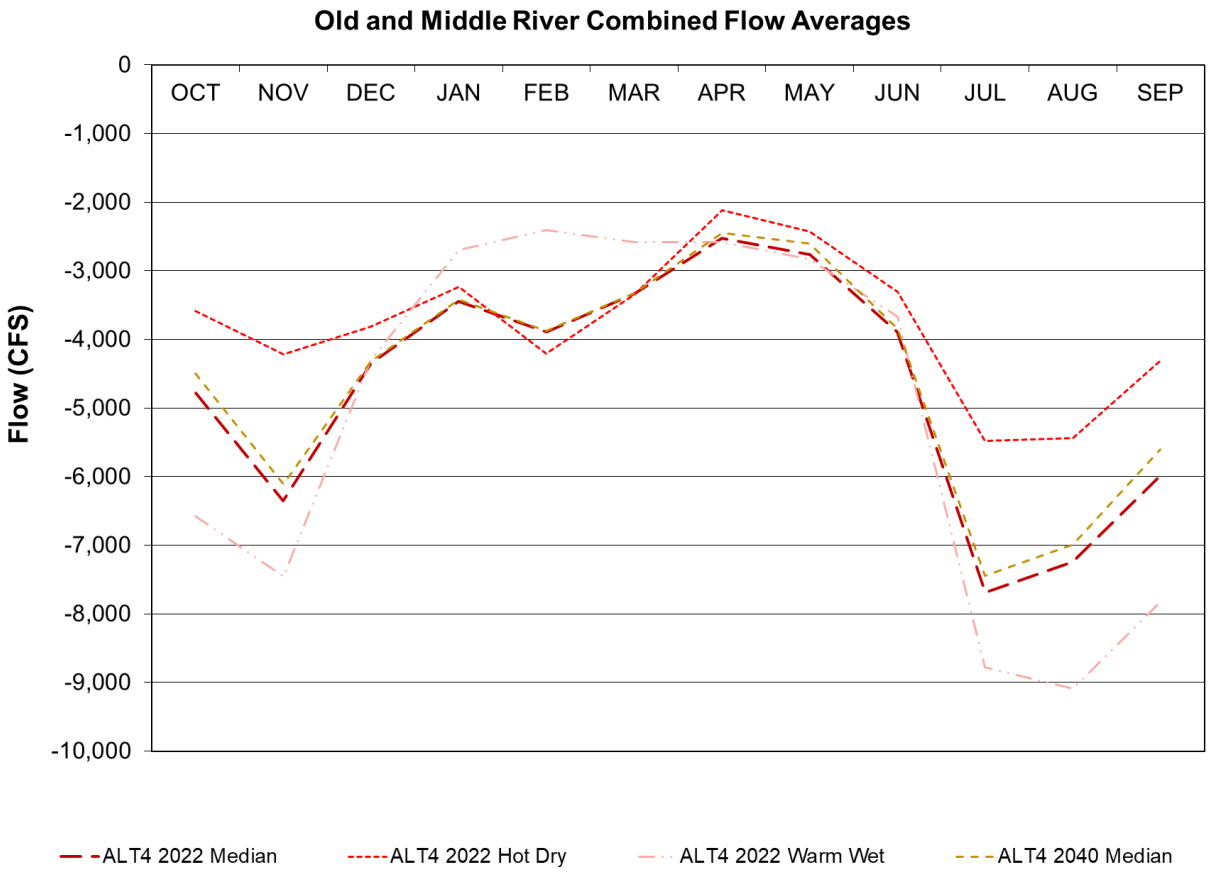

Figure F.2-8-20. Long-term Average Old and Middle River Combined Flow

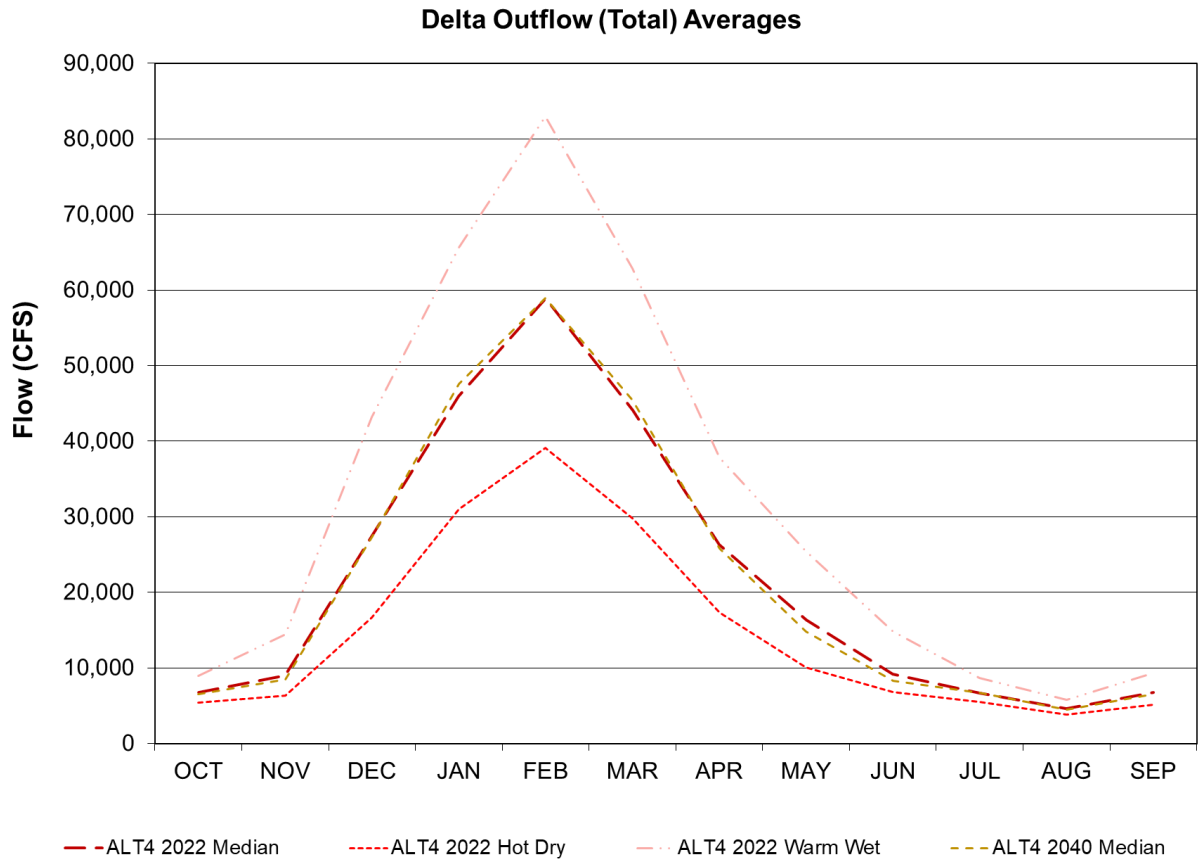

Figure F.2-8-21. Long-term Average Delta Outflow

F.2-8.2.2 HEC5Q

F.2-8.2.2.1 Sacramento

Figure F.2-8-22 through Figure F.2-8-27 evaluate the temperature outcomes in the Sacramento River under the climate sensitivities using the Alternative 4 logic. Temperature dependent mortality (TDM) was calculated using the standard LTO parameterization.

The Alternative 4 TDM estimate shown in Figure F.2-8-22 demonstrates substantial climate variability. Under the 2022 Median climate scenario, TDM using the carryover logic exceeds 60% in approximately 15% of the simulated years. Under the 2022 Warm Wet climate scenario which is cooler and wetter than the 2022 Median climate scenario, the TDM using the carryover logic exceeds 60% in approximately 3% of the simulated years. Conversely, the 2022 Hot Dry climate scenario which is warmer and drier than the 2022 Median scenario has large TDM values occur more frequently with 60% TDM using the carryover logic occurring in approximately 45% of the simulated years. The 2040 Median scenario performs similarly to the 2022 Median scenario, albeit with an approximately 10% upward exceedance shift surrounding the 20% exceedance. When comparing the 2021 temperature tiers logic to the carryover logic, the mean TDM of each climate scenario is reduced under the 2021 temperature tiers logic.

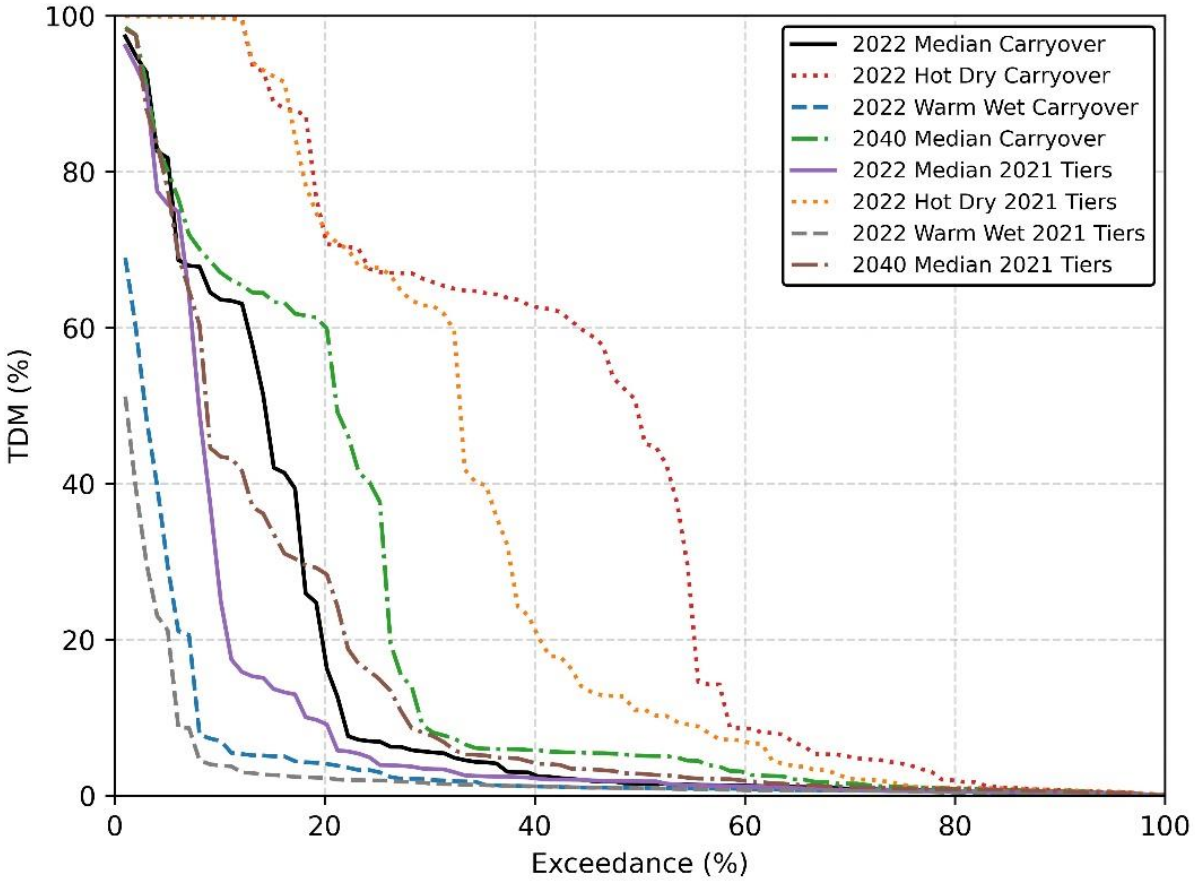

Figure F.2-8-22. Martin model TDM exceedance plot for Alternative 4 under various climate assumptions for water years 1922 through 2021

The Alternative 4 TDM values are driven by the Sacramento River temperatures from Clear Creek down to Red Bluff. Figure F.2-8-23 and Figure F.2-8-24 show the average and maximum May through end of October temperatures in the Sacramento River below Clear Creek with Figure F.2-8-25 and Figure F.2-8-26 providing the same information for Red Bluff.

The scaling of TDM follows the temperatures outcomes with the 2022 Hot Dry scenario having the largest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest temperatures of the scenarios. While the scenarios have a clear incremental increase in average temperatures, temperatures above the 60% exceedance threshold are largely similar. This is due to the extended shoulder period in the 2021 temperature targets which allows for better temperature performance later in the temperature management season at the expense of early season temperatures. The better performance of the 2021 temperature tiers logic later in the temperature management season results in lower TDM.

An analogous trend between the climate scenarios is visible in Figure F.2-8-27 with the volume of water less than 52 degrees Fahrenheit (°F) at the end of April. More cold water correlates with lower TDMs across the climate scenarios. However, despite having generally similar cold-water

volumes, the 2040 Median condition exhibits worse TDM outcomes than the 2022 Median, likely due to the higher average temperatures under the 2040 Median scenario. The higher average temperatures under the 2040 Median scenario are likely due in part to the greater in-stream and reservoir warming.

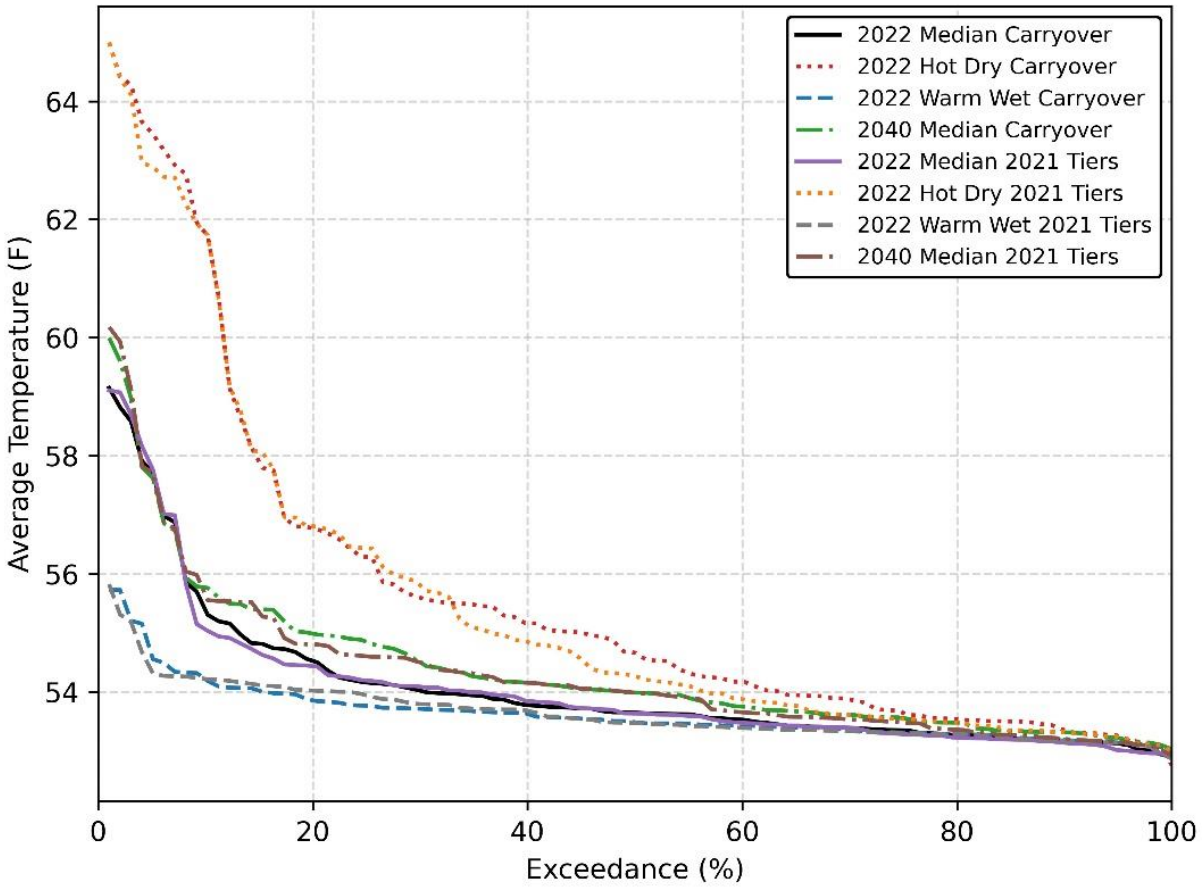

Figure F.2-8-23. Average May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 4 under various climate assumptions for water years 1923 through 2020

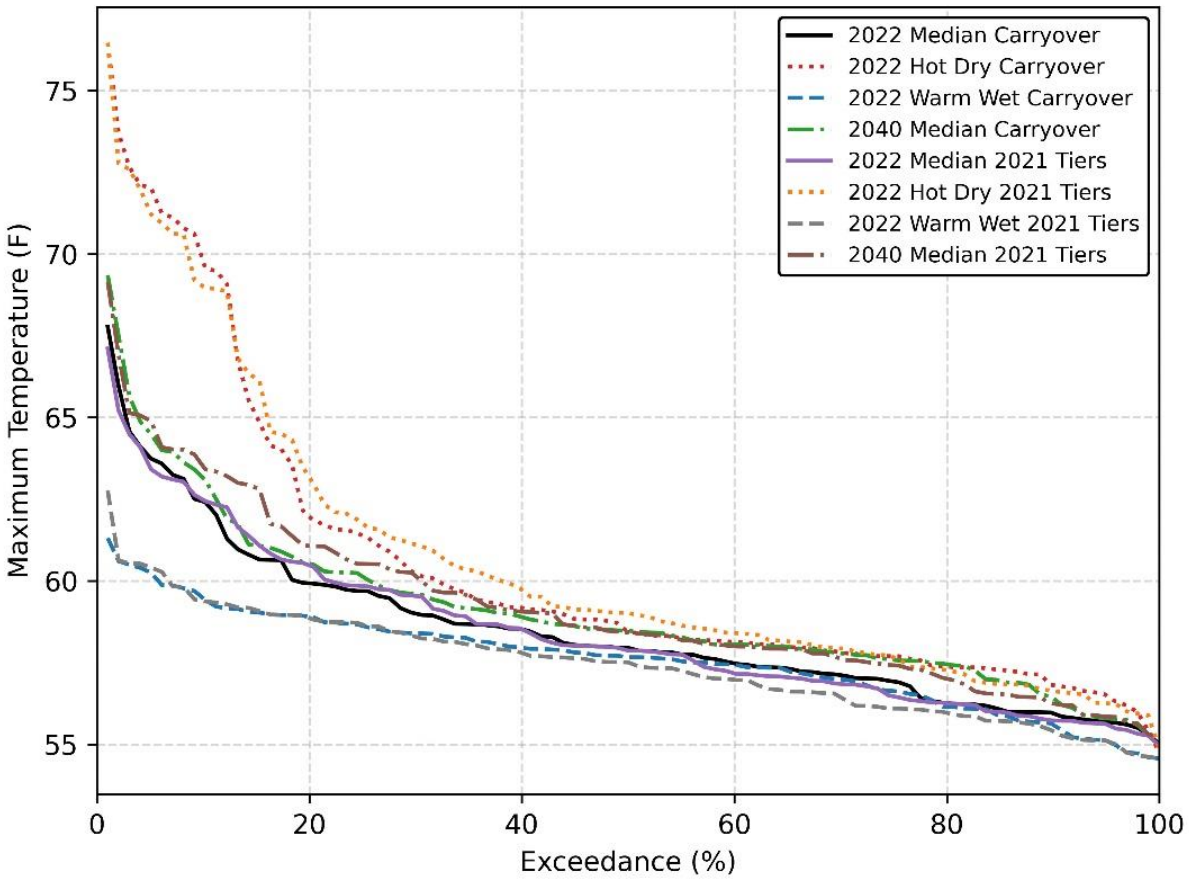

Figure F.2-8-24. Maximum May through end of October temperatures on the Sacramento River at Clear Creek for Alternative 4 under various climate assumptions for water years 1923 through 2020

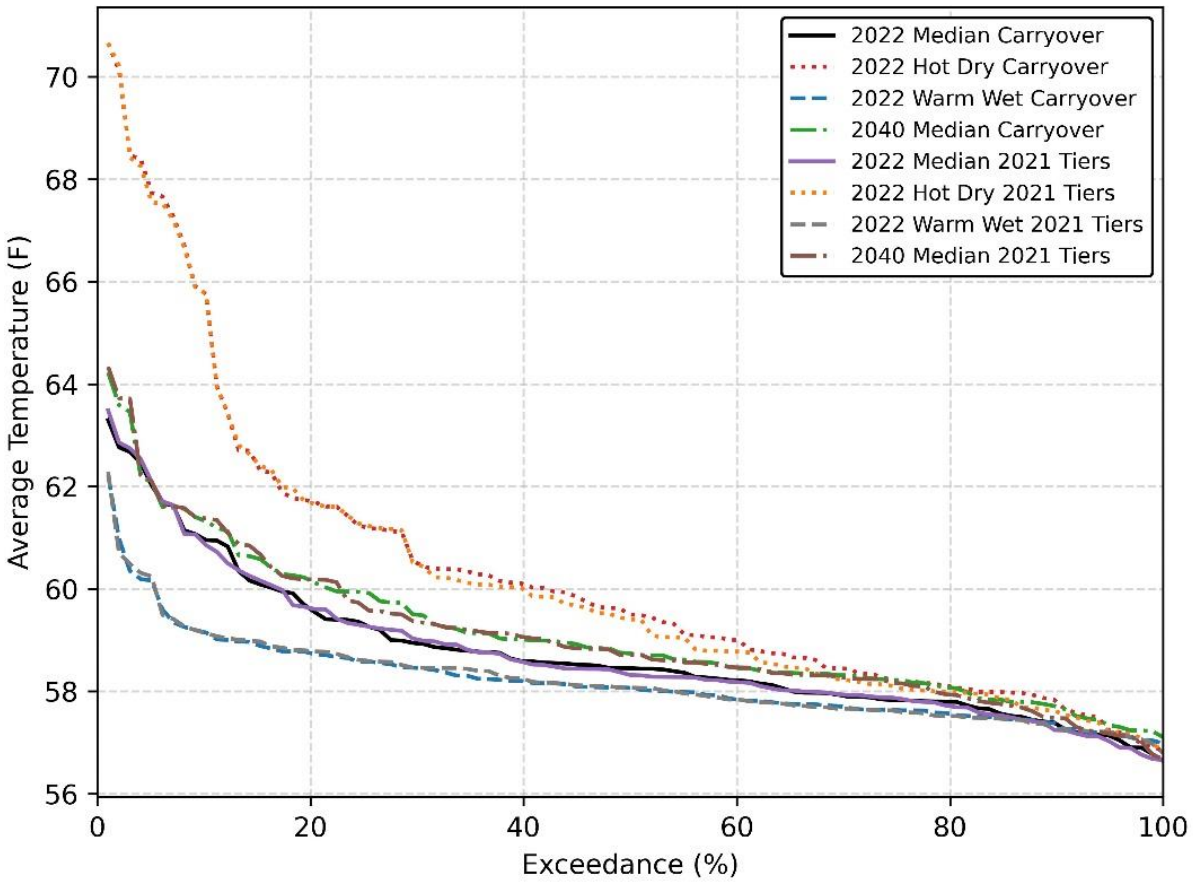

Figure F.2-8-25. Average May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 4 under various climate assumptions for water years 1923 through 2020

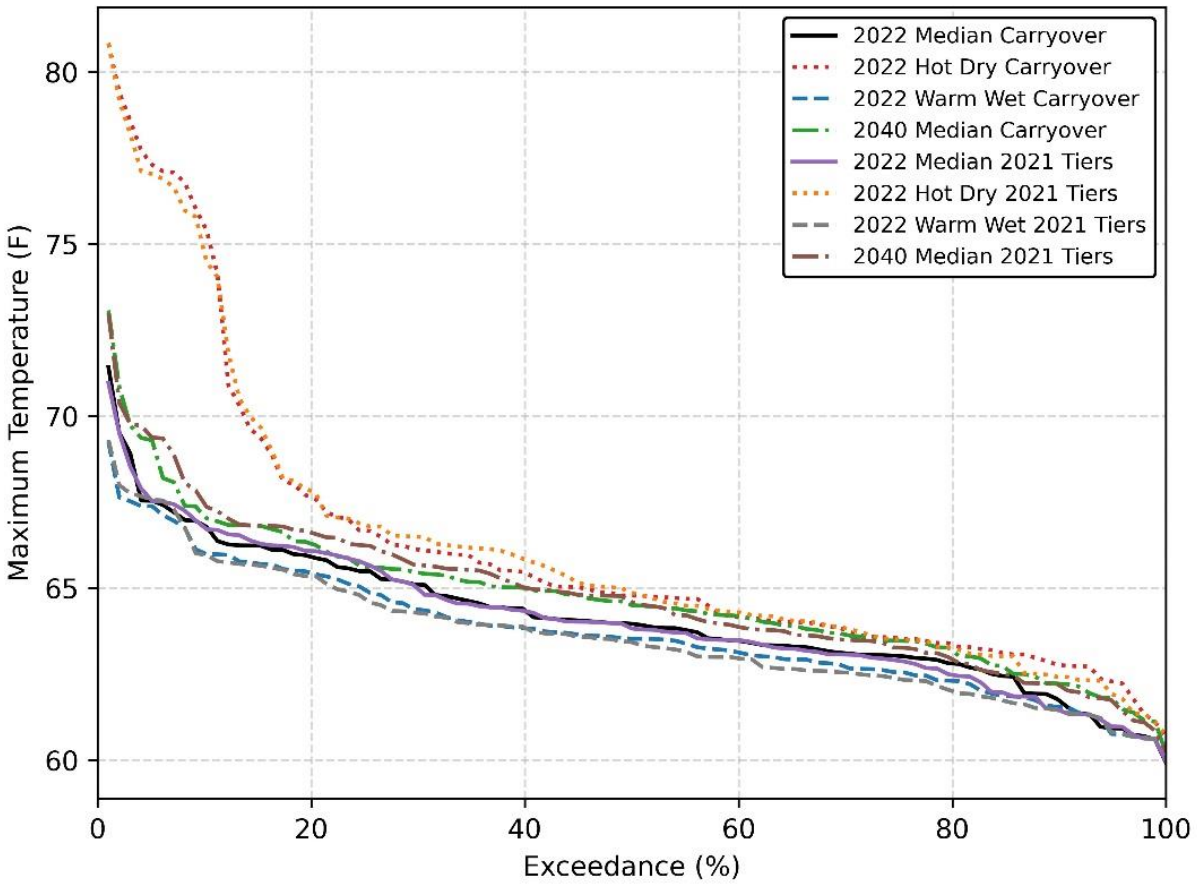

Figure F.2-8-26. Maximum May through end of October temperatures on the Sacramento River at Red Bluff for Alternative 4 under various climate assumptions for water years 1923 through 2020

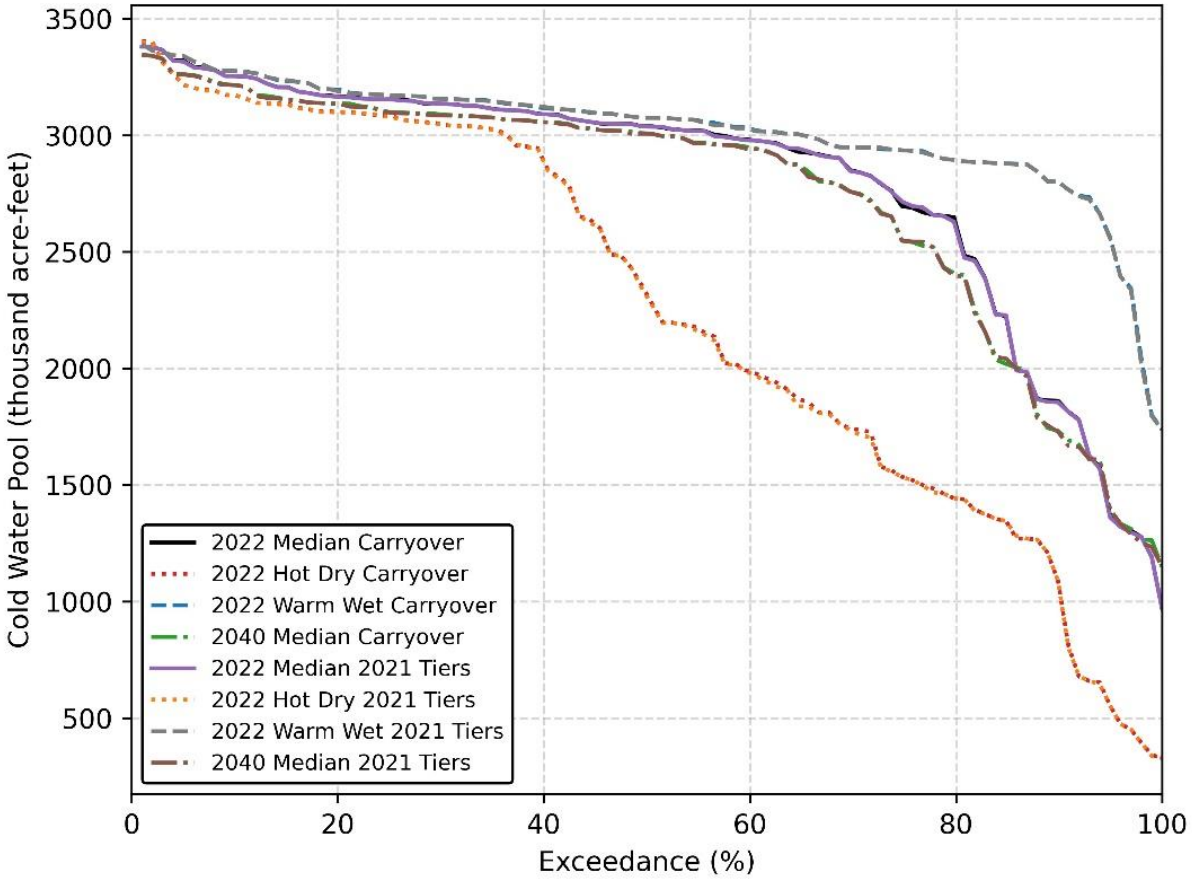

Figure F.2-8-27. Volume of water at the end of April less than 52°F in Shasta Lake for Alternative 4 under various climate assumptions for water years 1923 through 2021

F.2-8.2.2.2 American

Figure F.2-8-28 through Figure F.2-8-30 evaluate the temperature outcomes in the American River under the climate sensitivities using the Alternative 4 proposed ATSP update logic. The 2022 Hot Dry scenario has the highest average and maximum temperatures at low exceedances. At high exceedances, the 2022 Hot Dry scenario has the hottest average temperatures and the 2040 Median scenario has the hottest maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures.

The trend in Watt Avenue temperature is generally reflected in the Folsom Lake cold-water pool. Figure F.2-8-30 shows the volume of water less than 52 °F at the end of April in Folsom Lake. The 2022 Hot Dry scenario has the lowest volumes of cold-water and the 2022 Warm Wet scenario has the highest volumes of cold-water. Despite the 2022 Median and 2040 Median having similar volumes of cold-water, the 2040 scenario exhibits higher average and maximum temperatures likely due in part to the greater in-stream and reservoir warming.

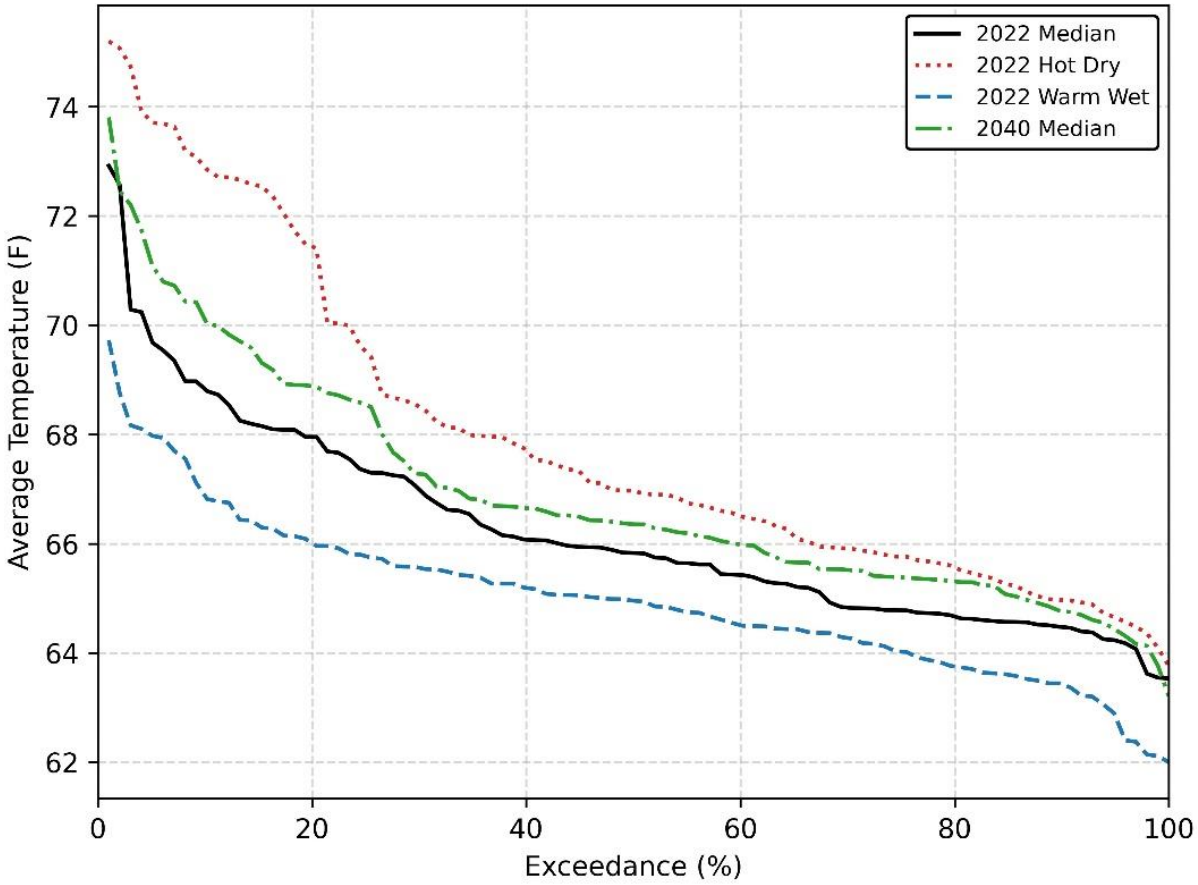

Figure F.2-8-28. Average May through end of October temperatures on the American River at Watt Avenue for Alternative 4 under various climate assumptions for water years 1923 through 2020

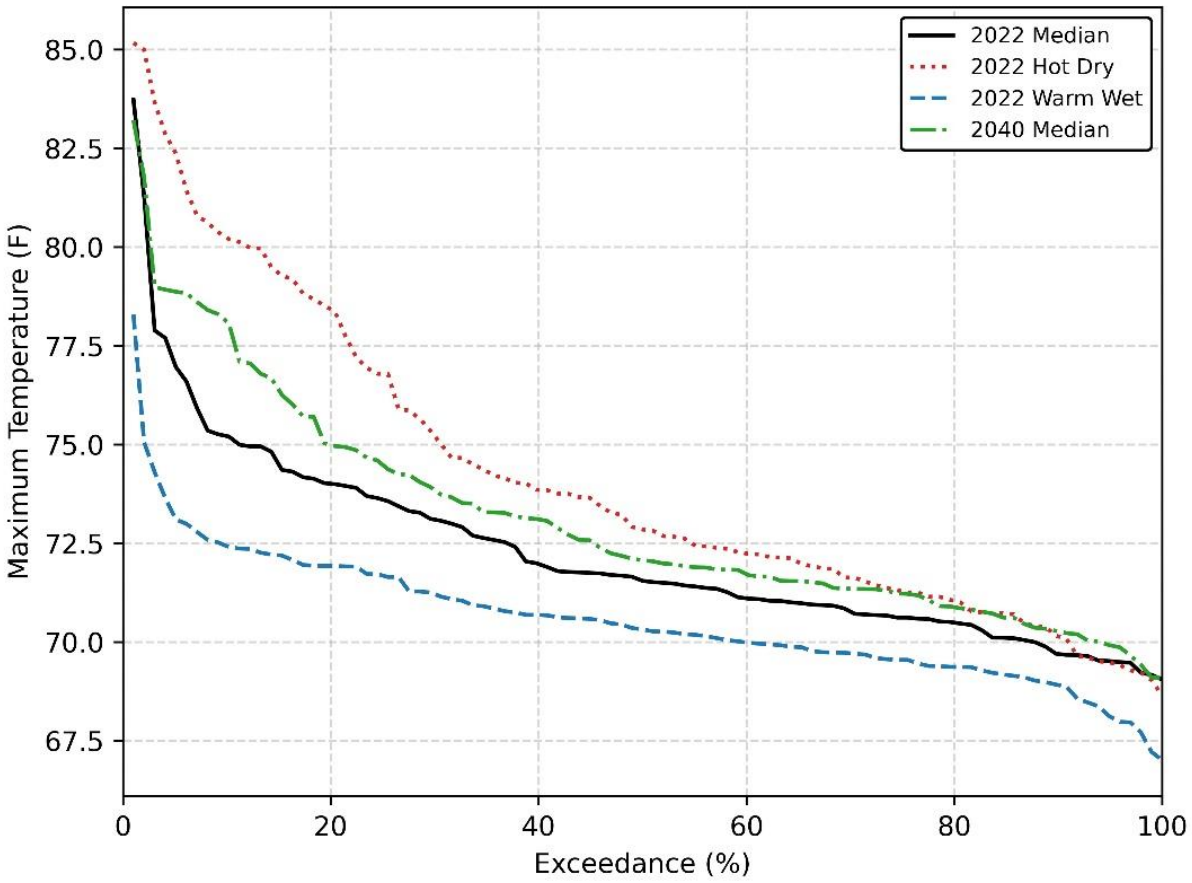

Figure F.2-8-29. Maximum May through end of October temperatures on the American River at Watt Avenue for Alternative 4 under various climate assumptions for water years 1923 through 2020

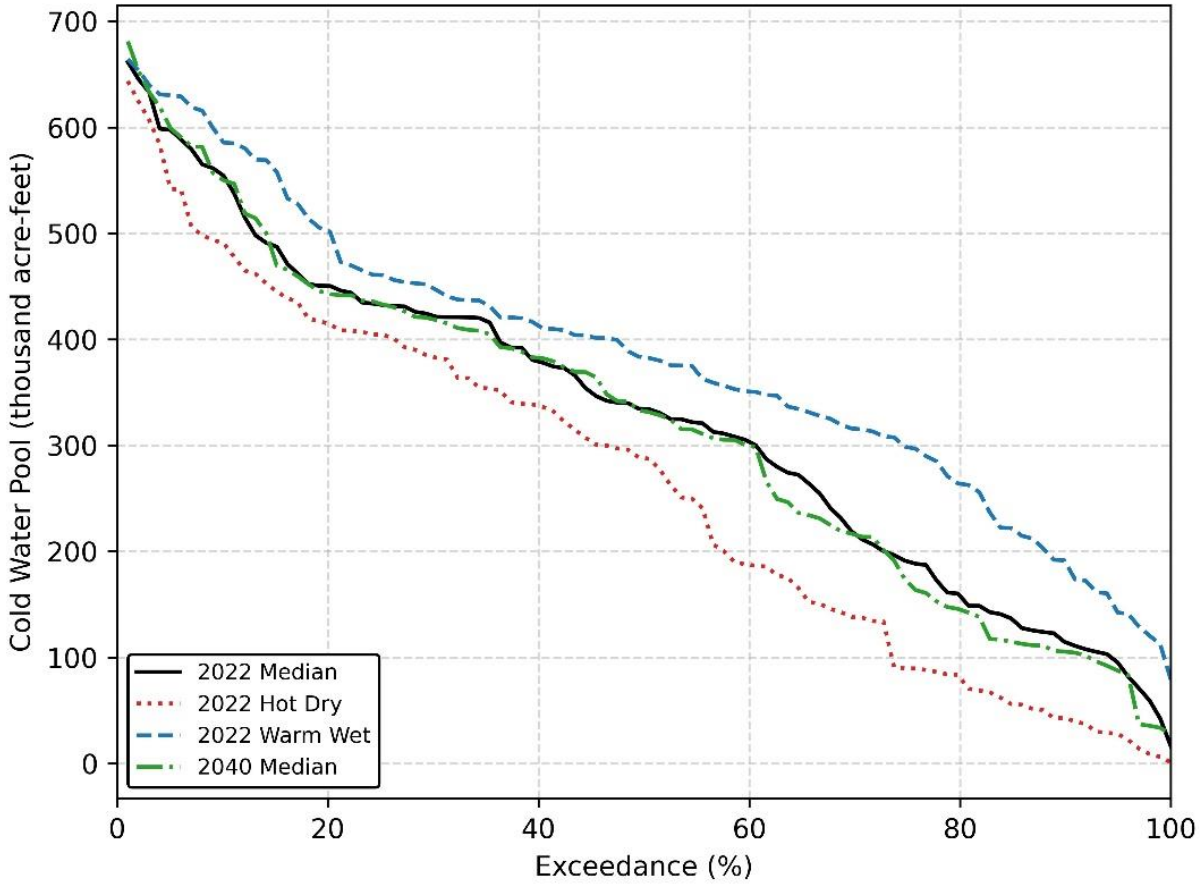

Figure F.2-8-30. Volume of water at the end of April less than 52 °F in Folsom Lake for Alternative 4 under various climate assumptions for water years 1923 through 2021

F.2-8.2.2.3 Stanislaus

Figure F.2-8-31 and Figure F.2-8-32 evaluate the temperature outcomes in the Stanislaus River under the climate sensitivities using the Alternative 4 logic. The 2022 Hot Dry scenario has the hottest average and maximum temperatures. The 2022 Warm Wet scenario has the coolest average and maximum temperatures. The 2040 Median temperatures are slightly higher than the 2022 Median due to instream warming.

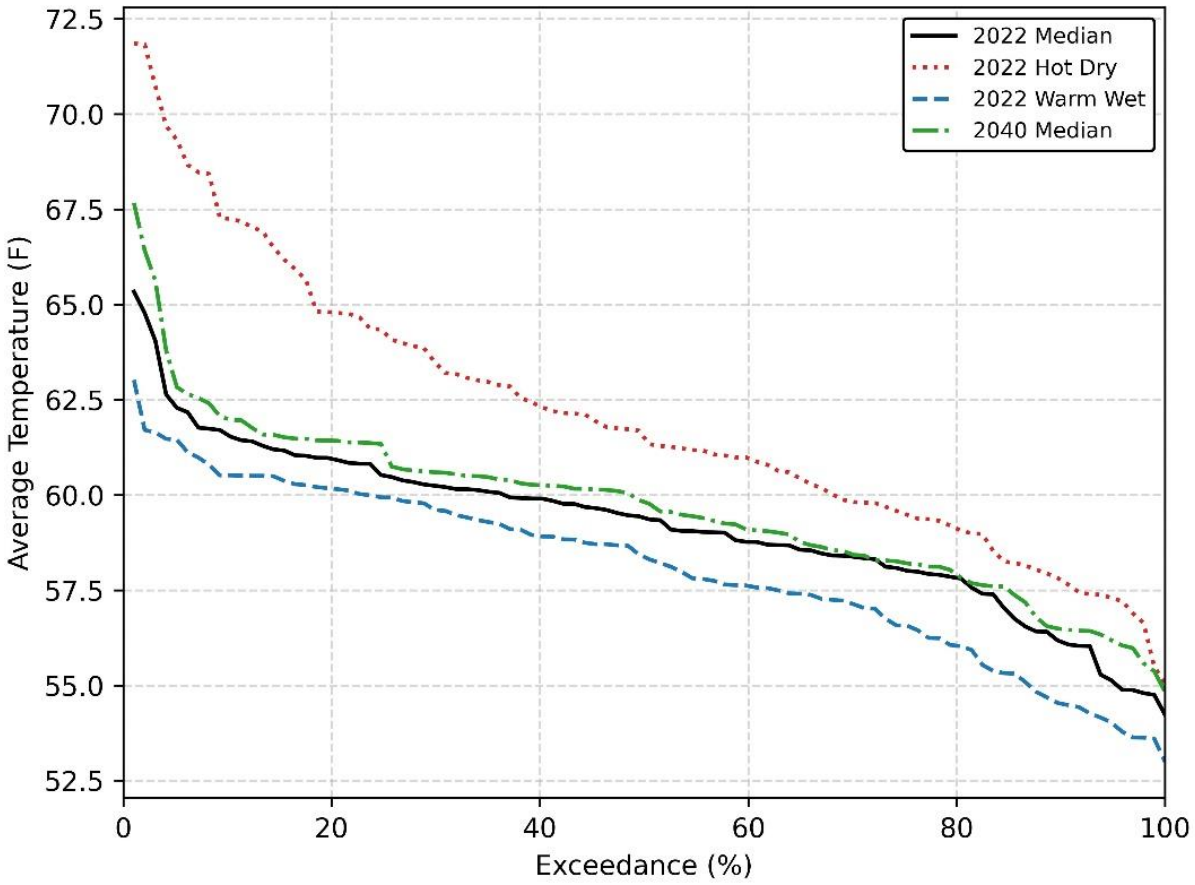

Figure F.2-8-31. Average May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 1 under various climate assumptions for water years 1923 through 2019

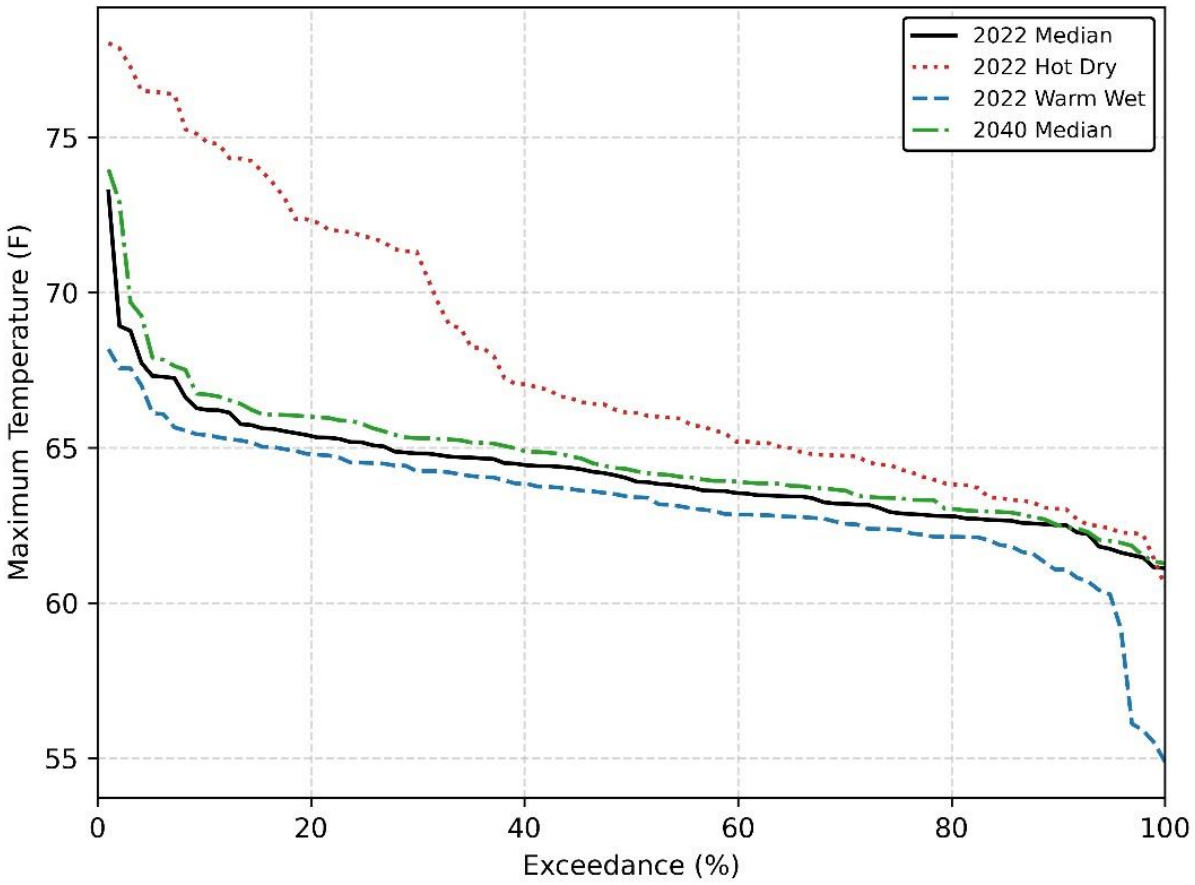

Figure F.2-8-32. Maximum May through end of October temperatures on the Stanislaus River at Orange Blossom for Alternative 1 under various climate assumptions for water years 1923 through 2019