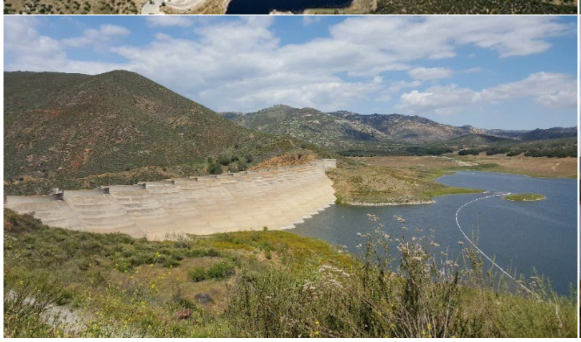
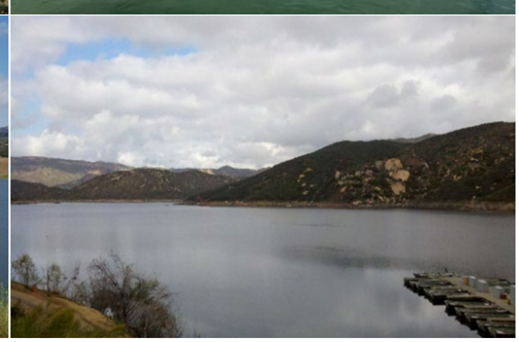
Development and Assessment of Modeling Tools for Forecast-Informed Reservoir Operation (FIRO) of San Diego Public Utility District (SDPUD) Reservoirs

Model Development for FIRO of City of San Diego (COSD) Reservoirs, California

California-Great Basin Region



Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Executive Summary

Reclamation water management is increasingly restricted by greater human usage, larger environmental compliance demands, and accelerating climate change. These factors interact to intensify the requirements on water resources infrastructure and the scrutiny regarding how those resources are managed. Forecast Informed Reservoir Operations (FIRO) can improve Reclamation water management and help it adapt to these factors. FIRO pilot studies have demonstrated the feasibility of utilizing improved meteorological/hydrological forecasts combined with better management techniques to simultaneously improve dam safety and water availability.

This project was conducted through collaboration between Reclamation, the City of San Diego (COSD), and the California-Nevada River Forecast Center (CNRFC) with the goal of demonstrating the benefits achievable from FIRO. COSD recently completed a basin study under Reclamation's WaterSMART Basin Study Program. The basin study conclusions suggested that FIRO could provide significant benefit to COSD in managing water transfers between its facilities to reduce water losses from spillage during extreme wet weather events (i.e., atmospheric rivers). The basin study also constructed models with the GoldSim simulation platform representing COSD's system. Using the basin study's work as a starting point, this project conducted a baseline assessment of current CNRFC forecasts versus historical data. Next, the utility of natural inflow records from the basin study were assessed for expanding the forecast calibration dataset, and then the CNRFC forecast suite was expanded to include Hodges and Otay basins and San Vicente and Hodges dams. The basin study GoldSim model was updated to include a FIRO methodology for simulating reservoir operations to maximize water supply for forecasted inflows, and the benefits attainable from FIRO under both baseline and future climate scenarios were assessed.

The baseline assessment of current CNRFC forecasts showed good agreement with historical data for peak time. However, the forecasts gave poor estimates about the peak discharge. Overall, although the forecasts made before Water Year 2021 had some successes in terms of the peak time, peak discharge, and 3-day volume, they are generally poor compared to a desired perfect 10-day-ahead forecast to facilitate FIRO operations. However, it is understood that the forecast model was not calibrated with the most recent observed data, and the observed dataset that is used in this analysis possesses flaws as well. All these factors affect the forecast model performance.

The new reservoir inflow forecasting sites created for this project are at Sutherland, Hodges, Barrett, El Capitan, and San Vicente Reservoirs. Data was provided by COSD to support implementation of the forecasting sites. The data from COSD required a processing method to account for gaps in the data record to reflect a realistic representation of both the small-scale daily variations of inflows during dry and low precipitation periods as well as the occasional large-scale events that correlate with flood risk considerations of importance to FIRO operations. Two processing methods were developed to fill in data gaps. The first method was based on a scaling of daily flow data, while the second method was based on performing a daily mass balance and solving for the reservoir inflow. CNRFC assessed the results from these two methods and used a hybrid set of results for all five forecasting sites to provide the most realistic representation possible of the historical flows.

All COSD watersheds had similar correlation statistics which generally decreased as the lead time of the forecast increased. Hodges Reservoir appeared to have the best statistics by a small margin. Overall, the skill of forecasts in the week 2 time period (Days 8-14) shows very poor skill.

The FIRO baseline model was applied to the historical period with available daily inflow data. Performance of each of the reservoirs and the whole city reservoir system was evaluated. El Capitan Reservoir levels during the biggest storm event in the data record never reached 700 ft, meaning no FIRO operation is triggered. However, the pre-season drawdown happened when water reached 680 ft and above. This operation lowered the reservoir further in a position that helps flood management during the wet season. Hodges Reservoir levels in the biggest storm event in the record resulted in the "without FIRO" operation being unable to lower the water level down below the restricted limit 295 ft for as long as 151 consecutive days. This could be very dangerous to the Hodges Reservoir dam due to the existing defects in the dam (DWR correspondence dated 9/4/2019). However, the "with FIRO" operation significantly reduces the number of days that Hodges Reservoir operates above the restricted level. The total number of days that Hodges Reservoir exceeds 295 ft is 19 days, with only 12 days consecutively in the same period. This is done through moving water temporarily to Lake Olivenhain using Lake Hodges Pumps. Additionally, our results show that the "with FIRO" operation captures more water than the "without FIRO" operation. This is done through reducing reservoir releases by moving more water to temporary storage facilities, i.e., Olivenhain Reservoir and R.E. Badger Filtration Plant.

To assess future climate scenarios, daily streamflow timeseries were acquired from applying downscaled General Circulation Model (GCM)data to the Variable Infiltration Capacity (VIC) Hydrological Model. This approach allowed for use of all the available climate projections to explore the full range of potential future hydrology as outlined by the GCM ensemble. This results in 29 GCMs each run at the two Representative Concentration Pathways (RCPs) (RCP 4.5 and RCP 8.5) for a total of 58 future scenarios as opposed to the 5 climate scenarios of the basin study. Results were compared using 30-year periods with 1951-1980 being the baseline period, 2020-2049 the "short-term" future, and 2050-2079 the "long-term" future. In general, the most common futures are those with lower annual average flow, increased frequency of high inflow events, and an increase in the expected number of dry years. These climate projections were used to determine both 1) the change in system performance under climate change and 2) the change in FIRO benefit under climate change. System performance was evaluated in terms of both water supply and flood prevention.

For the COSD's Reservoir System, appreciable FIRO benefit is observed across all time periods as seen by an increase in Deliveries, and a reduction of Releases by approximately 15-20% in the median scenarios. For system deliveries, we see a median benefit of at least 15 thousand acre-feet (TAF) per year for both the historic reference period and the future periods examined. Although in some scenarios the potential FIRO benefit is slightly reduced, in every scenario or time period there is a benefit without negative impact on Deliveries. For Releases, a median reduction of over 15 TAF per year is also observed for the historical and future periods. This benefit increases in the future periods when wet weather events are projected to become more prevalent.

For El Capitan, there was an appreciable benefit from FIRO in the baseline period (median of 21.4 TAF) in both Releases and Deliveries. In the 2020-2049 period, we notice a doubling of the median FIRO benefit. There is also an improvement from the baseline in the 2050-2079 period though less than the increase in the 2020-2049 Period. There does not appear to be significant correlation between RCP and FIRO benefit. Under all the climate change scenarios, at least a slight FIRO benefit is observed, and so the implementation of FIRO is never maladaptive for El Capitan.

For Hodges, there was a substantial benefit from FIRO in the baseline period for median Deliveries (442.6 TAF) and Releases (492.5 TAF). In the 2020-2049 period, we notice a modest increase of the median FIRO benefit for both metrics. There is also an improvement from the baseline in the 2050-2079 period though less than the increase in the 2020-2049 period. There does not appear to be significant correlation between RCP and FIRO benefits. Under all of the climate change simulations, an appreciable FIRO benefit is observed. In the lowest performing case we see a FIRO benefit of approximately 125 TAF for both Deliveries and Releases

System performance was also assessed in terms of correlation with streamflow changes. In terms of annual average streamflow (AAS), at El Capitan we see that for the futures with the lowest amount of AAS (0-25), we have the smallest FIRO benefit. In contrast, in projections with the greatest AAS (75-100) we have the largest FIRO benefit. At both El Capitan and Hodges we see a similar correlation with streamflow. With increased AAS, or an increase in the number of wet weather events (WWE), the potential benefit of FIRO increases. This result is consistent with the results seen using the period of record where FIRO benefit is limited in dry years simply by there being no risk of exceeding reservoir elevation restrictions and thus no FIRO operations are triggered.

Finally, a sensitivity analysis was conducted with respect to changes in operational scenarios for forecast horizon, level restrictions, and water quality. Our results show a decline in FIRO benefits at El Capitan with reduced forecast horizon, which is expected as the Forecast Horizon is the limiting factor in how much water can be drawn out of the reservoirs before a high inflow event. However, there is not as much sensitivity to the forecast horizon at Hodges, indicating that the rate at which water can be transferred out of Hodges is not the limiting factor.

Under changing level restriction scenarios, we see an increase in Deliveries and a reduction in Releases at higher level restrictions in both current operations and with FIRO. With higher level restrictions, we also observe a decrease in FIRO benefit. This is due to an overall reduction in the need for FIRO operations with the more flexible level restrictions. At low level restrictions, FIRO operations occur more often, and so the benefit from FIRO is larger.

The FIRO benefit declines under all water quality (WQ) scenarios, with the restrictions in March and April showing a greater impact on Deliveries than restrictions in February. Overall there is only a modest impact to operations, and there remains a modest benefit from FIRO under all WQ scenarios.

The study presented herein represents an initial exploration into the potential benefits of FIRO for the COSD reservoir system for both current and future climate conditions. Recommended steps for a more comprehensive assessment of the feasibility of FIRO of COSD reservoirs include a preliminary viability assessment (PVA), water operations strategy document, final viability assessment (FVA), and coordination with responsible agencies (e.g., California Department of Water Resources – Division of Safety of Dams) with the authority to ensure adequate flood control goals are met. The outcomes of the PVA will include 1) a determination of whether FIRO is viable enough to take more concrete steps towards implementing the approach into SDPUD's actual operations and 2) a water operations strategy document that will give a more complete accounting of how FIRO can be implemented into all aspects of the system's reservoir operations than the conclusions documented in this report. If the PVA determines that FIRO is viable, then an FVA will be initiated based on recommendations from the PVA. The FVA will address any remaining aspects of the operations that need to be more fully assessed before formal incorporation of FIRO into the SDPUD operation of the COSD reservoirs can be achieved. Results of the FVA will be used in the final step of coordination/approval with/from agencies responsible for flood safety and ensuring regulatory compliance is met.

It is important to note that while this study demonstrates the benefits of FIRO with no negative impacts, these results are dependent on the access to forecasts of sufficient skill. The assessment of the current CNRFC forecasts against historical data suggests that some improvements in forecasting of the COSD watersheds and the available data on which the construction of forecast models rely may be needed to reliably implement FIRO. Furthermore, due to the limited nature of the historical observation period and the use of an uncalibrated hydrological model to derive the climate change scenarios, any conclusions drawn from these results should be seen as preliminary. With regard to the climate change analysis, results should be looked at as qualitative indicators of future change rather than quantitative projections.

Chapter 1 – Assessment of Existing Forecast Model Results

The first step in exploring the potential benefits of FIRO for the SDPUD system was to perform a baseline assessment (i.e., hindcast skill determination) of current operational forecasts from the CNRFC for the San Vicente and El Capitan basins against an 8-year historical inflow record provided by SDPUD. The 10-day forecast for SV and EC published by CNRFC started from August 10, 2017. Older forecasts are not available. Next, we evaluated the utility of the natural inflow record developed under the basin study using VIC modeling for expanding the calibration dataset.

1.1 Inflow Forecasts for San Vicente and El Capitan Reservoirs

CNRFC developed the forecast model for San Vicente and El Capitan in the San Diego region based on daily inflow data from the 1980s to 1990s (personal communication, Peter Fickenscher – CNRFC). The goal of the forecast focuses on extreme events for flood management purposes with flood events defined as having peak flow greater than 1,000 cfs. There is 1 event in the El Capitan basin and 2 events in the San Vicente basin for the period from August 10, 2017, to December 31, 2020. Performance of the forecast is evaluated by means of the ratio of forecasted peak discharge to actual peak discharge, forecasted peak time away from actual peak time away, and the ratio of 3-day volume. A perfect forecast would have a peak time difference of 0 days and a peak discharge ratio of 1. A positive peak time difference means that the forecasted peak appears later than actual peak, and a negative peak time difference means that the forecasted peak appears earlier. If the peak ratio is greater than 1, the forecast overestimates peak discharge. Otherwise, it underestimates peak discharge. This is the same as the 3-day volume ratios. The following tables and charts show the performance of forecasts made on certain days ahead of the actual peak for the three events.

Observation	Peak Time	2/15/2019	Peak Discharge (cfs)	2521	3 Day Volume (af)	6008
Forecast at different days ahead	Peak Time	Peak Discharge (cfs)	Date Difference (days)	Peak Ratio	3 Day Volume (af)	Ratio
1	2/15/2019	1711	0	68%	6808	113%
2	2/15/2019	1715	0	68%	6502	108%
3	2/15/2019	924	0	37%	3394	56%
4	2/15/2019	408	0	16%	1662	28%
5	2/14/2019	320	-1	13%	1129	19%
6	2/14/2019	352	-1	14%	1014	17%

Table 1-1 – El Capitan Forecast Performance

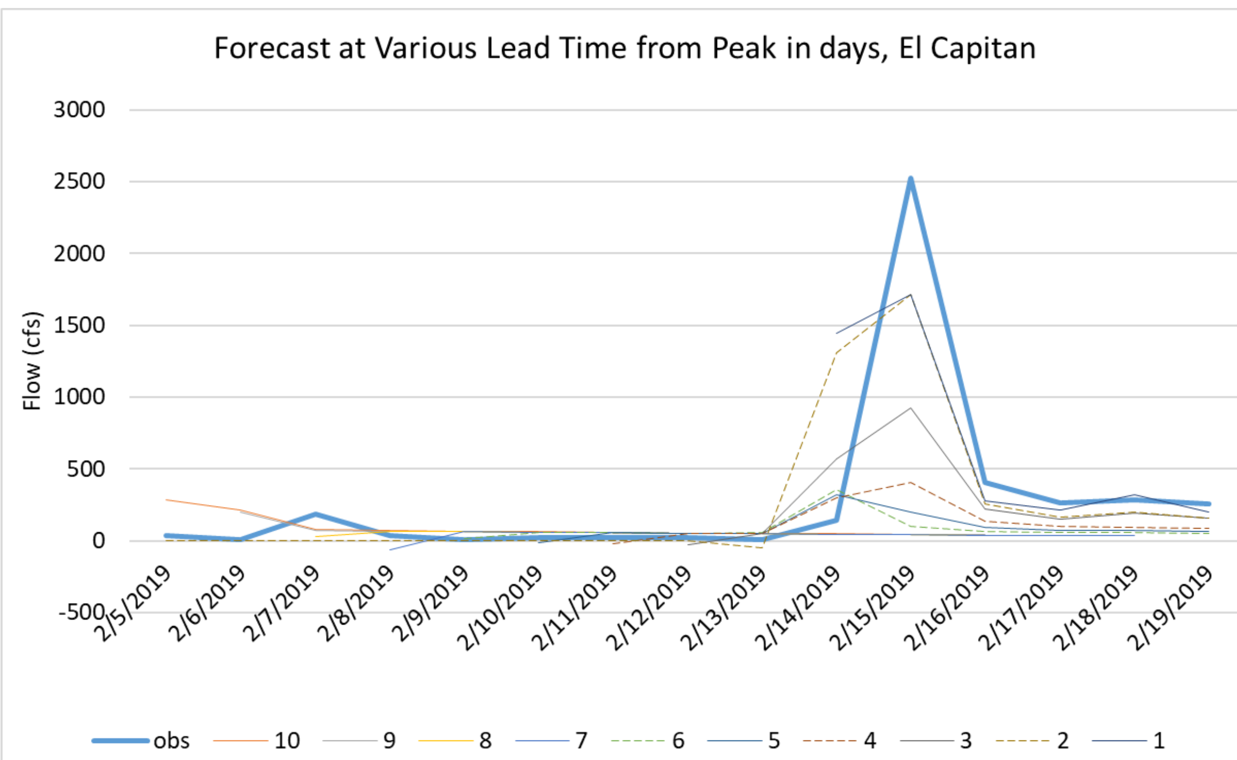

Figure 1-1 – El Capitan Forecast Lead Times

Observation	Peak Time	2/15/2019	Peak Discharge (cfs)	1320	3 Day Volume (af)	3172
Forecast at different days ahead	Peak Time	Peak Discharge (cfs)	Date Difference (days)	Peak Ratio	3 Day Volume (af)	Ratio
1	2/15/2019	2458	0	200%	6792	214%
2	2/15/2019	3986	0	325%	12231	386%
3	2/15/2019	1732	0	141%	6110	193%
4	2/15/2019	967	0	79%	3670	116%
5	2/14/2019	633	-1	52%	2620	83%
6	2/14/2019	961	-1	78%	1473	46%

Table 1-2 – San Vicente Event #1 Forecast Performance

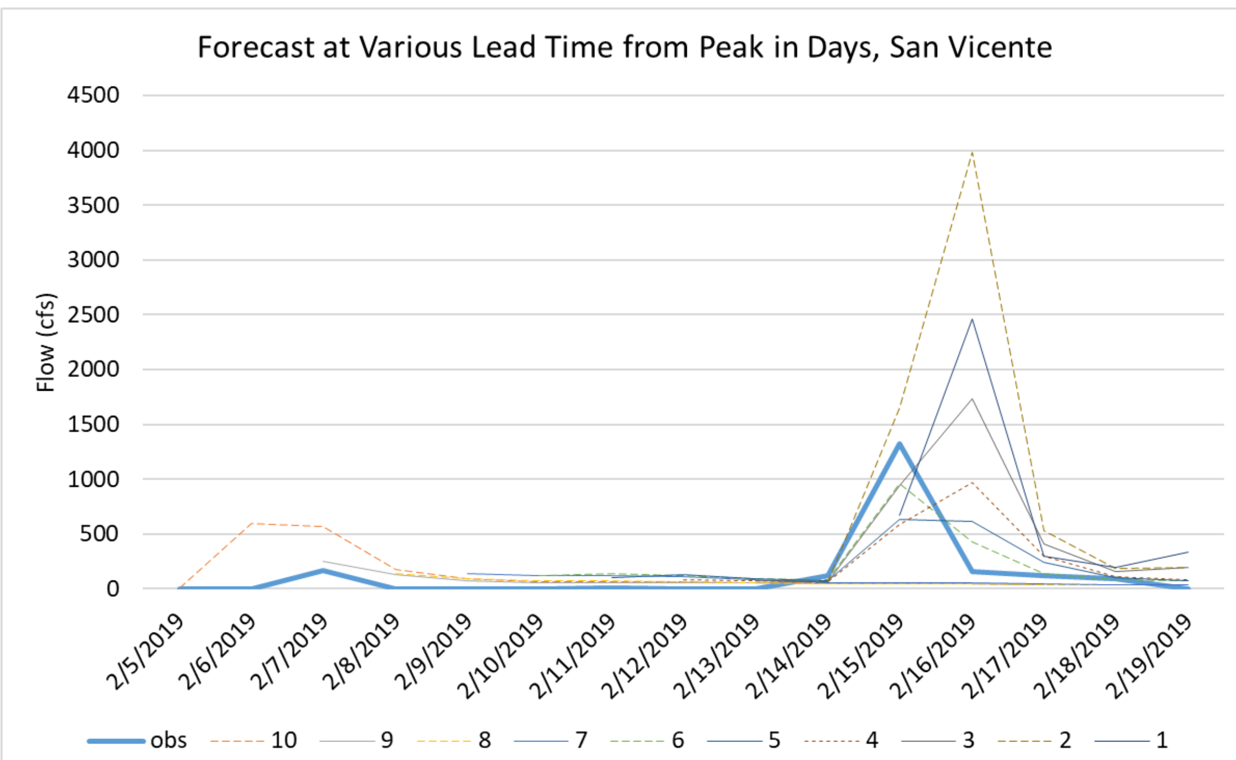

Figure 1-2 – San Vicente Forecast Lead Times Event 1

Observed	Peak Time	4/11/2020	Peak Discharge (cfs)	1227	3 Day Volume (af)	3350
Forecast Horizon	Peak Time	Peak Discharge (cfs)	Date Difference (days)	Peak Ratio	3 Day Volume (af)	Ratio
1	4/11/2020	1794	0	146%	7658	229%
2	4/11/2020	960	0	78%	4053	121%
3	4/10/2020	407	-1	33%	2009	60%
4	4/8/2020	906	-3	37%	3928	117%
5	4/9/2020	414	-2	34%	2215	66%
6	4/9/2020	444	-2	36%	2009	60%

Table 1-3 – San Vicente Event #2 Forecast Performance

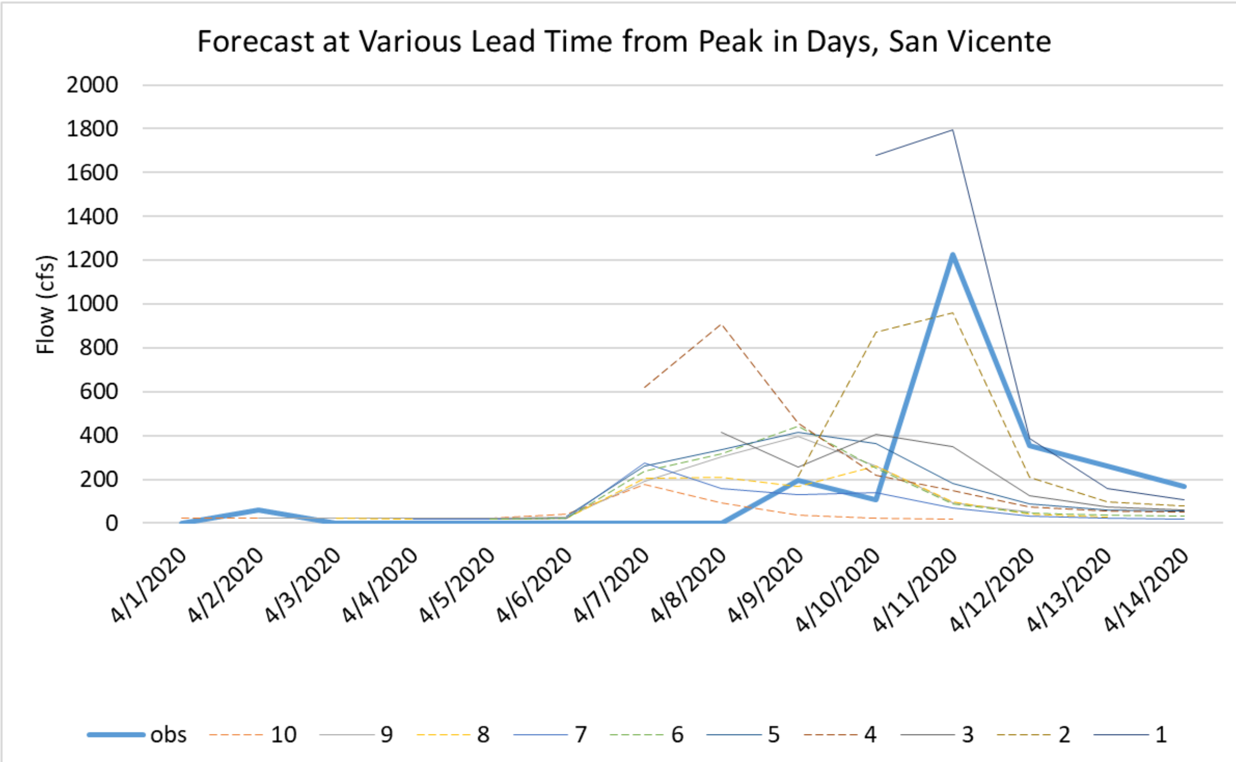

Figure 1-4 – San Vicente Forecast Lead Times Event 2

It can be seen that the forecasts of the three events gave good estimates about the peak time. With two of the three events, the February 15, 2019, flood in both El Capitan and San Vicente watersheds, the forecasts predicted exact peak time for up to 3 days ahead and within only 1 day off for up to 6 days ahead. In one event, the April 11, 2020, flood in San Vicente watershed, the forecasts predicted 2 days off for 6 days ahead. However, the forecasts gave poor estimates about the peak discharge. In the February 15, 2019, flood in El Capitan watershed, the forecasts underestimated the peak discharge throughout the time and the best predictions were within 70% of actual measurements in the first 2-days-ahead forecast. In both of the two floods in San Vicente watershed, the forecasts overestimated the peak discharge by 141% to 325% for shorter time-ahead forecasts but underestimated for longer time-ahead forecasts. For 3-day volumes, the flood in El Capitan watershed was on par for the first 2-days-ahead forecast but underestimated for the other forecasts; the February 15, 2019, flood volume in San Vicente watershed was overestimated by 193% to 386% in the first 3-days-ahead forecasts and underestimated in the 5- and 6-days-ahead forecasts; the April 11, 2020, flood volume in San Vicente watershed was overestimated in the first 2- and 4-days-ahead forecasts, and underestimated in the 3-days-ahead forecast and the 5- and 6-days-ahead forecasts.

In conclusion, although the forecasts made before year 2021 has some successes in terms of the peak time, peak discharge, and 3-day volume, they are generally poor compared to a desired perfect 10-day-ahead forecast to facilitate FIRO operations. However, it is understood that the forecast model was not calibrated with most recent observed data, plus the observed dataset that is used in this analysis is not in perfect shape. All these factors affect the forecast model performance. The procedures of processing the observed dataset are discussed in Chapter 2. An effort has been undertaken by CNRFC to calibrate the model using most recent data. The results are also presented in Chapter 2.

It is desirable for this study to identify a forecast threshold for the city operators to determine if they need to operate in FIRO mode when storms come. It is understood that the observation period is too short to cover all hydrologic conditions to enable a flood frequency analysis. COSD provided the team with a previously developed El Capitan reservoir inflow volume-frequency curve, as shown in Figure 1-5 below. For context, the 24 hour maximum inflow during the periods to be examined in the climate change analysis of Section 4 are displayed in Figure 1-6 below. The 2019 flood was plotted on the curve and the probability is found to be about 5%. From the provided document it is known that the 1980 flood forced the reservoir to release water, compared to the 2019 flood in which no water was released although it has a higher peak than the 1980 flood. This tells that not only the peak flow of a flood but also the total volume of the flood event plays a role in the release of extra water. It is also clear that the position of the reservoir before the storm will affect the release. Clearly, the threshold for making an operational decision to run FIRO is affected by several factors. This needs to be studied with adequate data and by analyzing a combination of several factors.

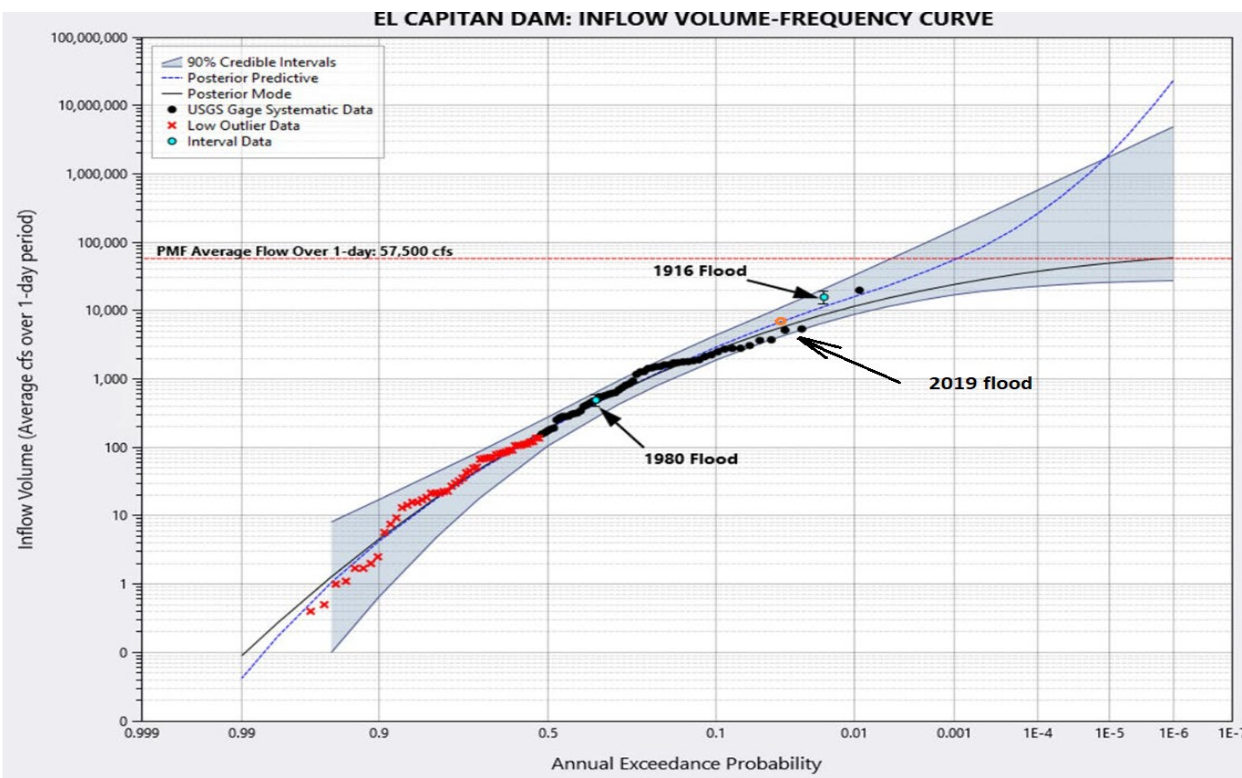

Figure 1-5 – Inflow Volume-Frequency Curve

To overcome the dilemma, Reclamation staff developed a model platform to aid the city staff in decision making. The platform will enable operators to leverage the SDFIROSim model which was created in this study by automation, removing the need of in-depth knowledge of GoldSim software and/or the model itself. To guide daily operation, operators can feed the model with different forecast, release, and delivery schedules, and analyze the results using an Excel spreadsheet. Appendix C has more details of the platform.

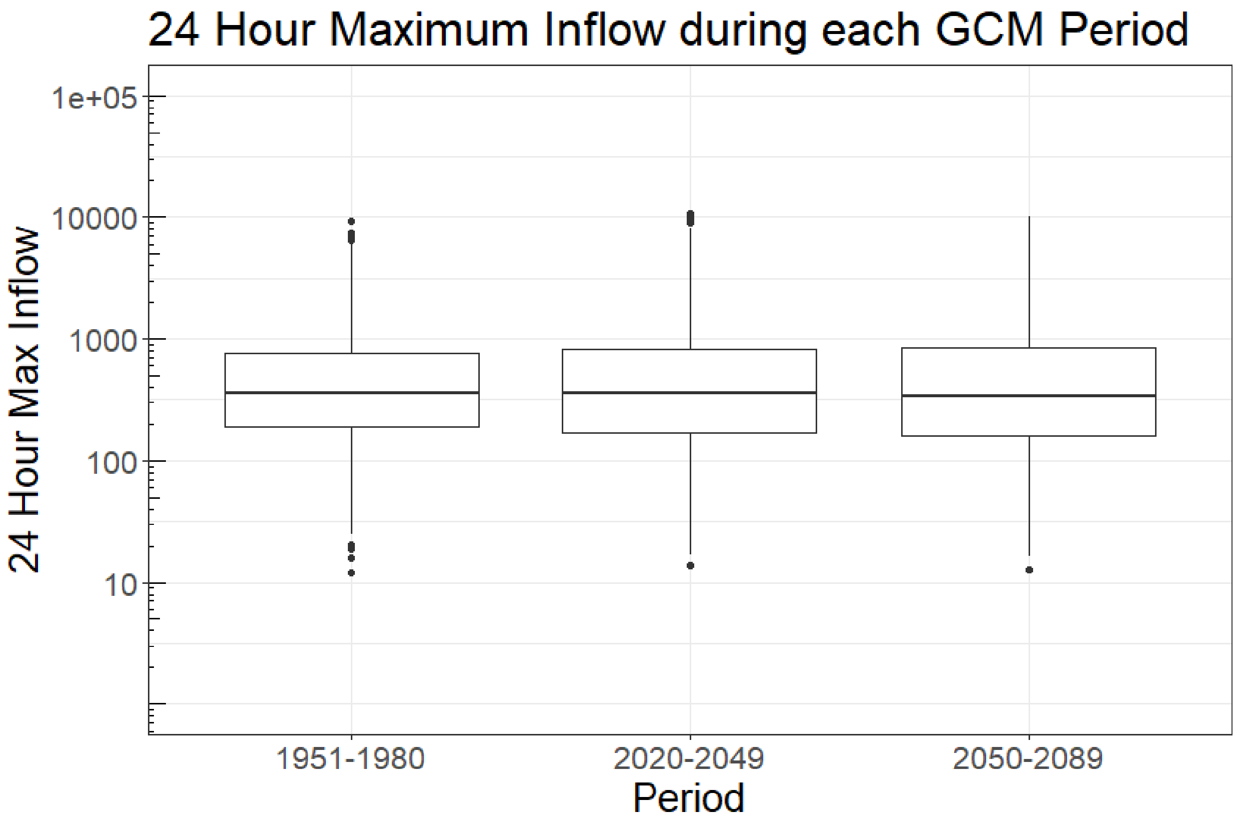

Figure 1-6 – 24 Hour Max Inflow Volumes at El Capitan from the uncalibrated GCM derived hydrology to be examined in section 4. Compared to the Inflow Frequency curves the maximum inflow events seen here correspond to approximately the 1 in 100 year inflows.

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Chapter 2 Development of New Reservoir Inflow Forecast Sites

The CNRFC of NOAA manages a real-time data and forecasting system that can be used to support FIRO by providing short-term forecasts of reservoir inflows. As part of this project, CNRFC has developed new reservoir inflow forecast sites within COSD's reservoir system. The data and forecasts will be accessible via the CNRFC's webpage at CNRFC - California Nevada River Forecast Center (noaa.gov).

2.1 Location of New Reservoir Inflow Forecasting Sites

The new reservoir inflow forecasting sites created for this project are at Sutherland, Hodges, Barrett, El Capitan, San Vicente, and Lower Otay Reservoirs. Data was provided by COSD in the summer of 2021 to support implementation of the forecasting sites at all locations except Lower Otay. Accordingly, CNRFC developed the five new forecasting sites and incorporated them into their online forecasting system in October 2021

2.2 Development of Supporting Datasets for CNRFC Forecasting

The supporting datasets for these new reservoir inflow forecast sites were assembled with data provided by COSD. This data includes rainfall, runoff, reservoir storage, evaporation, leak, draft, and spill data for the years 2013 through 2020. The CNRFC used this data in conjunction with historical meteorological data to create their forecasting models for each location.

In order to calibrate the watershed runoff models, continuous daily inflow data is required. The data provided by COSD included gaps which needed to be estimated. The data record needed to reflect both the small-scale daily variations during dry periods, as well an accurate representation of the magnitude and timing of large-scale events. The large-scale events are most important for flood risk management at potential FIRO operations.

Two processing methods were developed for this purpose. The first method was based on a scaling of daily flow data, while the second method was based on performing a daily mass balance and solving for the reservoir inflow. The scaling method was based on the assumption that the monthly total inflow data was more reliable than the daily data. Thus, a scaling factor was calculated that would be used to scale all daily inflow data such that the sum of these daily inflows equals the monthly total. The daily mass balance method was based on the fact that the COSD data included daily values for all days for all terms except for inflow. Thus, the inflows could be solved for on a daily basis. CNRFC assessed the results from these two methods and used a hybrid set of results for all five forecasting sites to provide the most realistic representation of the historical flows possible. The final datasets used in calibration are summarized in Table 2-1.

Forecasting Site	**Scaled Performance**	**Daily Balance Performance**	**Method Used**
Sutherland	Good	Good	Daily Balance
El Capitan	Good (except for Jan-Mar 2017)	Many days with errors (but good in places)	Scaled
San Vicente	Good	Mediocre	Scaled
Hodges	Good	Poor	Hybrid
Barrett	Mediocre	Good	Daily Balance

Table 2-1 – Qualitative comparison of the two methods developed for deriving historical daily inflow timeseries, and the final method chosen for model calibration

The CNRFC processed the meteorological forcings needed for the hydrologic simulations. Two timeseries (temperature and freezing level) were processed from gridded data produced outside of the CNRFC. For mean areal temperature (MAT) gridded data from NOAA's Analysis of Record Calibration (AORC) were processed to the individual watersheds. The median elevation of the watershed was used for the MAT timeseries. For the mean areal freezing level (ZELV), historical data from the ERA5 reanalysis was used. Again the median elevation of each watershed was used to derive the ZELV timeseries. The mean areal precipitation (MAP) timeseries was produced from a combination of two sources. CNRFC's historical gridded quantitative precipitation estimates (QPE) was used for water years (WY) 2004-2020. The MAP data for WY 1980-2003 was developed in the CNRFC from point rain gage data and normalized to the PRISM long-term annual precipitation normals for each watershed.

A summary of the historical forcings is below:

– Mean Areal Precipitation: from CNRFC's gridded QPE field (WY 2004-2020) & CNRFC calibration point data records (WY 1980-2003)

– Mean Areal Temperature: AORC data (WY1980-2020)

– Mean Areal Freezing Level: ERA5 reforecast data (WY 1980-2020)

The CNRFC also developed five inflow forecast models using the above-mentioned historical forcings and individually calibrated hydrologic models. The core models come from the Office of Hydrologic Development (OHD) suite of hydrologic models and are configured to run on the CNRFC's Community Hydrologic Prediction System (CHPS). These include:

- Rain-Snow Elevation Model (RSNWELEV): This model lapses atmospheric freezing level data to a rain-snow elevation for differentiating snow and rain over a watershed.
- Snow Model (SNOW-17): SNOW-17 is used for the accumulation and melting of snow when present. Bias adjustments to the historical precipitation forcings are also included. The output is a rain plus melt timeseries.
- Sacramento Soil Moisture Accounting Model (SAC-SMA): Produces runoff from the SNOW17 output. The soil column is simulated with conceptual tanks which fill and release runoff.

The runoff models are continuous simulations, keeping track day to day of snowpack, rainfall, evapotranspiration, and movement of water through the soil column. Therefore, previous storms will add moisture to the soil column and impact the runoff potential for any future storm events.

2.3 Performance of new CNRFC Inflow Forecast vs. Observations

The CNRFC forecasting models for the first five locations implemented (Sutherland, Hodges, Barrett, El Capitan, and San Vicente) achieved a reasonably good representation of the historical inflows. A summary of these results is given in Table 2-2.

Model calibration was performed from January 2013 through September 2020 in most basins. While this represents a fairly short timeframe from a climatological perspective, a few larger storm events were present during the 2017 and 2019 water years. (Note: WY 2017 and 2019 were not as wet as WY 2023. Based on nearby river gages, WY 2017 and WY 2019 were about the 85th and 83rd percentile respectively.)

Model parameters were optimized using the University of Arizona's Shuffle Complex Evolution optimization program. Final model parameters and simple reservoir models were configured into CNRFC's CHPS in September 2021.

Forecasting Site	Root mean squared error (RMSE)	Percent Bias (Sim-Obs)	Correlation Coefficient
Sutherland	0.324	-15.68	0.9462
El Capitan	1.608	-17.64	0.7938
San Vicente	0.673	-22.11	0.9440
Hodges	1.129	-15.03	0.9008
Barrett	0.49	-1.52	0.8581

Table 2-2 – Output statistics for daily inflows for the calibration period of record (1/1/2013 -9/1/2020). Note: the large negative bias is partly by design due to the over-estimation of daily inflow volumes in comparison to the monthly inflow volume data.

Note: A negative bias indicates the model under-simulates the observed flow. The large negative bias is partly by design due to the over-estimation of observed daily inflow volumes in comparison to the monthly inflow volume data. Also, the higher RMSE in El Capitan and Hodges is partly due the larger catchment areas and higher observed flows.

During the limited calibration period of record (January 2013 – September 2020), only two to three major inflow events were recorded. The limited observed dataset and associated biases resulted in greater uncertainty in the robustness of the calibrated parameters.

2.4 Performance of Ensemble vs. Deterministic Inflow Forecasts

A. Historical forecasts – Computing Statistical Parameters

In HEFS, the historical forecasts from different sources such as CNRFC, Global Ensemble Forecast System Version 12 (GEFSv12), and climatology are preprocessed to obtain the relative skill of the forecasts for precipitation and temperature. The statistics documented below are for precipitation forecasts used in HEFS. The first three days of forecasts (Days 1-3) are from the CNRFC Quantitative Precipitation Forecasts (QPF) during the historical period of WY 2010-2021. The statistics for the remaining days (Days 4-14) are derived from the precipitation forecasts from the GEFSv12 hindcast for WY 1980-2020. Below is an excerpt from the "HEFS at CNRFC" documentation on the statistical preprocessor called MEFPPE (Meteorological Ensemble Forecast Processor Parameter Estimator):

The HEFS uses statistical parameters to describe the relationships between past forecasts and observations. For temperature, the five parameters listed below are computed for each canonical event by the MEFPPE and saved for operational use by the MEFP.

μ_x = mean of observations

σ_x = standard deviation of observations

μ_y = mean of past forecasts

σ_y = standard deviation of past forecasts

γ = Pearson's product-moment correlation coefficient

Together, the five parameters can be used to define a joint probability surface, with the first pair of parameters defining the marginal distribution of observations and the second pair defining the marginal distribution of past forecasts. The fifth parameter defines how well observations are predicted by forecasts.

To compute the five parameters, the MEFPPE extracts data pairs of forecasts and observations (of precipitation and air temperature) for each available past forecast. For each past forecast, one data pair will be extracted for each canonical event. Next, the MEFPPE pools the extracted data pairs. The CNRFC has configured the MEFPPE to create a pool of data pairs for every fifth calendar day, using 61-day windows. Suppose the first day for which parameters are to be computed is January 1. Then for each canonical event, the MEFPPE pools all data pairs having forecast calendar days within plus or minus 30 days (a 61-day window) of January 1. If a past forecast is available for each day, then the number of data pairs for each canonical event will be equal to 61 times the number of years of past forecasts (11 for HAS QPF, 41 for GEFS). For each canonical event, the five parameters are then computed and saved. The MEFPPE then advances the 61-day time window by 5 days and repeats the process to compute and store the five parameters associated with January 6. The process is repeated until the five parameters have been computed and stored for every fifth day of the calendar year. Operationally, the MEFP adopts the parameter set corresponding to the "fifth day" nearest to the current forecast day.

B. Correlation statistics for selected basins

Below are the correlation statistics for precipitation forecasts at different lead times. Forecast statistics were gathered from forecasts made during the months of December–March. The first 3 days of precipitation forecasts are from the CNRFC HAS forecasters. Days 4-14 are from the GEFSv12 ensemble forecasts.

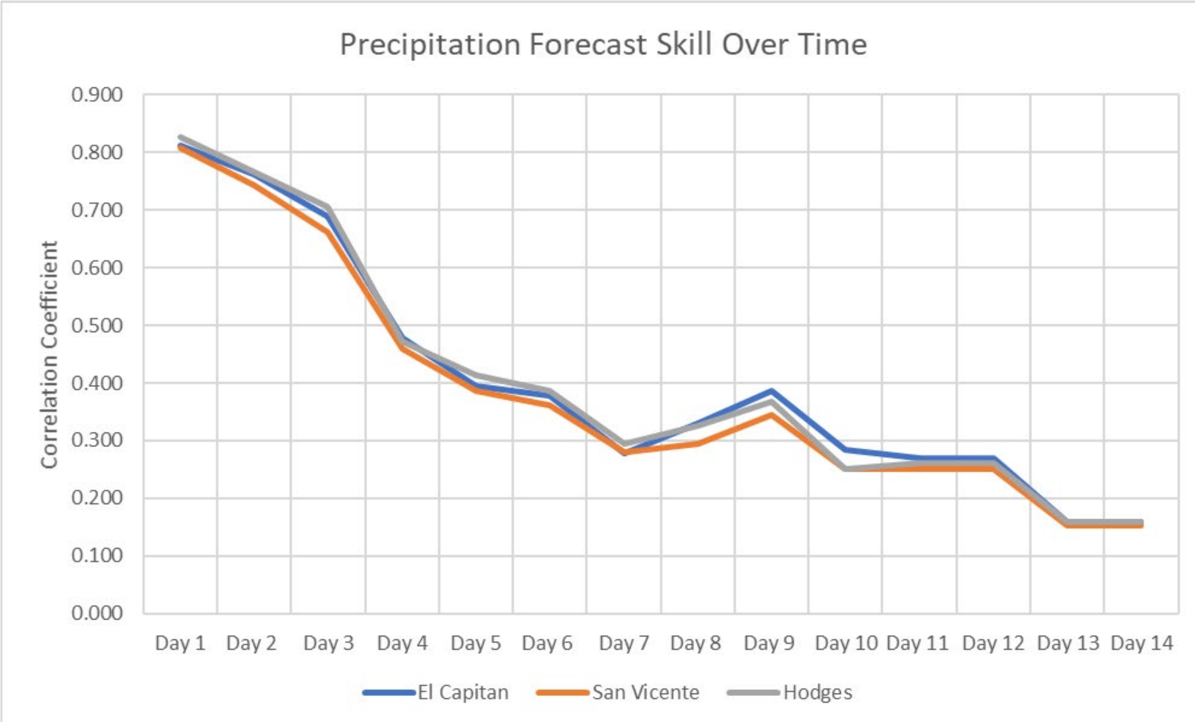

Figure 2-1 – Precipitation Forecast Skill Over Time

All three watersheds had very similar correlation statistics with correlation decreasing as the lead time of the forecast increased. Hodges Reservoir appeared to have slightly better statistics than the other two reservoirs. The slight rise in correlations for Days 8 and 9 is due to a change in aggregations of the forecasts and is not an indication that forecasts in these periods are better than Day 7. Overall, the skill of forecasts in the week 2 time period (Days 8-14) is very poor.

In Figures 2-2 and 2-3 below, Day 1 and Day 3 precipitation forecast skill from two sources are compared. The CNRFC forecasts were consistently better than the GEFSv12 forecasts.

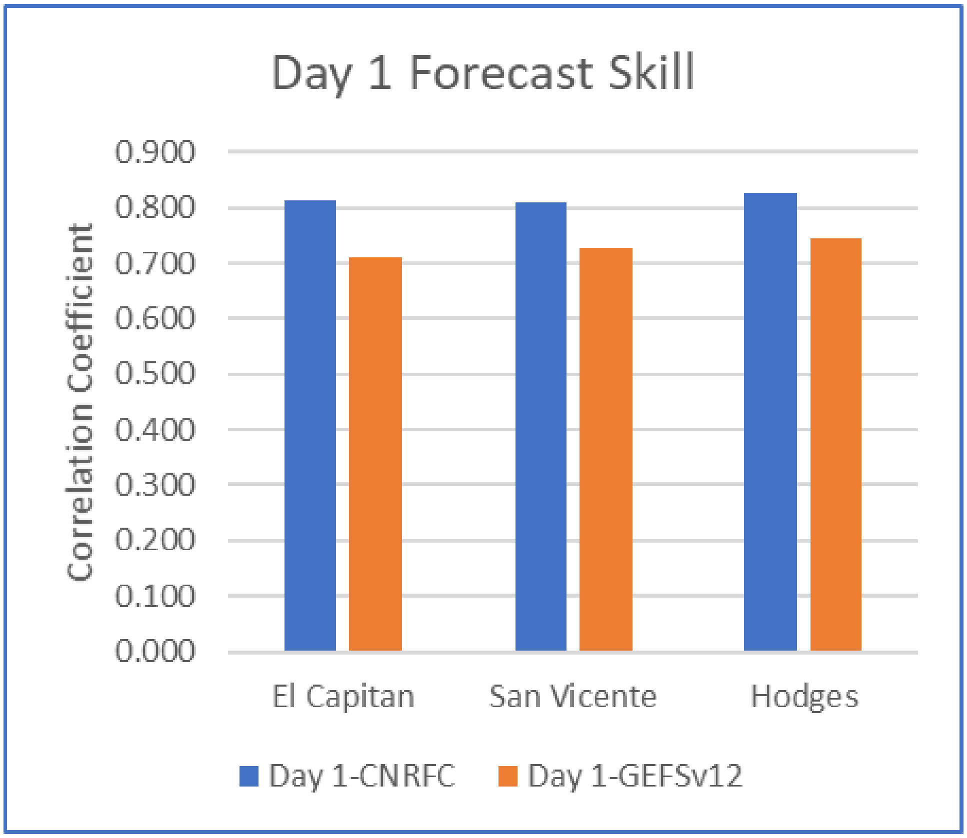

Figure 2-2 – Day 1 Forecast Skill

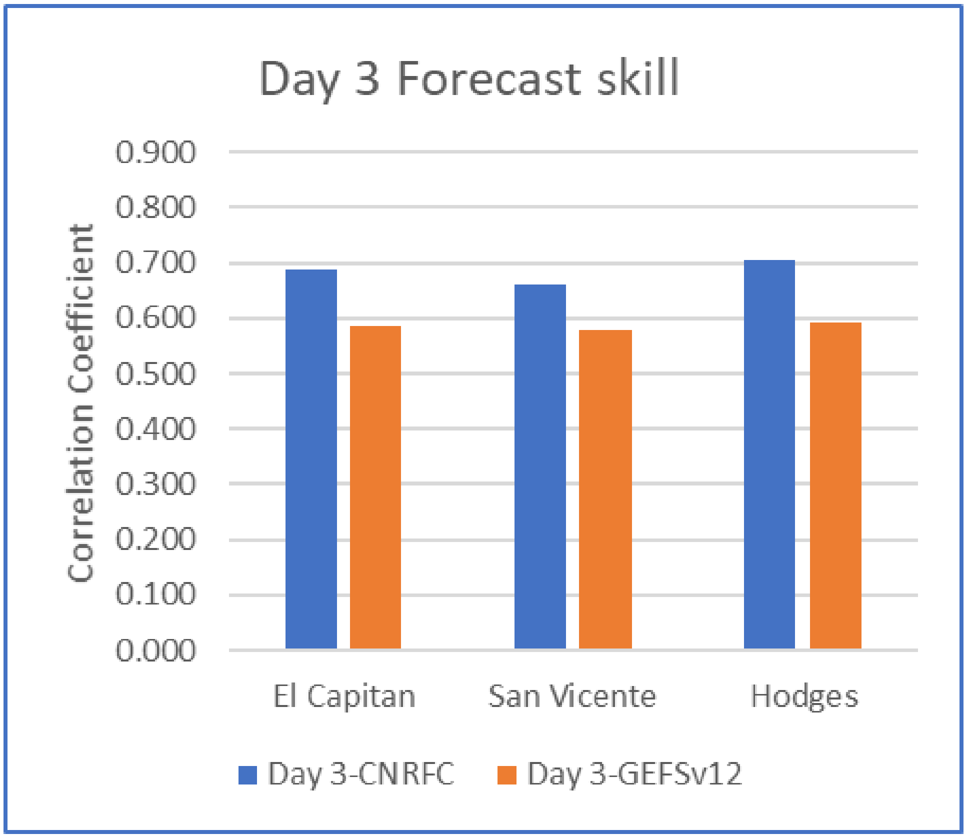

Figure 2-3 – Day 3 Forecast Skill

Chapter 3 – GoldSim Modeling of FIRO Scenarios

In December 2018, Reclamation published the San Diego Basin Study which analyzed potential climate change impacts on water supplies and demands within the San Diego region and identified potential mitigation strategies that could mitigate supply shortages. As part of the study, the CWASim model was developed using the GoldSim modeling platform to represent the system and simulate different scenarios. In this work, we used the Baseline model of CWASim as the basis for a model to investigate the utility of implementing FIRO in COSD's reservoir system. We will refer to the resulting model as SDFIROSim.

3.1 Review of San Diego Watershed Basin Study GoldSim Model

This review is based on the CWASim Master Plan Aqueduct System Model Documentation (San Diego County Water Authority, June 2015) of the current climate scenario Baseline model. We note that two versions of CWASim were developed for the Basin Study: Baseline and Baseline+. These two versions represent different portfolios of potential projects being considered within the San Diego water system. COSD recommended using the Baseline version for this study, as the additional projects considered in Baseline+ are not expected to be implemented, with the exception of Pure Phase I. Thus, the Baseline model can be used for the FIRO study with Pure Phase I turned on in the GoldSim dashboard. The model review in this section focuses on the Baseline model (with particular attention to the COSD portion of the system) as described by the CWASim Master Plan Aqueduct System Model Documentation.

The Baseline model divides the water system into four main containers (GoldSim's term for model components): South, Central, First Aqueduct, North. For brevity, this review focuses on operations within the South Container, including reservoir operations, demands, and water treatment. Additional details on operations relevant for all COSD reservoirs can be found in Appendix A.

It should be noted that the objective of CWASim was to create a modeling tool for planning purposes with operational rules based on Water Authority staff experience with historical operations. However, it can be expected that these rules may be changed in the daily operation of the system.

South Container

The South container has 10 reservoir containers, 12 demand containers, 1 tank container, and 5 water treatment plant (WTP) containers. The model schematic of the system is given in Figure 3-1.

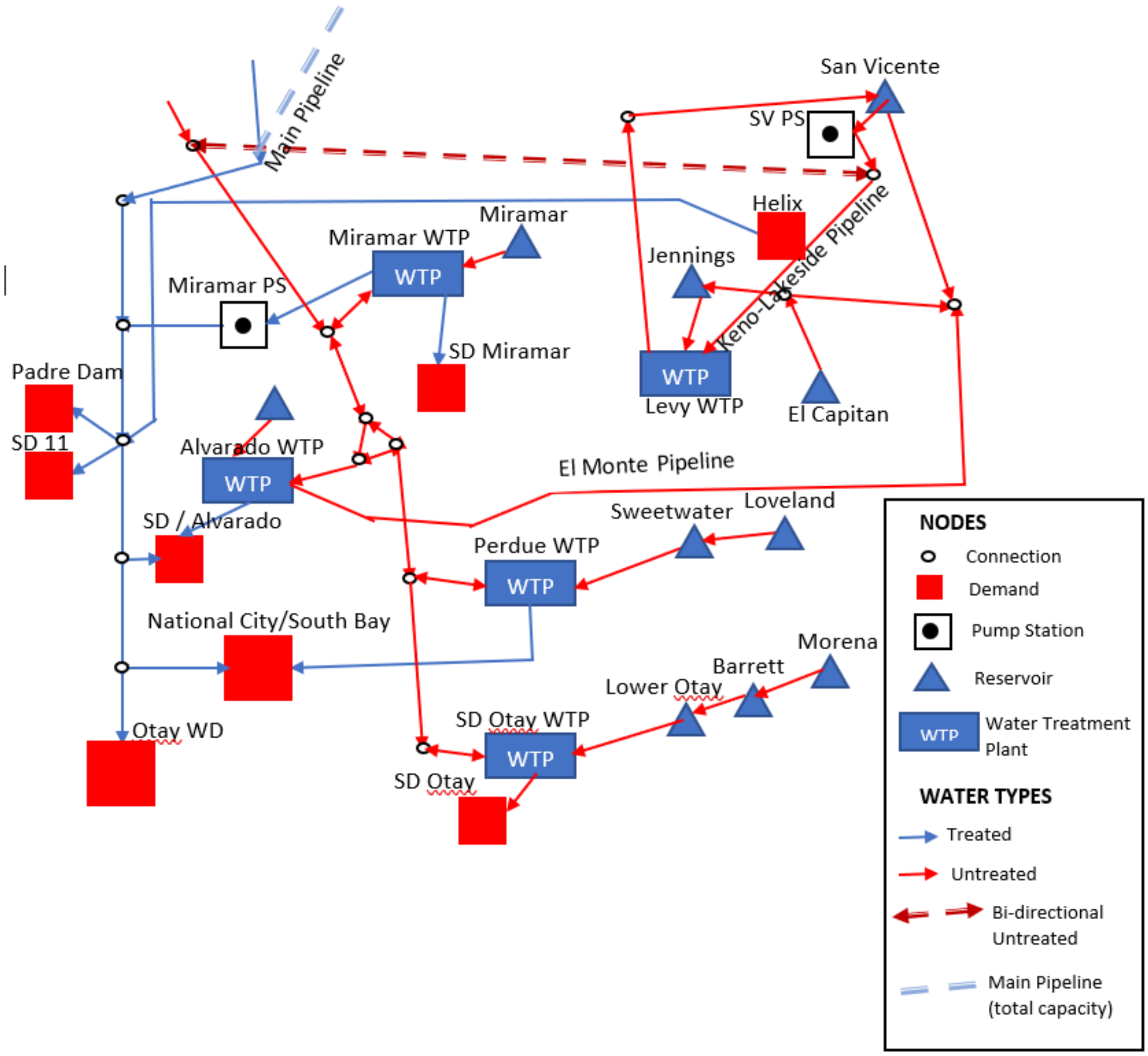

Figure 3-1 – CWASim South Container

In general, the operations represented in CWASim are a function of the physical attributes and constraints of the system (e.g., pipe capacities, connectivity, flow directions) and historical operations (e.g., reservoir storage zones and associated rules). Some representative examples of these operational rules in CWASim are given below. For more details, please see Appendix A at the end of this report and the CWASim Model Documentation (San Diego County Water Authority, 2015).

Morena/Barret/Lower Otay Reservoir System

Starting at the southern end, the Morena, Barrett, and Lower Otay reservoirs form a connected system leading to the Lower Otay WTP. These reservoirs have a combined storage capacity of 138 TAF. Morena is recharged by local runoff and spills into Barrett based on COSD’s rule curve. Lower Otay receives water primarily from Barrett. Zone 2 of Lower Otay can also be filled by Metropolitan Water District (MWD) water delivered from the aqueduct, following Barrett releases. The maximum storage values of Morena, Barrett, and Lower Otay adding up to 138 TAF are given in Appendix A, along with their minimum storage values, maximum release capacities, and operating rules.

The operating rules for Morena are as follows. Inflows are given by the monthly hydrology of the current climate scenario. Outflows are given by

$$\text{Outflow} = \text{Evaporation} + \text{Releases} + \text{Flood Releases}$$

where Releases corresponds to requests made by Barrett. Flood Releases are given by

$$\text{Flood Releases} = \text{MAX}\{0, \min[\text{maximum release}, (\text{Storage} - \text{Minimum Storage})/1 \text{ day}, (\text{ZS.z1} + \text{ZS.Unused})/1 \text{ day}) - \text{Releases}\}$$

where ZS.z1 = storage of the flood zone = 7,432 acre-feet. The term ZS.Unused is a placeholder for storage outside of the eight reservoir zones and in general is equal to zero.

Evaporative losses are given by the scaling relationship

$$\text{Losses} = 0.12 * \text{Releases}$$

Releases from Morena flow into Barrett, and releases from Barrett flow into Lower Otay. The releases from Lower Otay flow into the WTP. The WTP has a capacity of 34 million gallons per day (MGD). (Note that the CWASim documentation incorrectly states the capacity as 40 MGD whereas the Basin Study lists the capacity at 34 MGD.) Otay WTP also receives raw water from Pipeline 3.

Releases from Otay WTP are given by

$$\text{Releases}_{\text{WTP}} = \text{Releases}_{\text{Demand}} + \text{Deliveries}_{\text{OtayTunnel}}$$

In general (anywhere in the system), demands can be met by seven different sources: water treated from local storage and treated at a local WTP; MWD raw water that is treated at a local WTP; TOVWTP treated water from Pipeline5; MWD treated water from Pipeline 4 or 1 & 2; desalinated CP water; desalinated Carlsbad water; San Vicente water.

El Capitan Reservoir

CWASim represents El Capitan Reservoir using bathymetry from a 1954 survey. A more recent bathymetric survey was completed in 1998. However, COSD uses rule curves based on the 1954 survey for their operations. Due to this plus the fact that another survey is being planned within the next two years, COSD advised not to update the rule curves using the 1998 survey, but rather to use the existing curves in the model unmodified.

3.2 CNRFC Inflow Forecast-Supported GoldSim Modeling Results

The baseline model is adapted from the Basin Study current conditions 2015 demand model. Changes have been made to the Basin Study model in order to implement FIRO strategies. First, the simulation period was changed from the Basin Study's 100 years to 7 years (2013-2020). Second, input reservoir inflow dataset was changed from CWA's monthly time step dataset to the daily time step dataset that provided by the city and processed by the project team. Third, initial reservoir storage was changed to the storage observed on January 1, 2013.

After the above-mentioned changes, the baseline model was calibrated using the processed reservoir dataset. The goal of the calibration is to make the model produce comparable storage and delivery levels. The demands were adjusted for this purpose. The demands in the Basin Study model followed the projected demands in the CWA 2013 planning study. However, in real-time simulation practices, changing demands is legitimized as long as reality is reflected in the simulation. For example, for El Capitan reservoir, the simulated results were compared with the processed dataset after a test run. The simulated storage was significantly lower than the observed storage. By comparison, the model made much more deliveries than the observed water drafted from El Capitan. Plus, the model also made releases which never happened in reality. After turning off the reservoir release, the simulated storage was still much lower because water from El Capitan has been sent to Alvarado WTP for treatment and then delivered to meet demand from Alvarado Demand Unit. The original demand for Alvarado Demand Unit was 68,402 acre-feet annually. A different reduction ratio was tested. It was found that with 70% reduction of the Alvarado Demand Unit demand, the simulated reservoir storage was able to be at a level that was comparable to observation. Figure 3-2 shows that when the actual draft was used as the release for demand, the calibrated model was able to produce an identical storage level. This indicates that the calibrated model was able to maintain overall mass balance. Figure 3-3 shows that when demand for the Alvarado Demand Unit was reduced by 70%, the model was able to produce a comparable storage level. Figure 3-4 shows that the total release for demand was close to actual draft. However, the shape of the release follows the shape of demand but nowhere near the shape of actual draft. This indicates that the actual draft was not driven by demand; rather, it was driven by operating decisions.

El Capitan Reservoir

For El Capitan, the reservoir was restricted at 700 ft elevation. When the forecasted inflow pushes the reservoir above 700 ft, FIRO operation is started and pre-drawdown water delivered to Alvarado and Levy WTPs. Pre-drawdown is limited by the El Capitan Pipeline, which has a 50 MGD capacity. If after pre-drawdown, the lake level still increases above 700 ft, then the blowoff will be opened. However, in real operation, this scenario never happened during the simulation period. The reservoir seldom reached 700 ft elevation.

A pre-season drawdown to 680 ft elevation for El Capitan was also coded and tested in the model. The pre-season was defined as the period from May 1 to November 1. Anytime during this period, delivery to the WTP is maxed whenever the lake level is above 680 ft elevation until it goes below. Since the pre-season drawdown forced the lake to maintain a lower level before the wet season, the simulation found no FIRO operation needed in the historical period.

Figures 3.3-3.5 shows that with the implementation of pre-season drawdown, the simulated storage is much lower. As shown in Figure 3-6, pre-season drawdown happened during 2013, 2017, and 2019. No FIRO operation is triggered.

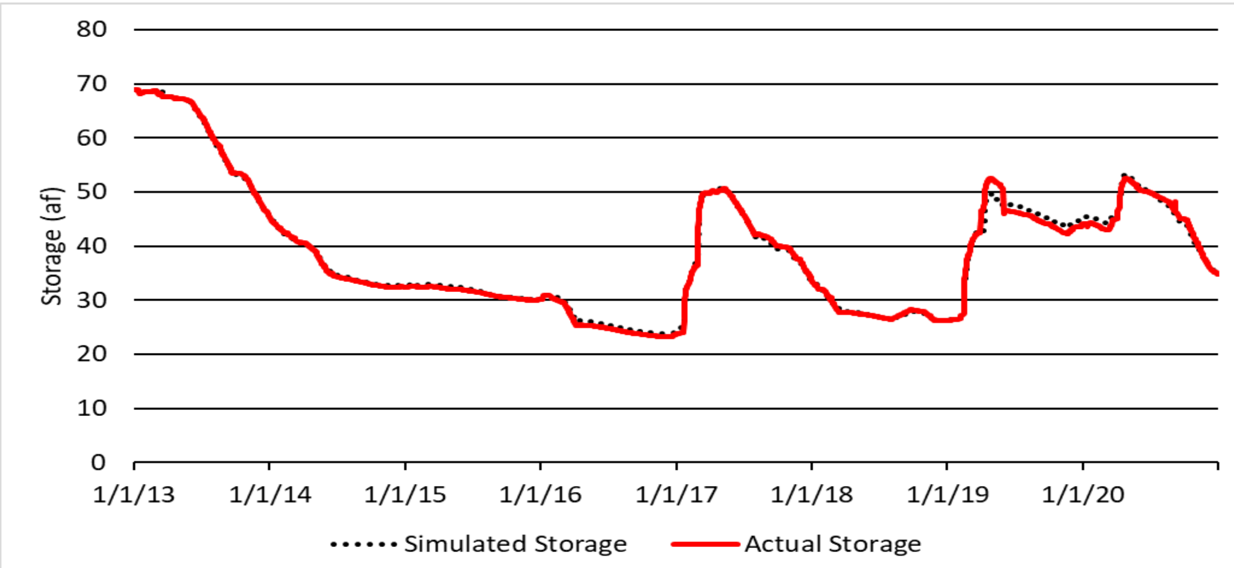

Figure 3-2 – El Capitan Reservoir, storage comparison with actual draft was used as delivery.

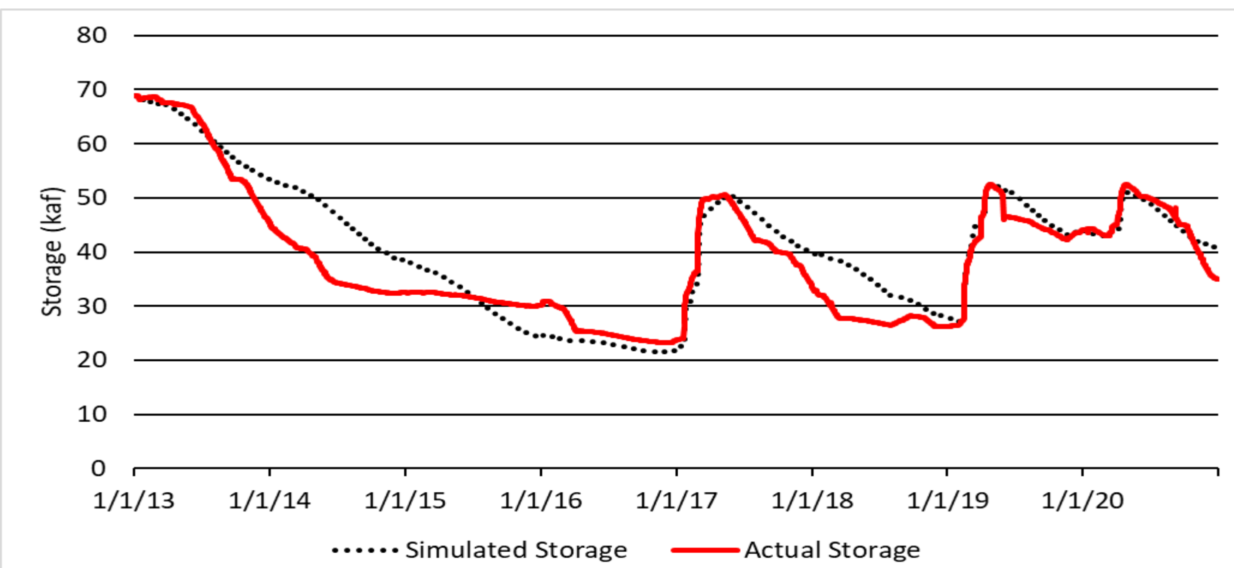

Figure 3-3 – El Capitan Reservoir, storage comparison with reservoir release turned off and Alvarado Demand Unit demand reduced by 70%.

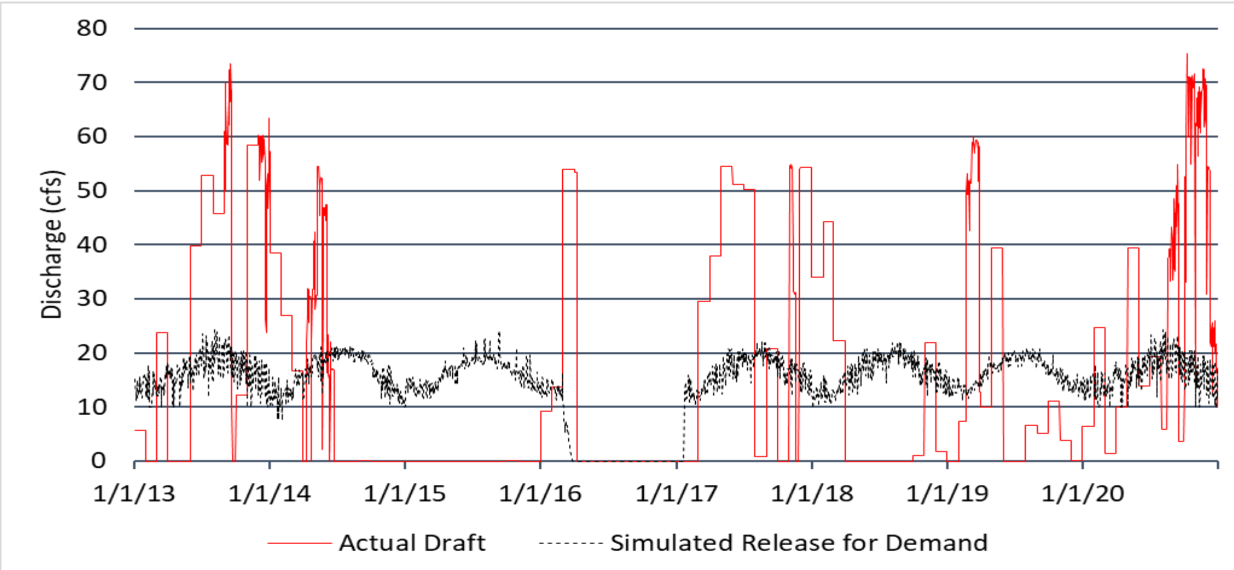

Figure 3-4 – El Capitan, comparison of release for demand and actual draft with reservoir release turned off and Alvarado Demand Unit demand reduced by 70%.

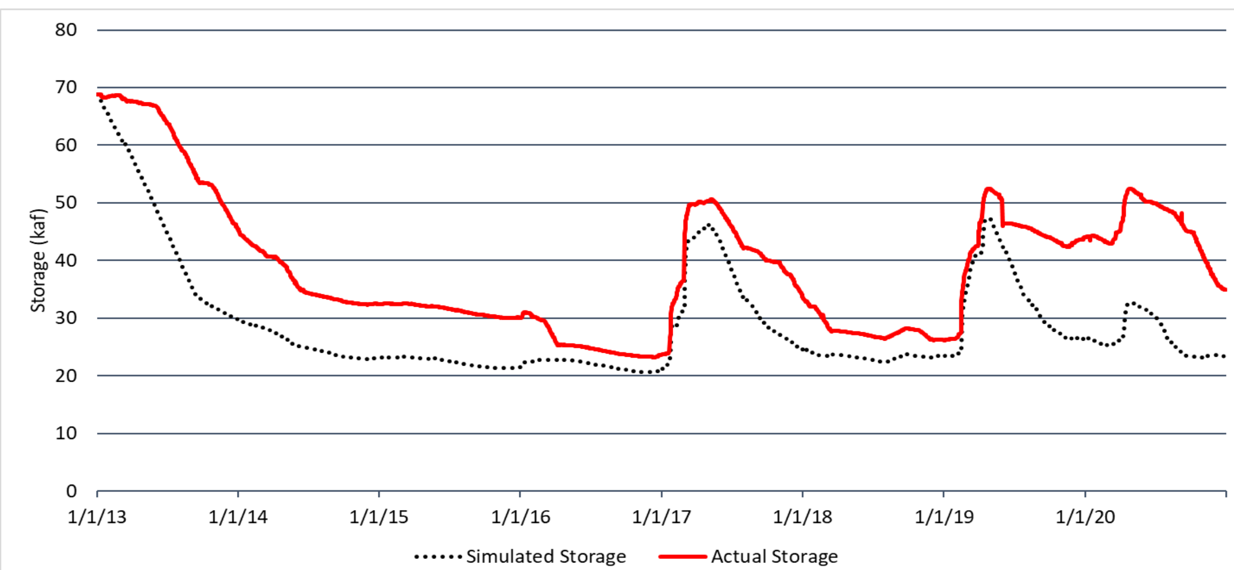

Figure 3-5 – El Capitan Reservoir, comparison of storage using calibrated model and 680 ft pre-season drawdown level restriction.

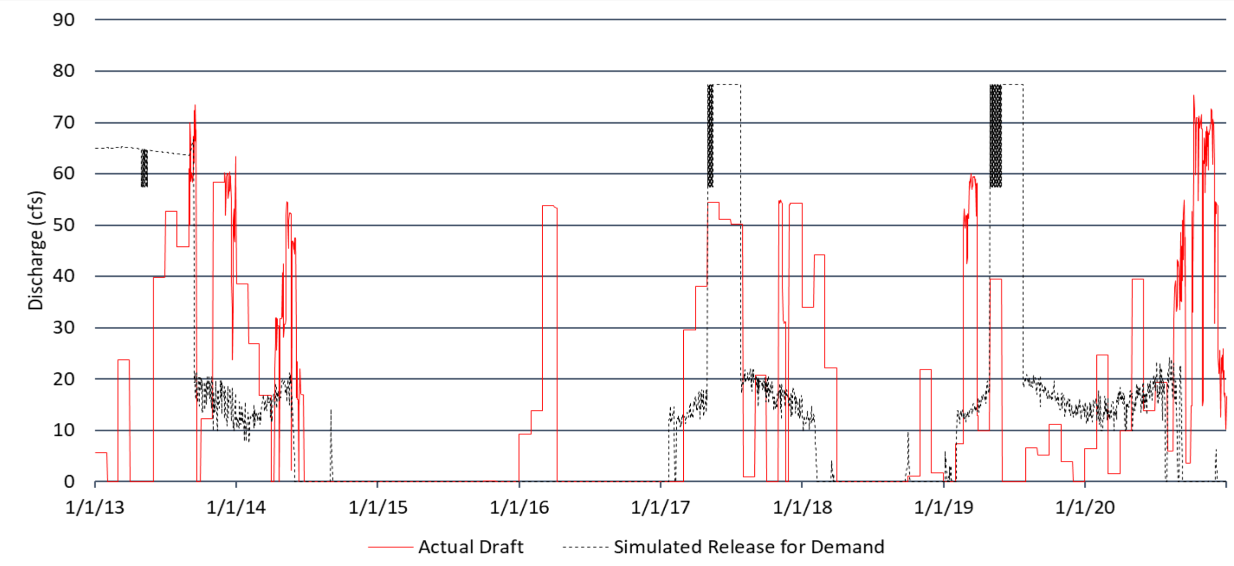

Figure 3-6 – El Capitan Reservoir, comparison of release for demand and actual draft using calibrated model with 680 ft pre-season drawdown level restriction. Pre-season drawdown only happened during 2013, 2017, and 2019.

Hodges Reservoir

Similar to El Capitan, reservoir restrictions and FIRO strategies were put in place for Hodges reservoir. For Hodges, the reservoir was restricted at 295 ft elevation. When the forecasted inflow pushes the reservoir above 295 ft, FIRO pre-drawdown will be started and the extra water above 295 ft elevation will be moved to Lake Olivenhain. Pre-drawdown water is passed through Lake Olivenhain and placed in a virtual storage facility. This arrangement makes sense because the processes of moving and utilizing the pre-drawdown water are still in the working. However, in case that the reservoir level exceeds 295 ft for more than 10 days, or at any time the reservoir level exceeds 297 ft, the blowoff of the dam will be opened to discharge water until the reservoir remains at or under 295 ft.

Figure 3-7 shows the simulated and actual reservoir storage for Hodges without FIRO operation. Figure 3-8 shows the difference between simulated release for demand and the actual draft before any FIRO operations was made. The total amount delivered in the model was close to the actual draft, but the shape was nowhere close. This means that the total demand is relatively close to actual but the delivery does not follow a preset pattern. Rather, it is dictated by situational operating decisions. Figures 3.9 and 3.10 show the storage and release with FIRO operations. FIRO operations happened in 2017, 2019, and 2020. During the simulated period, FIRO operation made a total of 46,148 ac-ft pre-drawdown delivery to prevent spill, as shown in Figure 3-11. The pre-drawn delivery is 5,770 acft/year averagely. This amount of water is the benefit of implementing FIRO operation, which would otherwise be a loss.

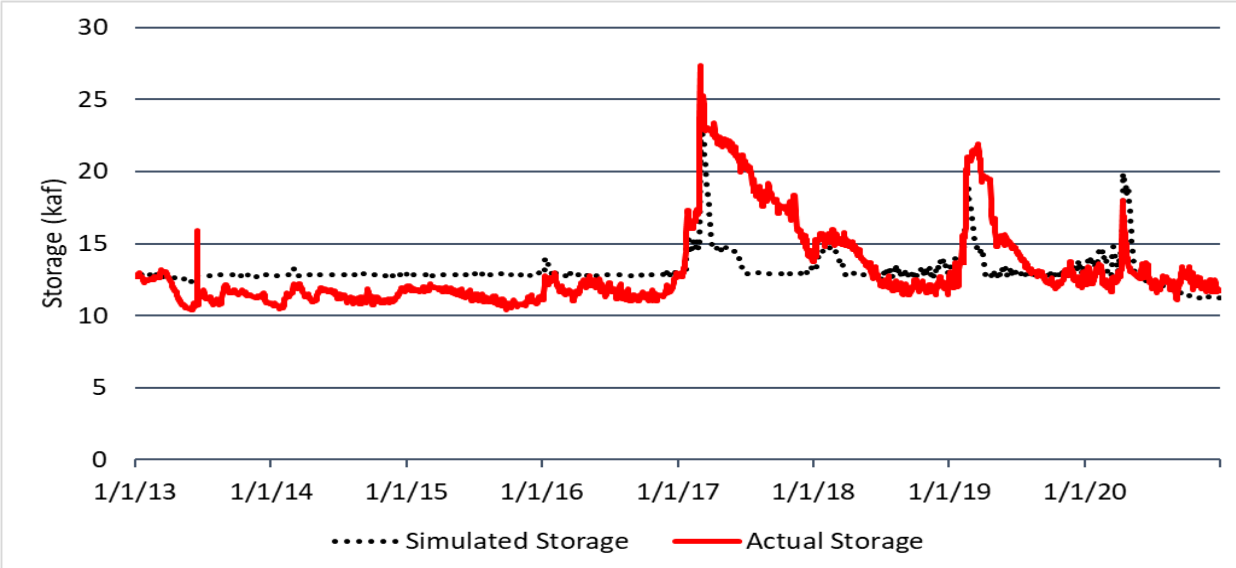

Figure 3-7 – Storage comparison, Hodges Reservoir without FIRO operation.

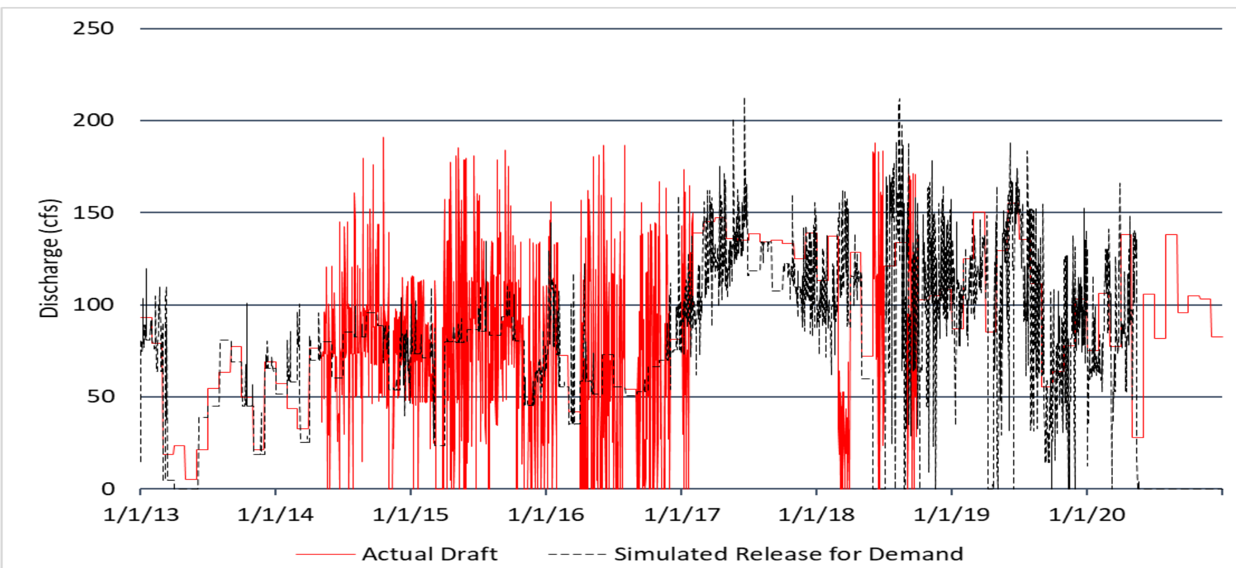

Figure 3-8 – Comparison of release for demand and actual draft, Hodges Reservoir without FIRO operation.

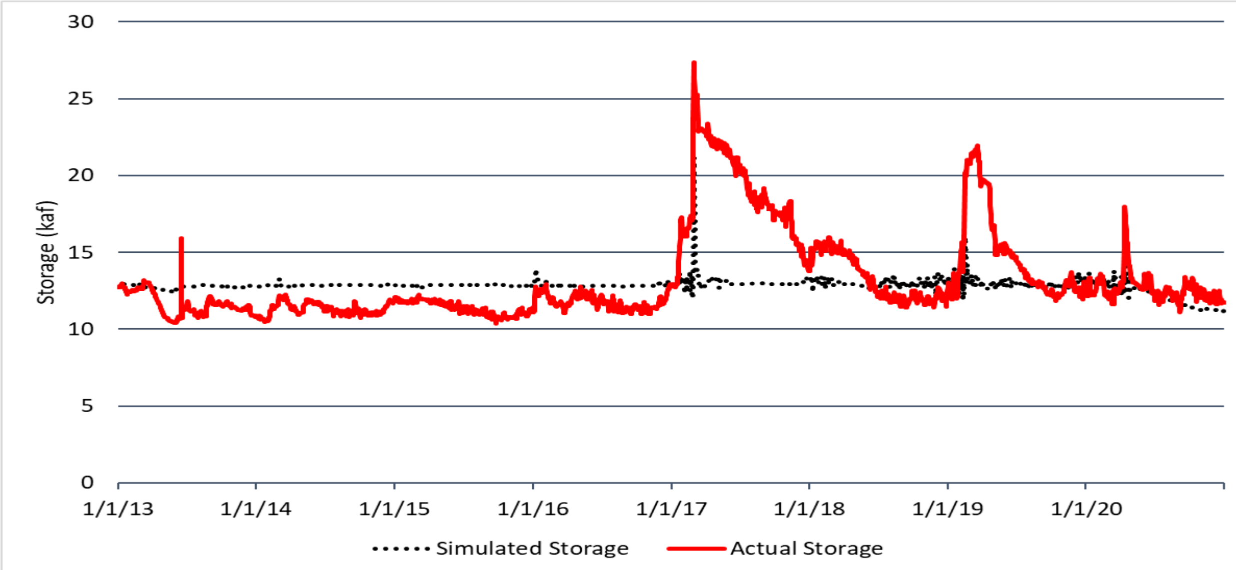

Figure 3-9 – Storage comparison, Hodges Reservoir with FIRO operation.

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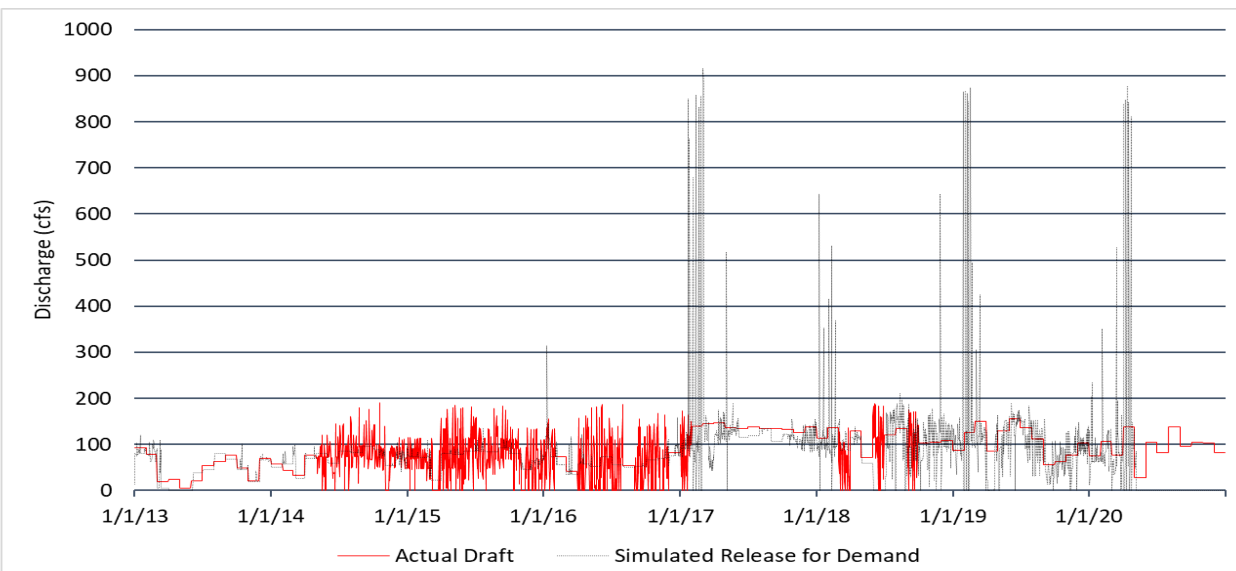

Figure 3-10 – Comparison of release for demand and actual draft, Hodges Reservoir with FIRO operation.

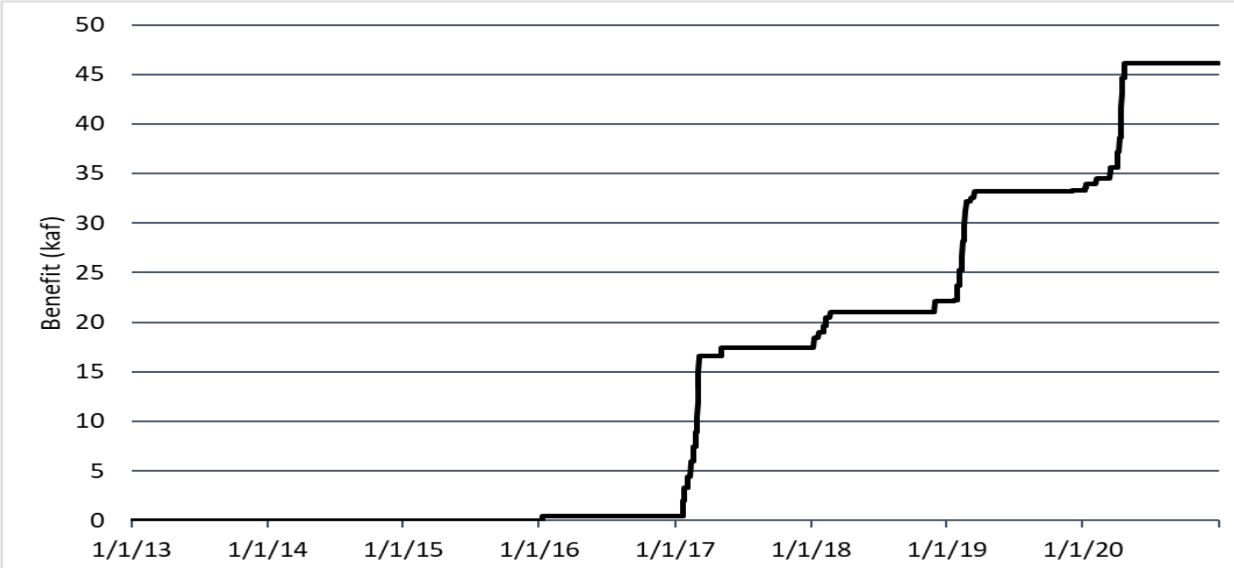

Figure 3.11 – FIRO Pre-Drawdown Release, accumulated for Hodges.

San Vicente, Sutherland, Morena, Barrett, and Lower Otay Reservoirs

Figures 3-12 through 3-21 show the storage and release comparisons for San Vicente, Sutherland, Morena, Barrett, and Lower Otay Reservoirs. For San Vicente, both storage and release for demand are very comparable. For Sutherland and Morena, draft from the reservoir is scarce and random. Therefore, Sutherland is forced to release water to meet demand only when there is actual draft. Similarly, Morena is forced to release as actual drafted. Barrett is forced to release only in times when there is draft but the total release is made to be comparable to actual draft. The reduced release from Barrett affects the simulation for Lower Otay, in which both storage and release are lower.

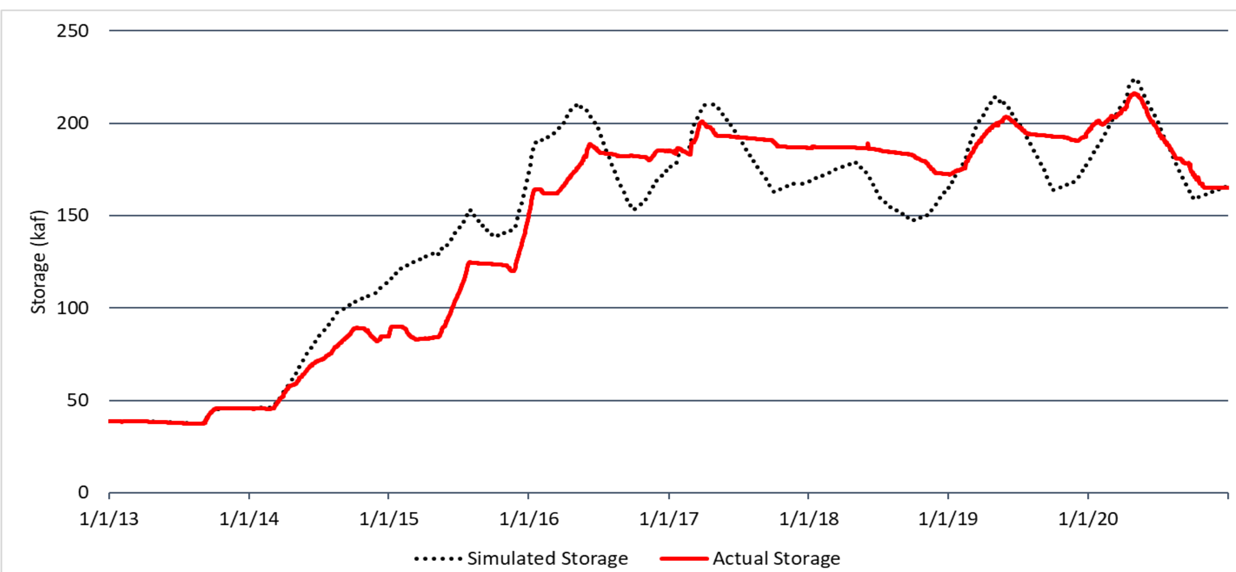

Figure 3-12 – San Vicente Reservoir, comparison between simulated and observed storage.

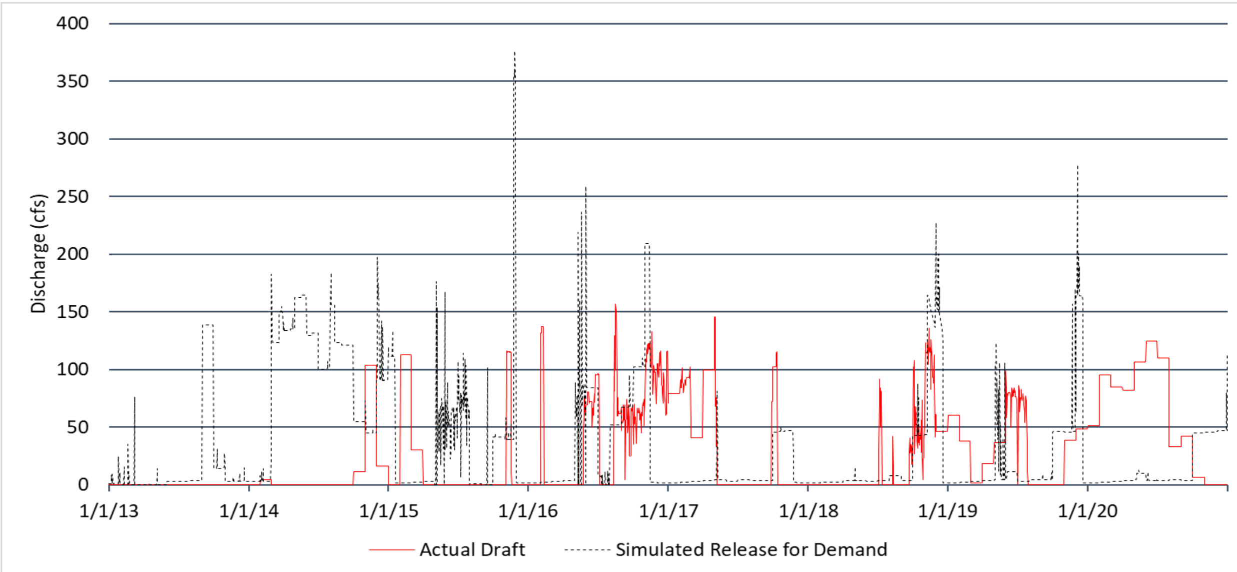

Figure 3-13 – San Vicente Reservoir, comparison between simulated release and actual draft.

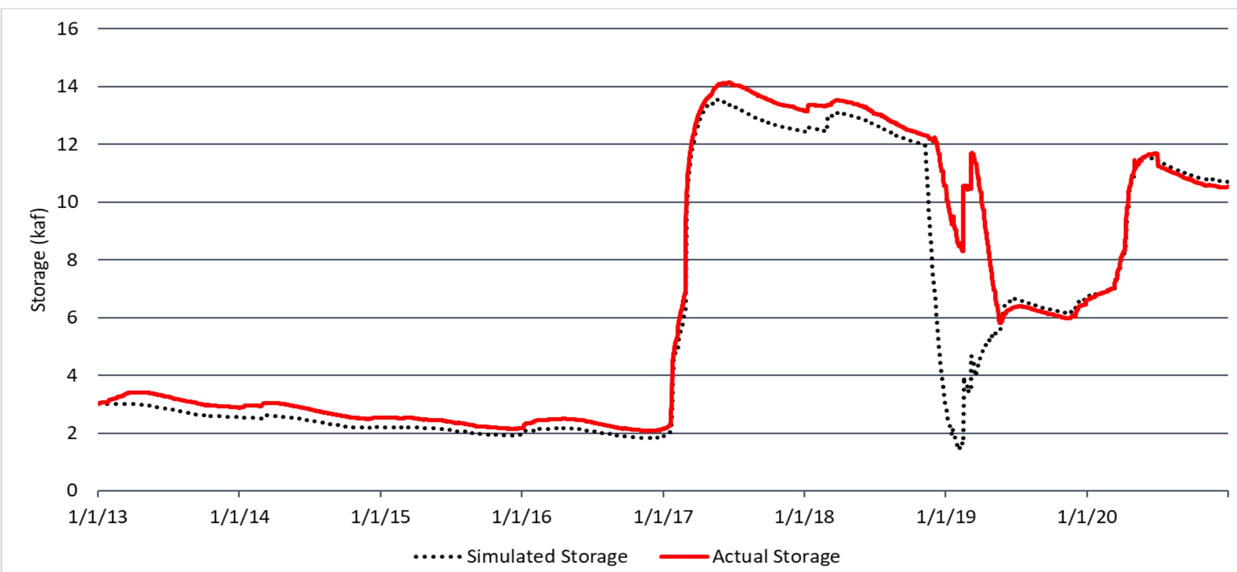

Figure 3-14 – Sutherland Reservoir, comparison between simulated and observed storage.

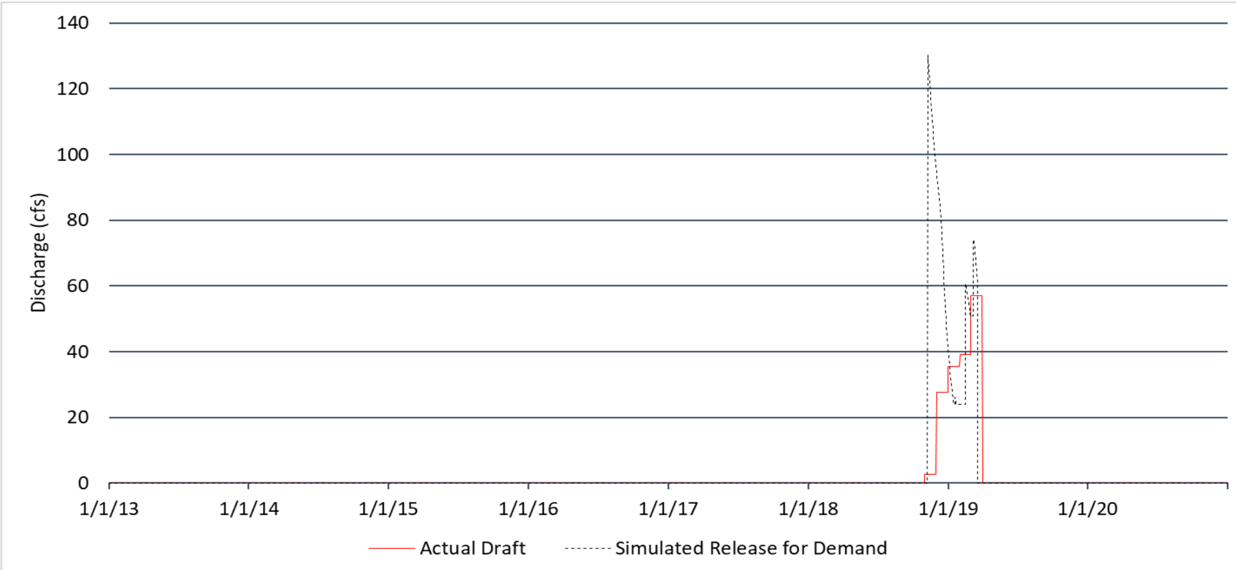

Figure 3-15 – Sutherland Reservoir, comparison between simulated release and actual draft.

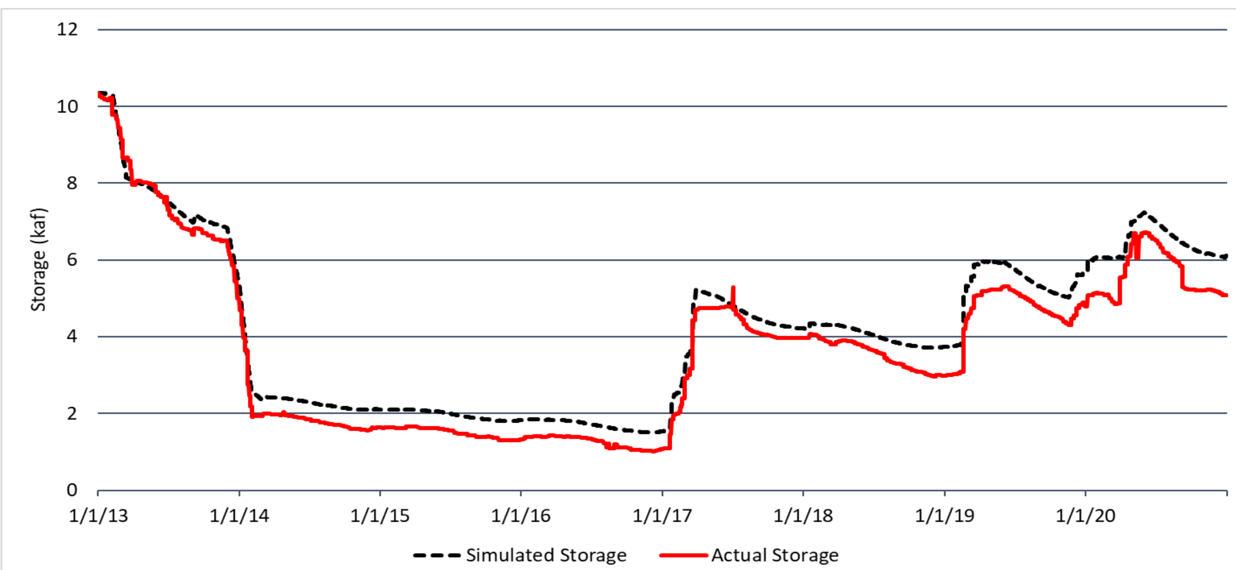

Figure 3-16 – Morena Reservoir, comparison between simulated and observed storage.

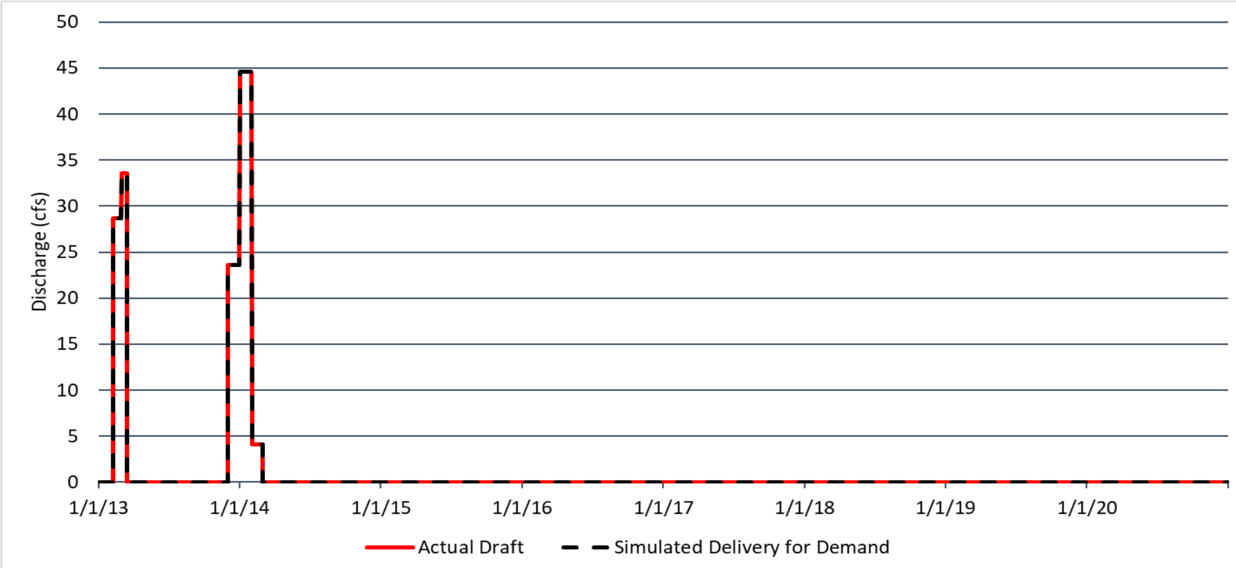

Figure 3-17 – Morena Reservoir, comparison between simulated release and actual draft.

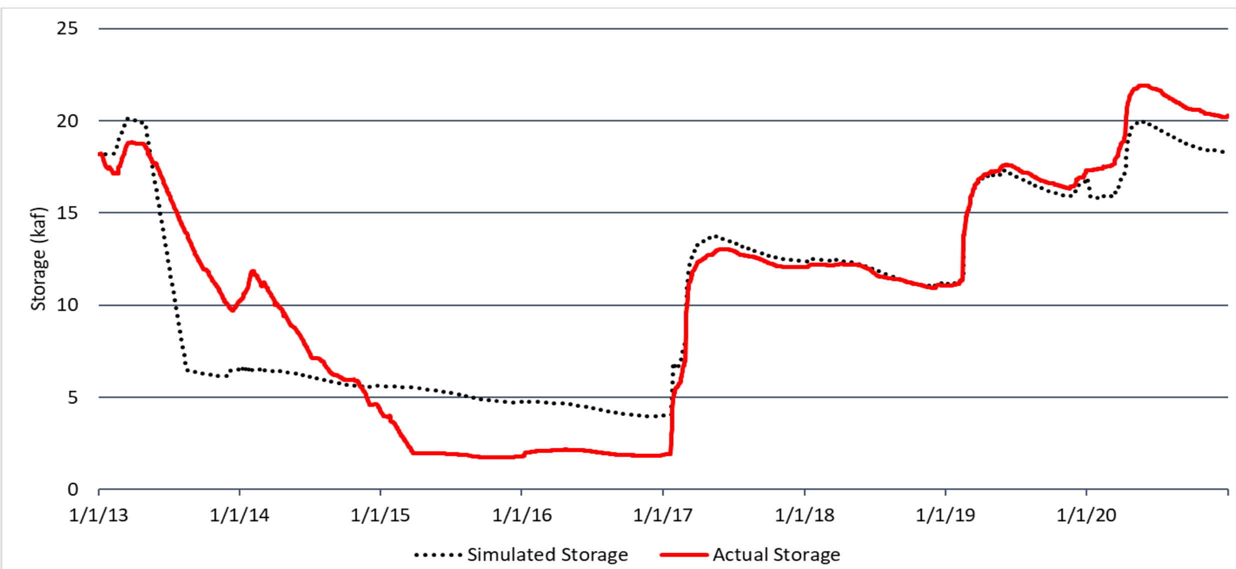

Figure 3-18 – Barrett Reservoir, comparison between simulated and observed storage.

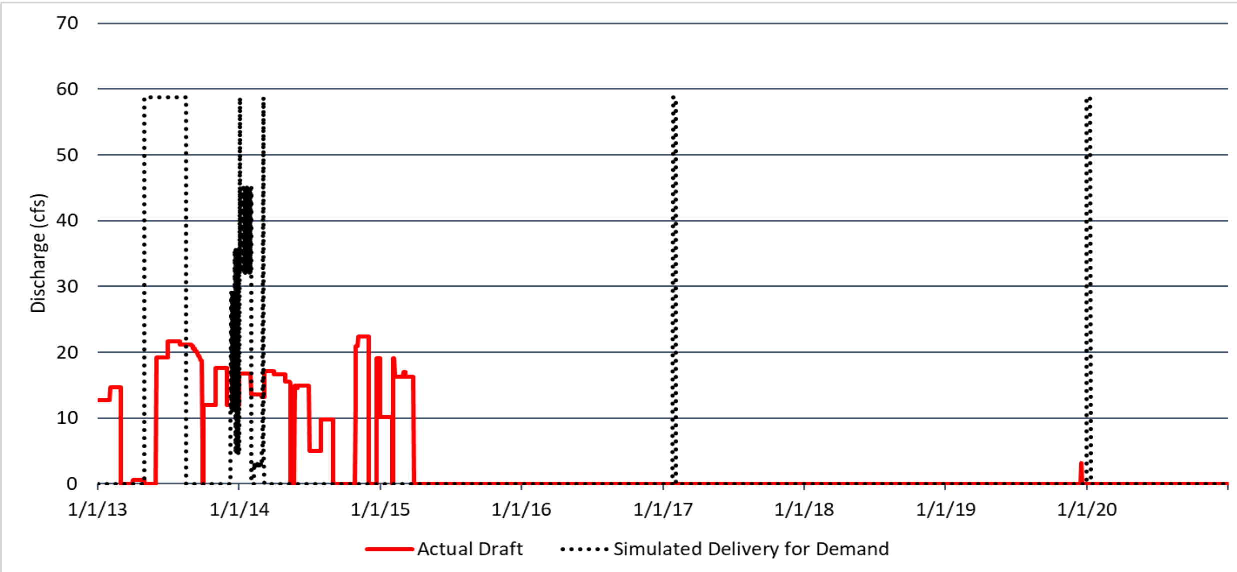

Figure 3-19 – Barrett Reservoir, comparison between simulated release and actual draft.

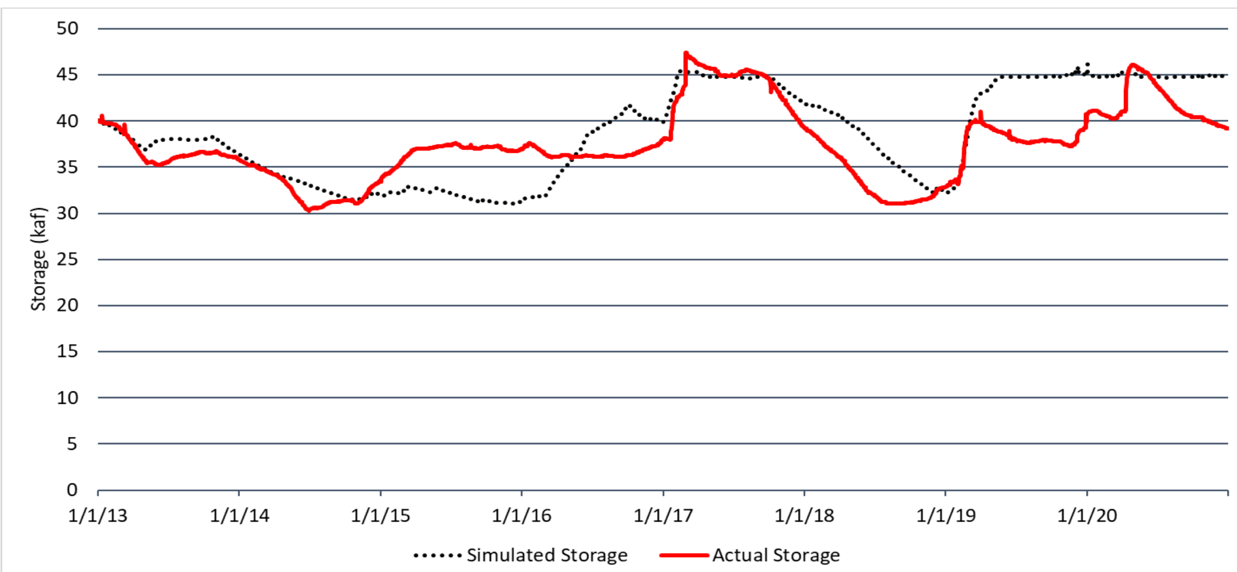

Figure 3-20 – Lower Otay Reservoir, comparison between simulated and observed storage.

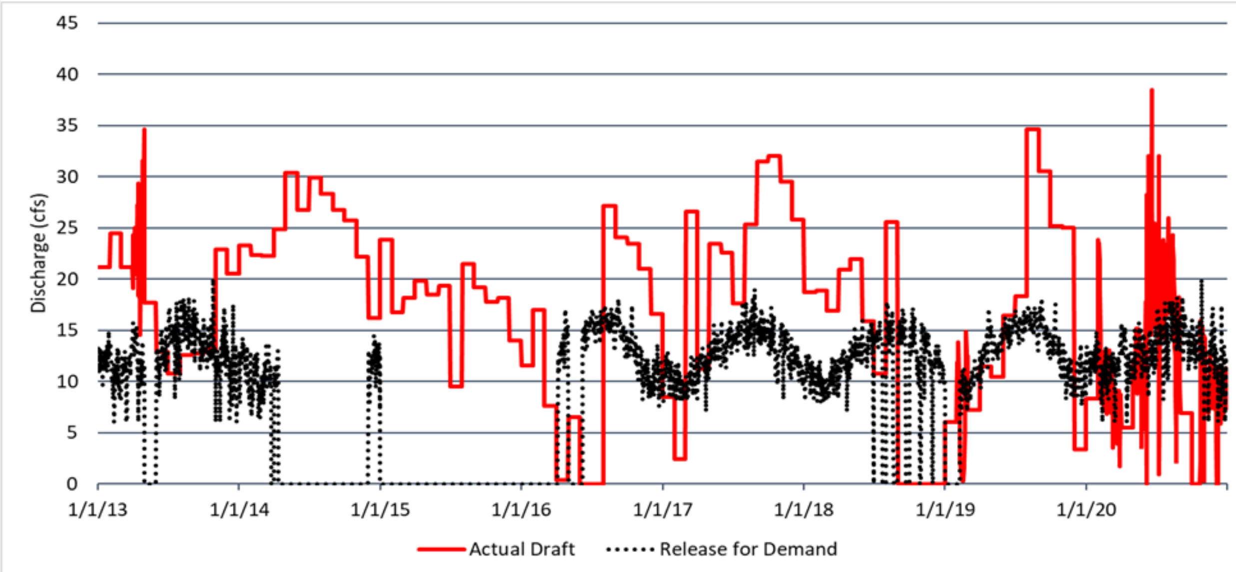

Figure 3-21 – Lower Otay Reservoir, comparison between simulated release and actual draft.

Current Condition Model Performance with the Performance Matrix

The FIRO baseline model was applied to the historical period with available daily inflow data. Performance of each of the reservoirs and the whole city reservoir system is shown below.

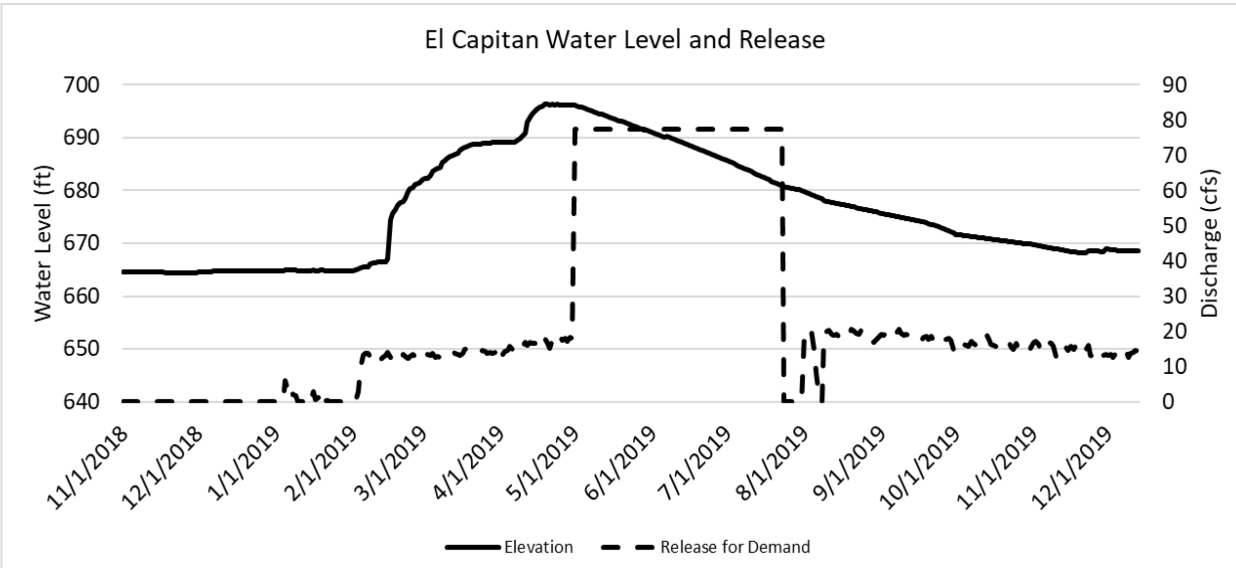

Figure 3-22 – El Capitan Reservoir operation comparison during biggest historical storm event.

This chart shows El Capitan Reservoir operations during the biggest storm event; peak discharge accounts for about 5% probability in the current condition period, water year 2019. It can be seen that the reservoir never reached the 700 ft level, therefore no FIRO operation is triggered. The pre-season drawdown happened when water reached 680 ft and above. This operation lowered the reservoir further in a position that helps flood management during the wet season.

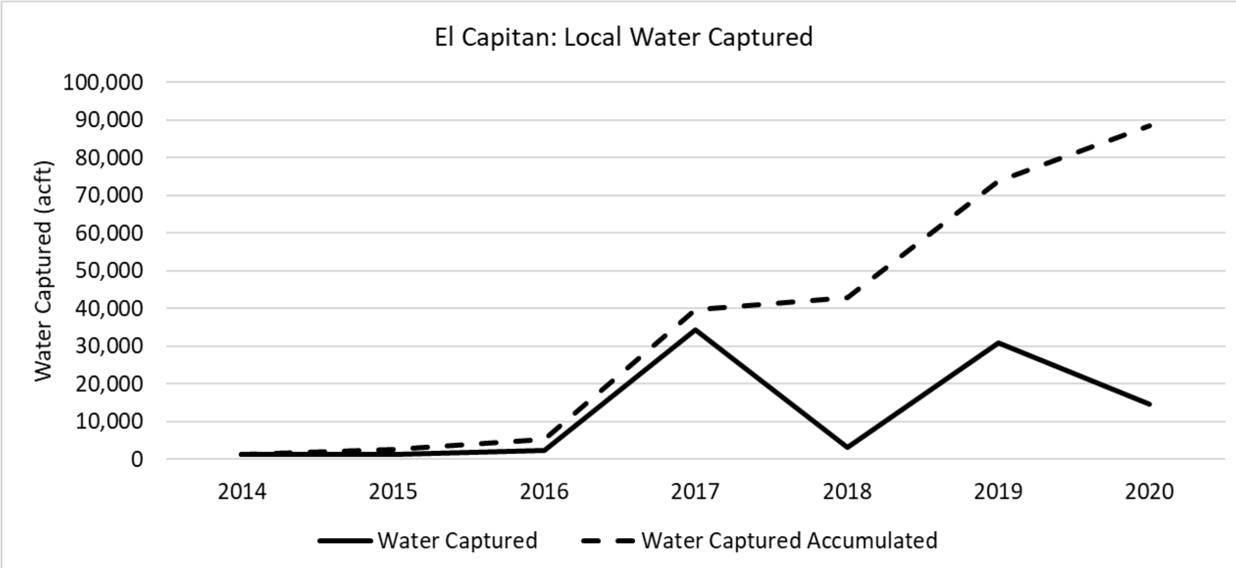

Figure 3-23 – Local water captured in El Capitan Reservoir.

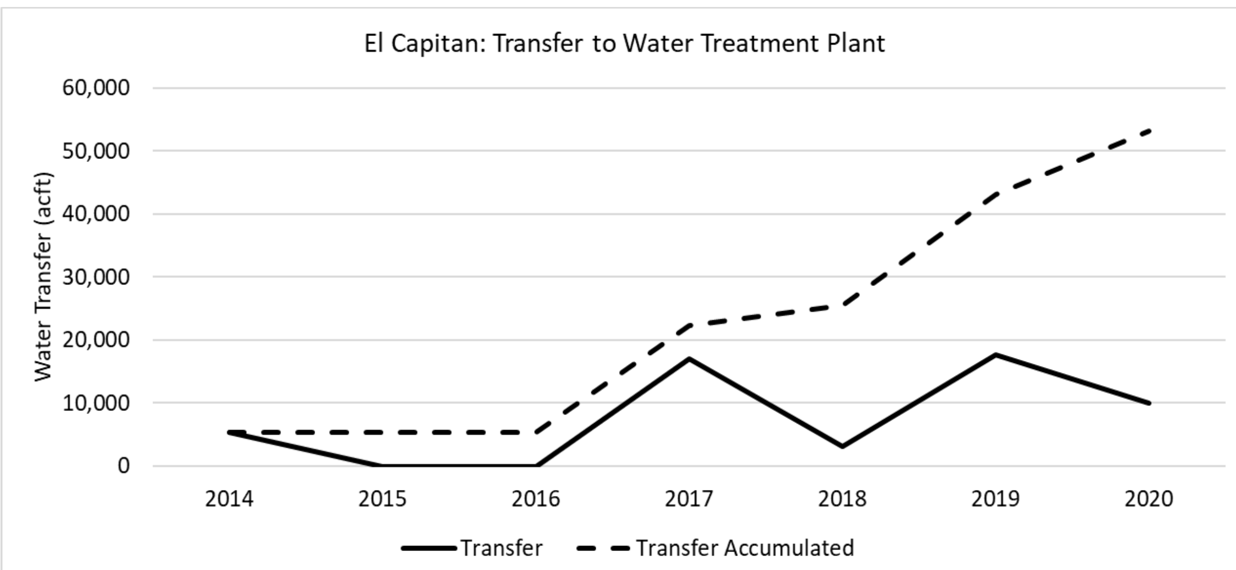

Figure 3-24 – Water transferred to water treatment plants.

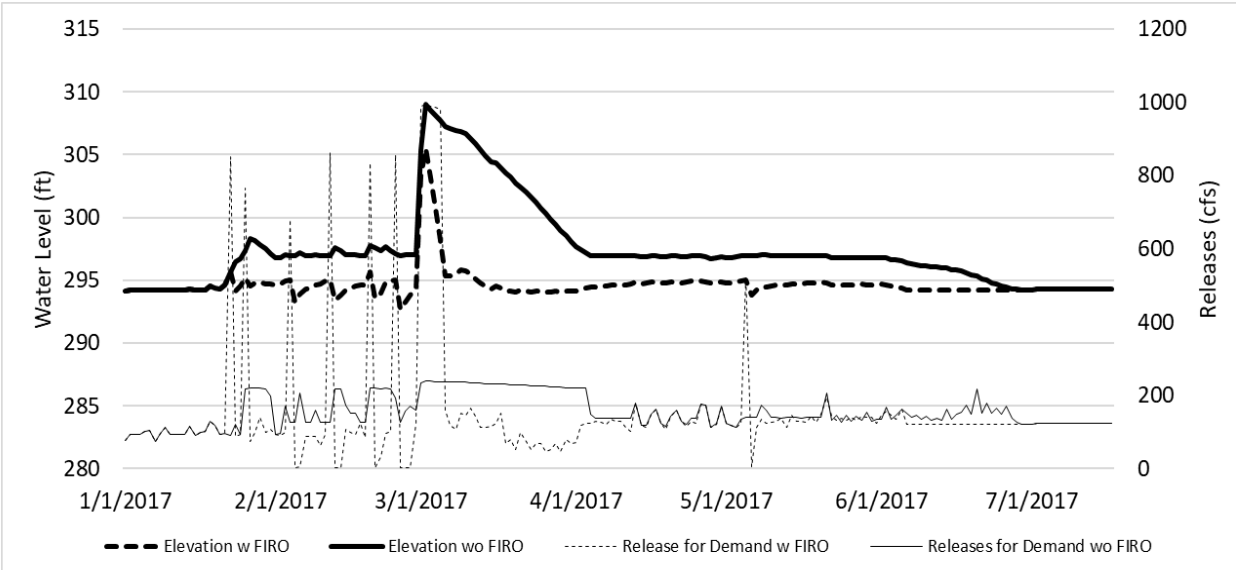

Figure 3-25 – Hodges Reservoir operation comparison during biggest historical storm event.

This chart shows Hodges Reservoir operations in the biggest storm event in the current condition period, water year 2017. It can be seen that the “without FIRO” operation was not able to lower the water level down below the restricted limit 295 ft for as long as 151 consecutive days. This could be very dangerous to the Hodges Reservoir dam due to the existing defections in the dam (DWR correspondence dated 9/4/2019). The regulation restricts water at Hodges Reservoir from exceeding 295 ft. The blowoff will need to be opened immediately after water exceeds 297 ft or exceeds 295 ft for more than 10 days. The reason for the 151-days-long Hodges Reservoir water above the restricted limit is that the discharge capacity of the blowoff at Hodges Reservoir is not big enough to handle the huge storm volume. On the other hand, the “with FIRO” operation significantly reduced the number of days that Hodges Reservoir operates above the restricted level. The total number of days that Hodges Reservoir exceeds 295 ft is 19 days, with only 12 days consecutively in the same period. This is done through moving water temporarily to Lake Olivenhain using Lake Hodges Pumps. The capacity of the pumps is 760 cfs, comparing to the blowoff capacity of 220.6 cfs at reservoir level of 310 ft.

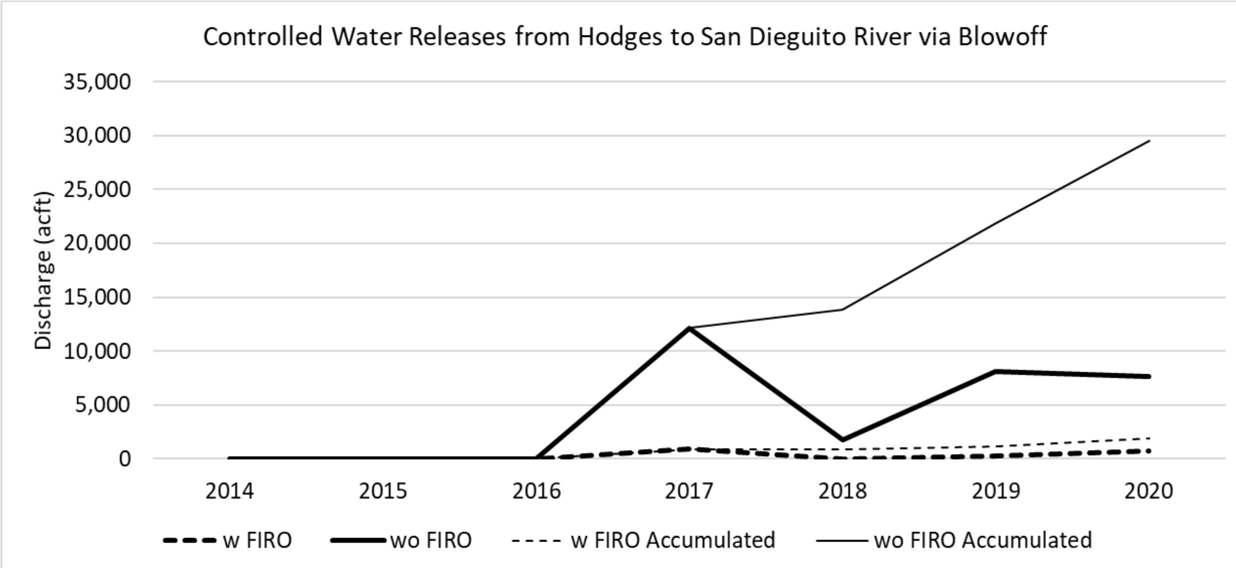

Figure 3-26 – Controlled water releases from Hodges to San Dieguito River via blowoff.

This chart shows that the "without FIRO" operation dumped close to 30,000 acre-feet of water to the San Dieguito River during the current condition period, while the "with FIRO" operation only discharged about 2,000 acre-feet of storm water.

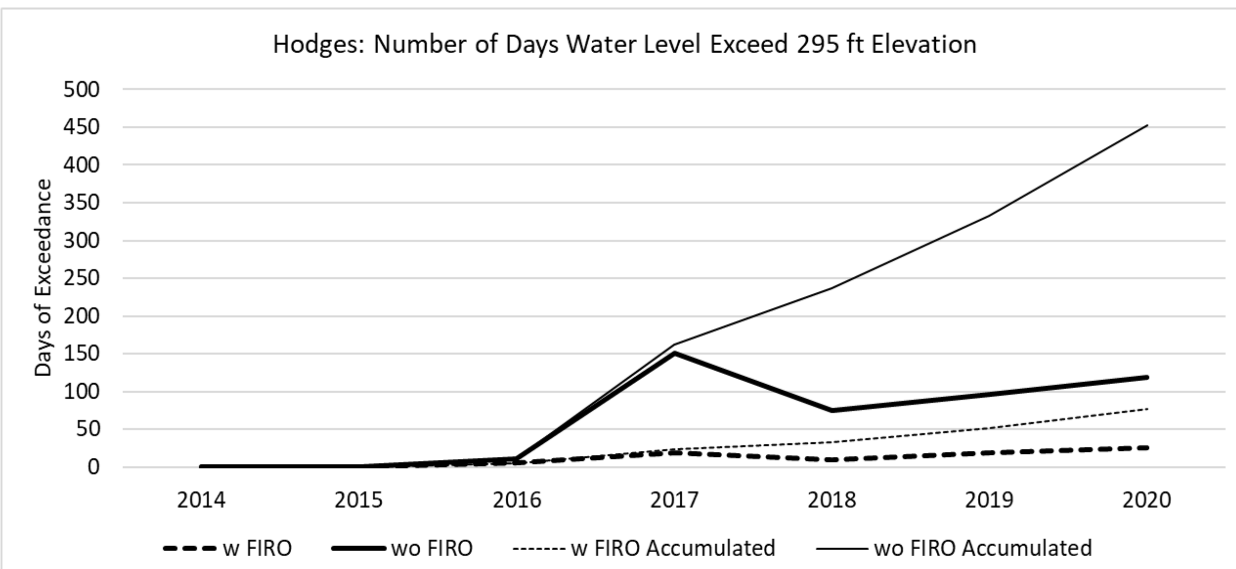

Figure 3-27 – Number of days that water level exceeded 295 ft restricted elevation for Hodges.

This chart shows that the "without FIRO" operation is not able to lower the reservoir level below the restricted level of 295 ft quickly. The total number of days the reservoir is above 295 ft is about 450 days in the current condition period. The "with FIRO" operation performs much better, with only about 80 days that the reservoir is above the restricted level in the same period.

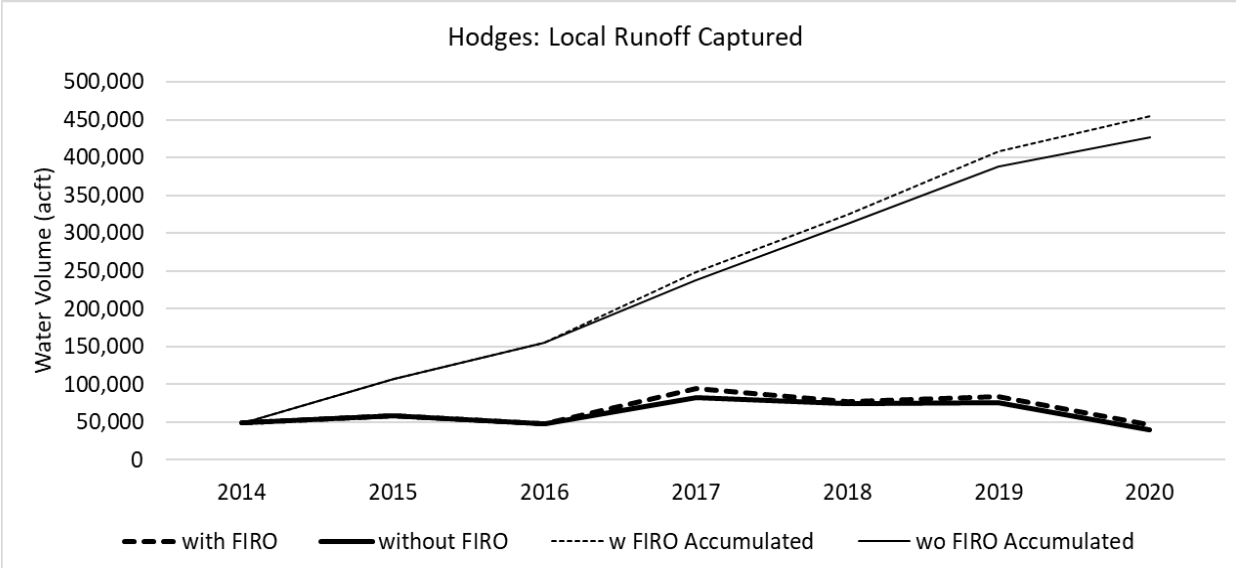

Figure 3-28 – Local water captured by Hodges Reservoir.

This chart shows that the "with FIRO" operation captures more water than the "without FIRO" operation. This is done through reducing reservoir release by moving more water to temporary storage facilities, i.e., Olivenhain Reservoir and R.E. Badger Filtration Plant.

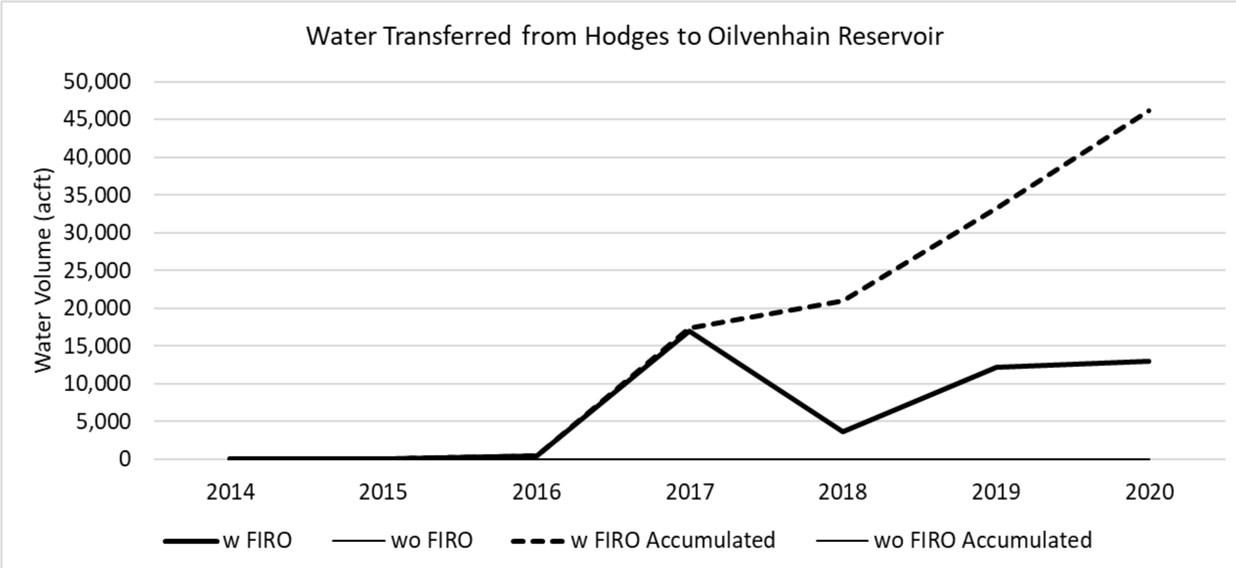

Figure 3-29 – Water transferred from Hodges to Olivenhain Reservoir.

This chart shows that "with FIRO" operation transfers water to Olivenhain Reservoir, while the "without FIRO" operation does not transfer water to Olivenhain Reservoir.

This quantity of water can also be labeled as the benefit of adopting FIRO operation. The water will eventually be transferred to Olivenhain Water Treatment Plant, or sent to San Vicente Reservoir through area aqueducts.

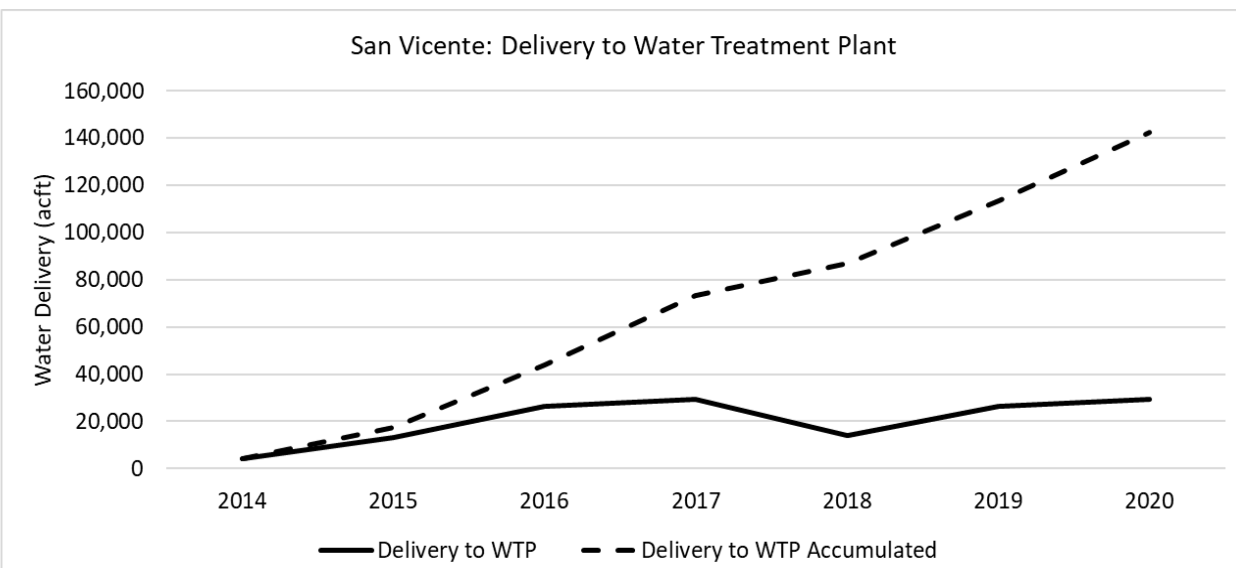

Figure 3-30 – Water delivered to water treatment plant from San Vicente Reservoir.

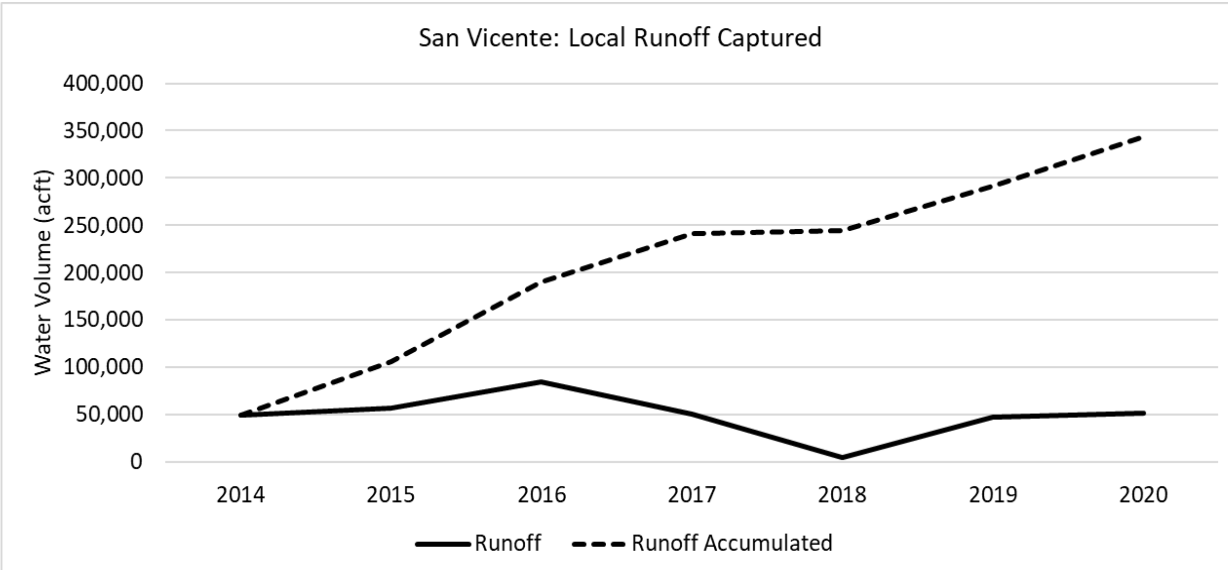

Figure 3-31 – Local runoff captured by San Vicente Reservoir.

The next three charts show situations in the Lower Otay Reservoir. About 300,000 acre-feet are captured in the reservoir in the simulation period, while only about 40,000 acre-feet transferred to the local treatment plant. A spill of about 6,500 acre-feet happened in 2017. Most of the water captured in the reservoir was lost, either through leakage or through evaporation.

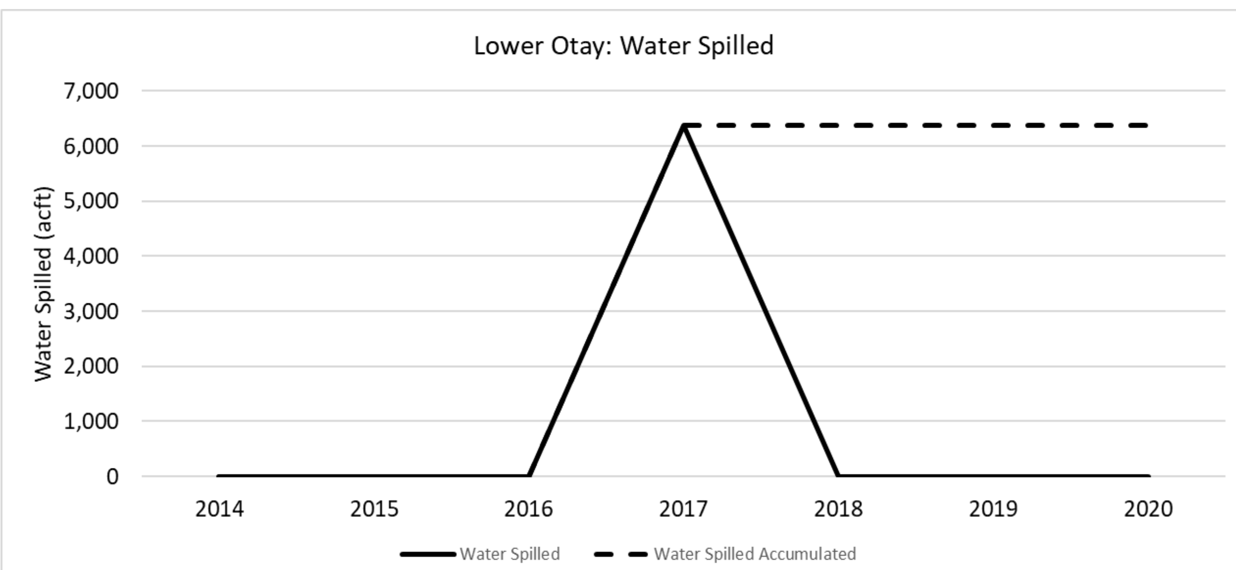

Figure 3-32 – Water spilled through Lower Otay Reservoir.

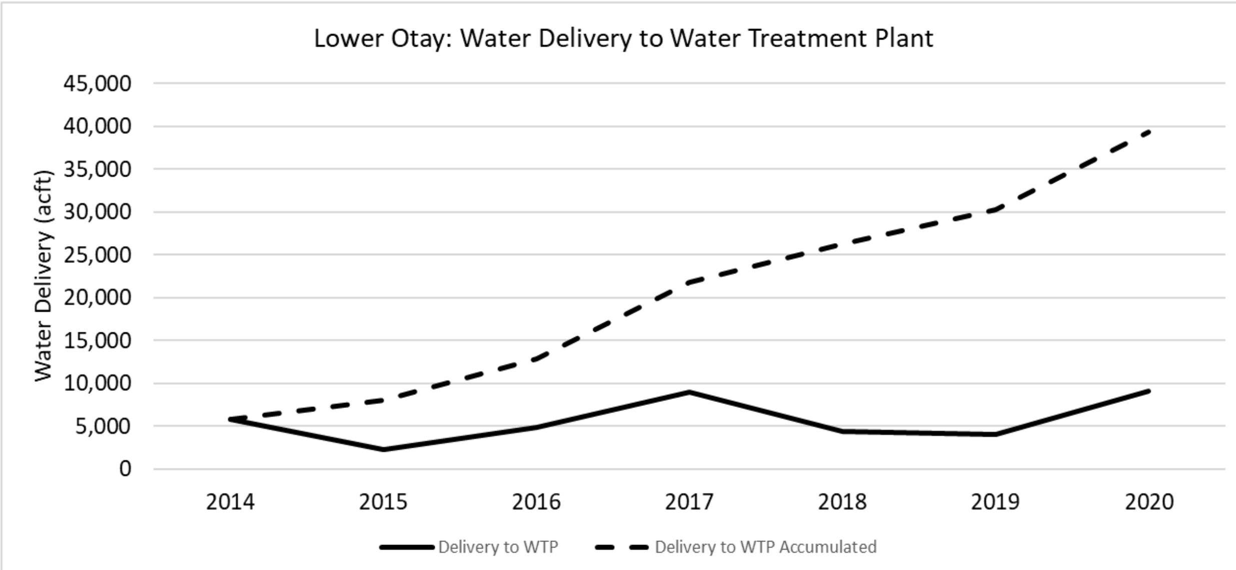

Figure 3-33 – Water delivered to water treatment plant from Lower Otay Reservoir.

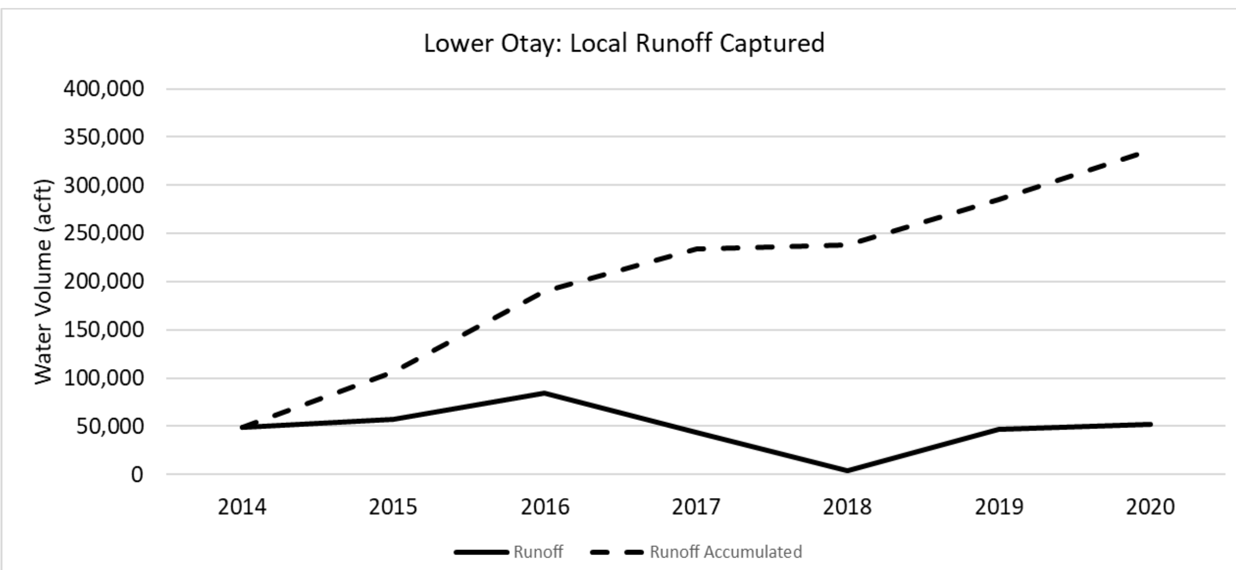

Figure 3-34 – Local runoff captured by Lower Otay Reservoir.

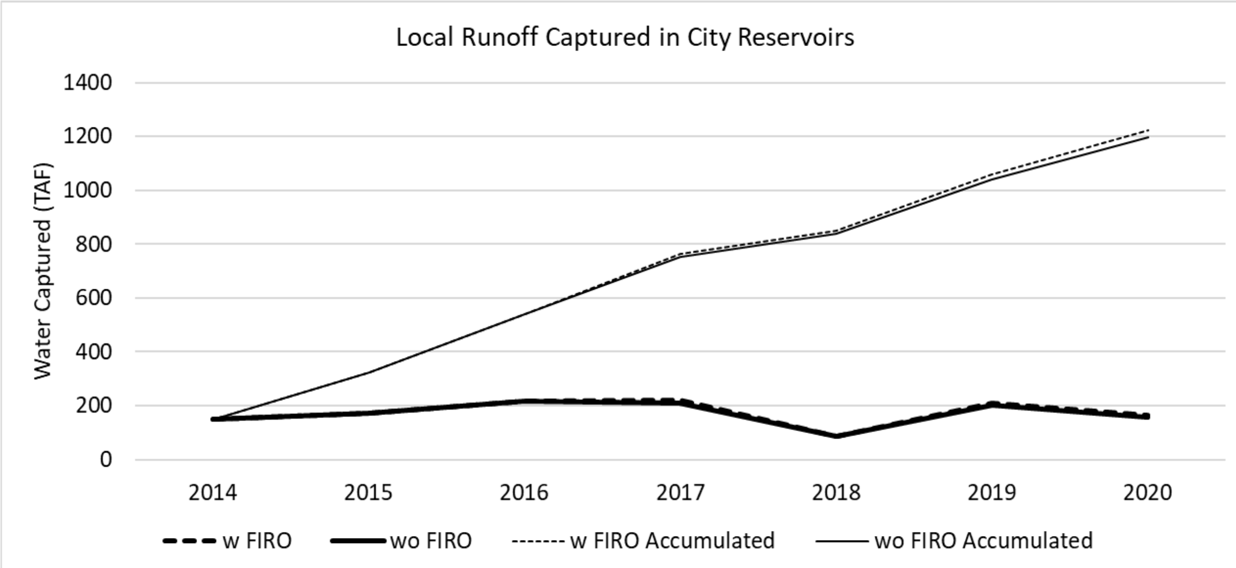

Figure 3-35 – Local runoff captured by City of San Diego Reservoirs.

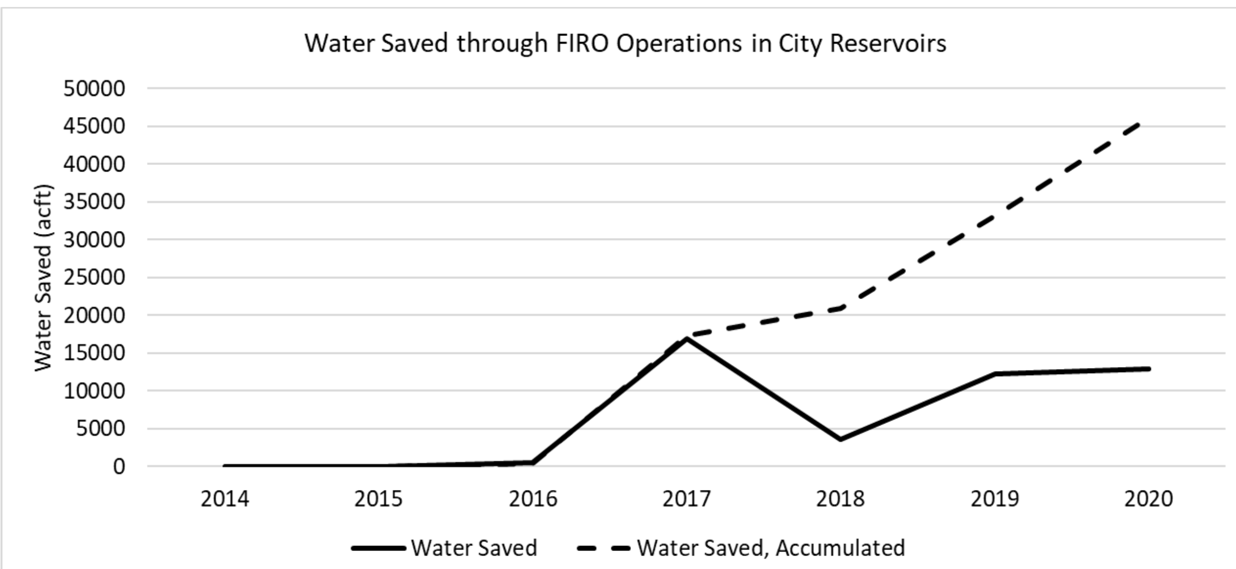

Figure 3-36 – Water Saved through FIRO operation for the City of San Diego Reservoirs.

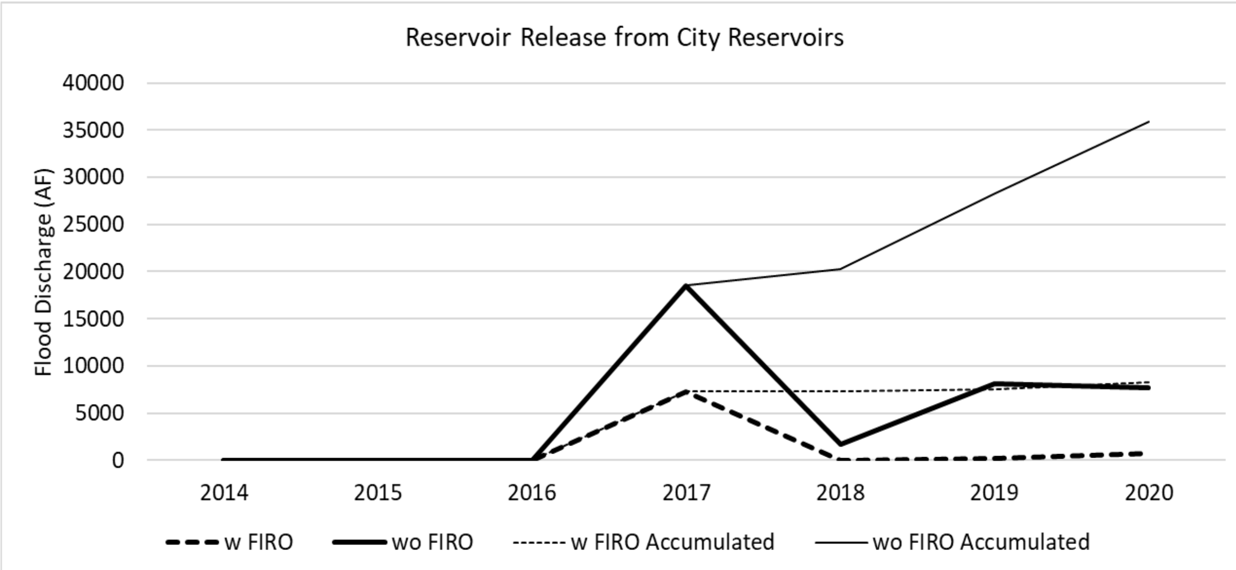

Figure 3-37 – Water released through the City of San Diego Reservoirs.

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Chapter 4 – Results & Next Steps

4.1 Climate Change Analysis

Similar to past work by Reclamation for the San Diego Basin Study (Reclamation, 2019), by the state of California in the California Climate Change Assessment (Pierce et al., 2018), and by the U.S. Global Change Research Program in the fourth National Climate Assessment (USGCRP, 2018), the work here examines potential future climate change using the General Circulation Models (GCMs) from the Coupled Model Intercomparison Project 5 (CMIP5). To simulate the effects of potential future warming due to greenhouse gas emissions, these models are used in conjunction with projections of greenhouse gas concentrations known as Representative Concentration Pathways (RCPs), commonly referred to as emissions scenarios (IPCC, 2014).

For the IPCC's fifth Assessment Report in 2014, four RCPs corresponding to possible future changes in greenhouse gas concentration were examined (IPCC, 2014). These four RCPs are RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5 and are labelled based upon the future radiative forcing due to changing GHG concentrations by 2100. For example, under RCP 8.5, the radiative forcing in 2100 is approximately 8.5 Watts per Meter Squared, compared to the current value of approximately 3.2 Watts per Meter Squared in 2021 and 2 Watts per Meter Squared in 1990 (NOAA Global Monitoring Laboratory - THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI)). These four pathways were selected amongst many possible emissions scenarios available at the time (Van Vuuren et al., 2011) so as to "Represent" the variability in the larger set of scenarios available in the scientific literature. RCP2.6 in this regard represented a best-case emission scenario, and RCP 8.5 represented the 90th percentile of scenarios available at the time of the IPCC's fifth assessment report. For this study, hydrological projections for 29 GCMs and both RCPs 4.5 and 8.5 from the San Diego Basin Study were used, totaling 58 simulations of future climate. Of these 58 projections of the future, large uncertainty in changes of annual average temperature, precipitation, and streamflow are observed. As no definitive probability can be given to any individual projection, for this study we examine each of the available potential futures in order to examine both the potential impact of climate change on COSD's infrastructure and the potential for FIRO to improve this performance in future hydrological conditions. This approach also encourages us to determine hydrological futures where system performance is degraded via reduced deliveries and increased water loss due to flood control releases. This analysis has the added benefit of enabling the city to begin the identification of alternative mitigation efforts in their ongoing planning activities.

The structure of this section is as follows: In section 4.1.1, we first revisit the previous work of the Basin Study and the methodology used to apply the GCM projections of future climate to the reservoir system. Next, in section 4.1.2 we discuss the modifications of this approach implemented in the current study, followed by a discussion on the uncertainty in future hydrology seen in the GCMs before proceeding to our analysis of COSD's reservoir operations with and without FIRO under future hydrology in section 4.1.3, the correlation with streamflow changes in section 4.1.4, and a sensitivity analysis to changing operational scenarios in 4.1.5.

4.1.1 Basin Study Work

The data and methodology to be used in the current study are largely drawn from the previous efforts of the San Diego Basin Study (Basin Study). The climate change analysis of the Basin Study focuses on two future periods to complement the Water Authority's long-term planning efforts: the 2020s (represented by the 10 water years 2020-2029) and the 2050s (represented by the 10 water years 2050-2059). The reference historical period used for comparison against projected future conditions is the 1990s (represented by the 10 years 1990-1999).

Here we briefly outline the hydrological data generated and its use in the Basin Study before discussing the modifications made for the present study.

Basin Study Climate Data

In the Basin Study, 29 CMIP5 GCMs under RCPs 4.5 and 8.5 were used to depict 58 future climate change scenarios. The output from these GCMs were statistically downscaled using the Bias Correction and Spatial Downscaling method (BCSD) (Wood et al., 2002) to 1/8-degree latitude by 1/8-degree longitude. These Downscaled CMIP5 climate projections were then used to provide precipitation, minimum and maximum temperatures, and near-surface wind speeds for application to the Variable Infiltration Capacity (VIC) macro-scale hydrology model to generate projections of hydrologic variables such as snowpack, evapotranspiration, and runoff (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997). For the Basin Study, Reclamation used the VIC hydrology model to develop inflows for various important locations for water management including the reservoirs used for the current study. For each location, simulated natural streamflow was computed using the approach of Lohmann et al. (1996), based on routing of grid-based VIC model output. For all identified locations, projected changes in mean streamflow were calculated at each location for the two future periods of interest (2020s and 2050s), relative to the 1990s reference historical period. This was done for mean annual streamflow, as well as mean December to March (cool season) and mean April to July (warm season) streamflow. Streamflow changes were estimated separately using projections from both sets of RCPs (i.e., RCP 4.5 and RCP 8.5).

Climate Scenarios

The 10th, 50th, and 90th percentile values were calculated for temperature change and precipitation change and used to group the CMIP5 projections into five climate change scenarios. The 10 CMIP5 projections closest to the percentile intersections were used to inform each climate change scenario.

VIC model simulations of natural streamflow for each of the selected groupings of projections were used to compute monthly streamflow change factors for developing climate-adjusted CWASim inputs. For each of the future time periods (2020s and 2050s), the mean change in streamflow across the 10 projections was computed, resulting in one change factor per month (e.g., January), per scenario. (e.g., hot-dry), and per time period (e.g., 2020s). Monthly streamflow change factors were then applied to historical CWASim inputs to develop climate-adjusted monthly streamflow inputs for the long term planning model.

Departures From This Methodology

For this study, several departures have been made from the previous Basin Study analysis. The key departure is that instead of using the GCM projections to develop the streamflow change factors used to perturb the historical hydrology, we here have used the daily streamflow timeseries acquired from applying the downscaled GCM data to the VIC Hydrological Model. The reason for this departure is primarily due to the need for a daily reservoir inflow timeseries, as opposed to the monthly timeseries developed for the basin study, to evaluate the implementation of FIRO.

Due to this change in approach, we instead make use of all the available climate projections to explore the full range of potential future hydrology as outlined by the GCM ensemble. This results in 29 GCMs each run at the two RCPs (RCP 4.5 and RCP 8.5) for a total of 58 future scenarios as opposed to the 5 climate scenarios of the basin study.

An additional divergence from the basin study is our selection of reference periods for baseline conditions as well as our "Short-Term" and "Long-Term" climate change periods. The basin study compared hydrological conditions between 10-year periods to develop their perturbations to the historical period for the above-mentioned climate scenarios; in this work we examined the performance of the reservoir during 30-year periods. The reference periods are shown in Table 6 both for the Basin Study and our study.

Time period	Baseline Period	"Short-term"	"Long-term"
Basin Study	1990 - 1999	2020 - 2029	2050 - 2059
SD FIRO	1951 - 1980	2020 - 2049	2050 - 2079

Table 4-1 – Water year periods examined in the previous Basin Study, and those to be examined as part of the current study (SD FIRO).

The short-term and long-term periods were chosen to start at the same date as the Basin Study analogues; however the Baseline Period was selected as the earliest 30-year period in the GCM derived time series to represent the period where effects from increasing greenhouse gas concentrations would be smallest.

These methodological choices also entail a number of limitations and uncertainty. Firstly, the GCM-derived streamflow data used in the previous basin studies is not calibrated to the watersheds. As a result, the analysis of this section should be seen as representing qualitative indicators for the future climate impact on COSD's reservoirs and the potential benefit of FIRO. Interpretation of the results should be done by comparing future performance to the baseline period, or by comparing FIRO performance to Without FIRO performance for a given time period. Direct comparison of these results to the current conditions analysis is not appropriate as that analysis uses observed streamflows which may have properties absent from this GCM-derived hydrology. However, the results in this section may indicate qualitative changes to the current conditions analysis results that may occur as a result of climate change.

4.1.2 Future Hydrology

GCM projections of climate change in the study area can be characterized by warming temperatures and uncertain changes to precipitation patterns (Reclamation, 2019). The impact of these changes on reservoir operations can be examined more explicitly through changes in reservoir inflow. Here we will examine the full distribution of hydrological changes as seen across 58 climate projections. Even though each individual GCM represents a self-consistent projection about future climate, attributing an exact probability or likelihood to any of these models is not possible. As a result, for this study we take the approach to examine the performance of the reservoir system under the full ensemble of projections available to us. This approach allows us to characterize the full range of future performance and to identify hydrological conditions where the COSD system may be more vulnerable to changing hydrology.

To examine the potential change in future hydrology, we examined several commonly used measurements of streamflow variability for all climate scenarios for each future period in reference to the historical reference period. A subset of these metrics will be further used to explore the system response under climate change.

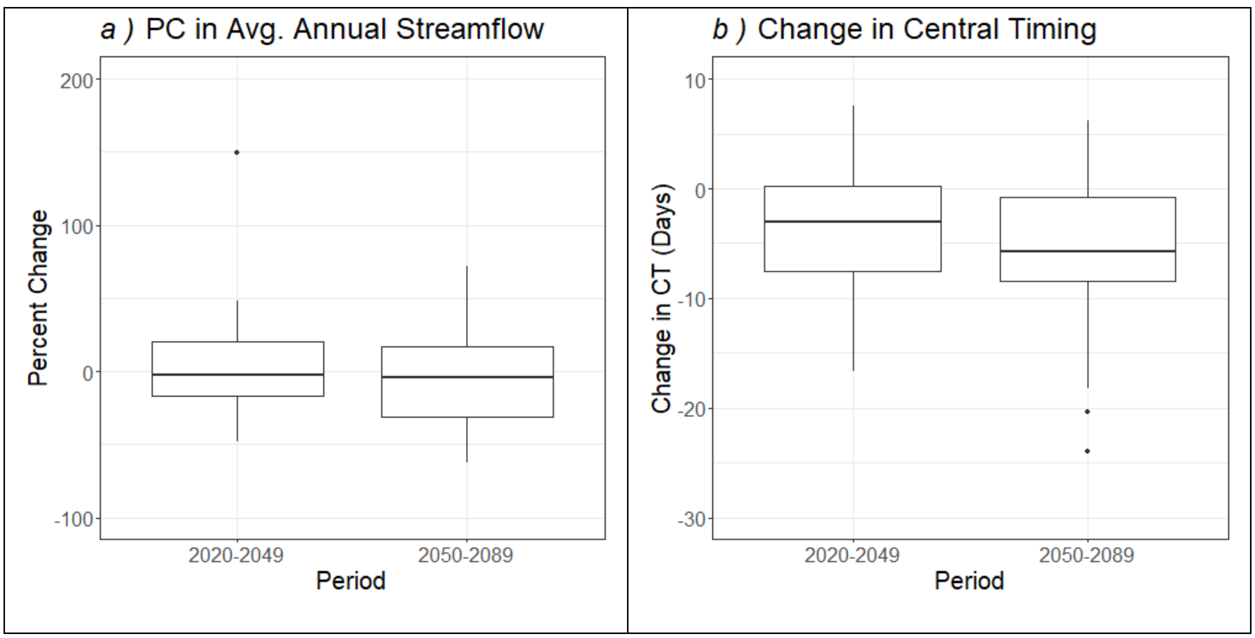
1. ***Annual Average Streamflow (AAS):*** The average of all daily mean streamflow values for a given year.
2. ***Central Timing (CT):*** The date marking the timing of the center of mass of annual flow center timing (CT) for each water year "i.e., the day on which half of the annual (water year, 1 October–30 September) flow volume has passed a particular point on a stream." (Stewart et al., 2005)
3. ***Wet Weather Events (WWE):*** Number of days where any reservoir inflow in the system experiences a daily inflow greater than 1000 cfs. This metric illustrates the change in frequency of high inflow events. In this application, high inflows at multiple reservoirs on the same day are each counted as separate events.
4. ***Percent of Annual inflow due to WWE inflow (WWP):*** What percentage of total annual inflows are attributable to Wet Weather Events.

For the purposes of evaluating drought at a high level, we examine the frequency and persistence of dry years in the record. A dry year is defined here by the 25th percentile of the annual cumulative inflow distribution at the seven reservoirs used in this study during the historical reference period (1951-1980).

5. ***Change in Dry Year Persistence:*** Average length of consecutive dry years compared to the baseline 1951-1980 period.
6. ***Change in Dry Year count:*** Total number of dry years in the 30-year period in comparison to the historical period. The historical period has 7 dry years (rounding down from 7.5) using the above definition of the 25th percentile of historical period inflow.

Projected Changes in Streamflow for City of San Diego

Here we show the above hydrology statistics for the cumulative inflows of the seven reservoirs in the model system. As mentioned above, here we evaluate the net change or percent change (PC) in these statistics from the reference period to both future periods.



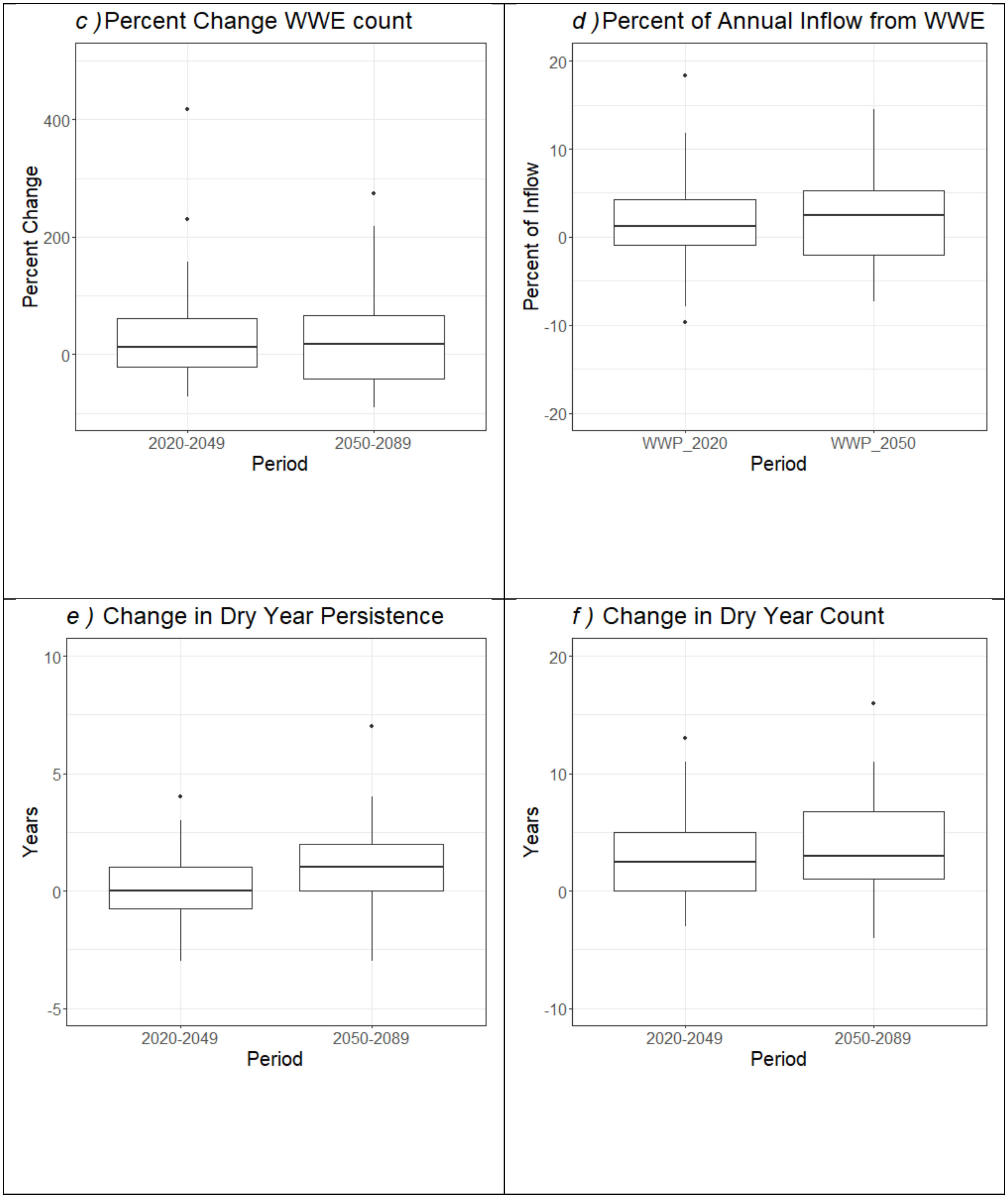


Figure 4-1 – Changes in streamflow for both short- and long-term climate periods. Quantities are for the cumulative inflow at each of the seven reservoirs. Boxplots show median, 25th, and 75th percentiles. Whiskers extend to a maximum of 1.5*IQR (Approximately 5th, 95th percentile).

We first look at the change in these properties across the whole reservoir system (summing the inflows of all reservoirs) for all GCMs, and for each future period, in reference to the baseline period of WYs 1951–1980, as shown in Figure 1. Plots broken down into emissions scenarios and for the individual reservoirs are included in Appendix B.

Here we will examine the median values to denote trends and use the interquartile range (IQR) to characterize the variance of the distributions. The Interquartile Range (IQR) is defined as the difference between the 25th percentile and the 75th percentile, and thus measures the spread of the middle 50% of the distribution. The IQR is thus a representation of the uncertainty associated with the climate model projections. These values are shown in Table 4-2

Change in Hydrological Signal from Reference Period (1951-1980	**2020 Change – Median (IQR)**	**2050 Change – Median (IQR)**
Annual Averaged Streamflow	-2.1%, (37.0%*)*	*-3.8% (*47.9%*)*
Central Tendency	-3 days (7.7 days)	-5.8 days (7.7 days)
Wet Weather Event Count	12.3% (83.9%)	18% (108.1%)
Percent of Annual Inflow from Wet Weather Events	1.2 % (5.2%)	2.4 % (7.4%)
Average Length of Consecutive Dry Years	0 Years (1.75 Years)	1 Years (2 Years)
Dry Year Count per period	2.5 years (5 years)	3 years (5.75 years)

Table 4-2 – Change in Streamflow characteristics for COSD from Figure 4-1. Values represent Change in Median properties from the baseline, and the IQR range around the median change for each period. (IQR is the difference between the 25th percentile and the 75th percentile.)

In Figure 4-1*,* it is observed that there is a slight decrease in the median (IQR) AAS from the baseline to the 2020 period of -2.1% (37.0%*)* and a further decrease for the 2050 period of -3.8% (47.9%*)*. The total change in central timing is also seen to decrease further into the future with a median change of -3 days (7.7 days) for the 2020 period and -5.8 days (7.7 days) for the 2050 period, implying that the wet season is slightly decreasing in duration. We also see an appreciable median percent increase in the count of wet weather events in the system: 12.3% (83.9%) in 2020, 18% (108.1%) in 2050. This change in wet weather events also reflects a slight increase in the percent of annual inflow due to wet weather events by 1.2% (3.7%) in the baseline period to 1.2% (5.2%) in the 2020-2049 period and 2.4% (7.4%) in the 2050-2079 period. On interannual timescales, it is observed that the number of dry years per 30-year period is expected to increase by 2.5 years to 9.5 years per period in 2020-2049 and similarly for 2050-2079.

For the metrics examined, we see the most common futures are those with lower annual averaged flow, increased frequency of high inflow events, and an increase in the expected number of dry years. We also notice increased uncertainty from the 2020-2049 period to the 2050-2079 period for all metrics as denoted by increasing IQR. These trends in the full reservoir system are also reflected in the individual reservoirs (see Appendix B).

In many of the cases we also observe notable outliers. For example, in figure 4-1(a) for the 2020-2049 period we see one GCM run has a change of 150% wetter annual averaged inflow. Though each data point here represents 1 out of 58 possible futures, it is not equivalent to say that this future has a 1 in 58 chance of occurring. First, the GCMs examined here do not represent the full ensemble of future projections available at the current time, just those previously used in the San Diego Basin Study. Secondly, due to the limitations and assumptions of GCMs due to their differing characterization of physical processes or course time/spatial resolutions, it is not possible to attribute a true probability to any of the GCMs. In light of this issue, these GCMs are more usefully interpreted as illustrative of potential futures for use in examining which hydrological conditions the system is sensitive to and to allow for possible adaptation methodologies to be examined alongside a more robust climate-focused analysis.

4.1.3 Evaluation of FIRO under Climate Change

We will now use the climate change projections discussed previously to determine both 1) the change in system performance under climate change and 2) the change in FIRO benefit under climate change. For this analysis we will focus on the two primary functions of the reservoir system: water supply and flood prevention. Here we measure these components by the overall system deliveries and “Releases” made due to exceeding elevation restrictions.

- Deliveries
    - Deliveries into the system made for all (including WTP) needs (excludes flood releases). For example, deliveries to Olivenhain are included here.
- Releases
    - Releases made as a result of violating elevation restrictions.
    - For these plots, a positive “benefit” indicates that under FIRO operations, a lower volume of releases are made. The larger the FIRO benefit, the larger the difference between releases

For each of these metrics, we will evaluate the system by comparing the average annual deliveries/releases made during each 30-year period identified earlier in Table 6. For each of the future periods, we will examine the following

1. Baseline Operations vs. FIRO
2. Total benefit from FIRO operations
3. The benefit according to emissions scenario (RCP 4.5, 8.5)
4. The percent benefit compared to the baseline performance without FIRO

We will present these four evaluations for the full reservoir system as well as the two reservoirs with FIRO operations: Hodges and El Capitan.

Full System

Full System Deliveries

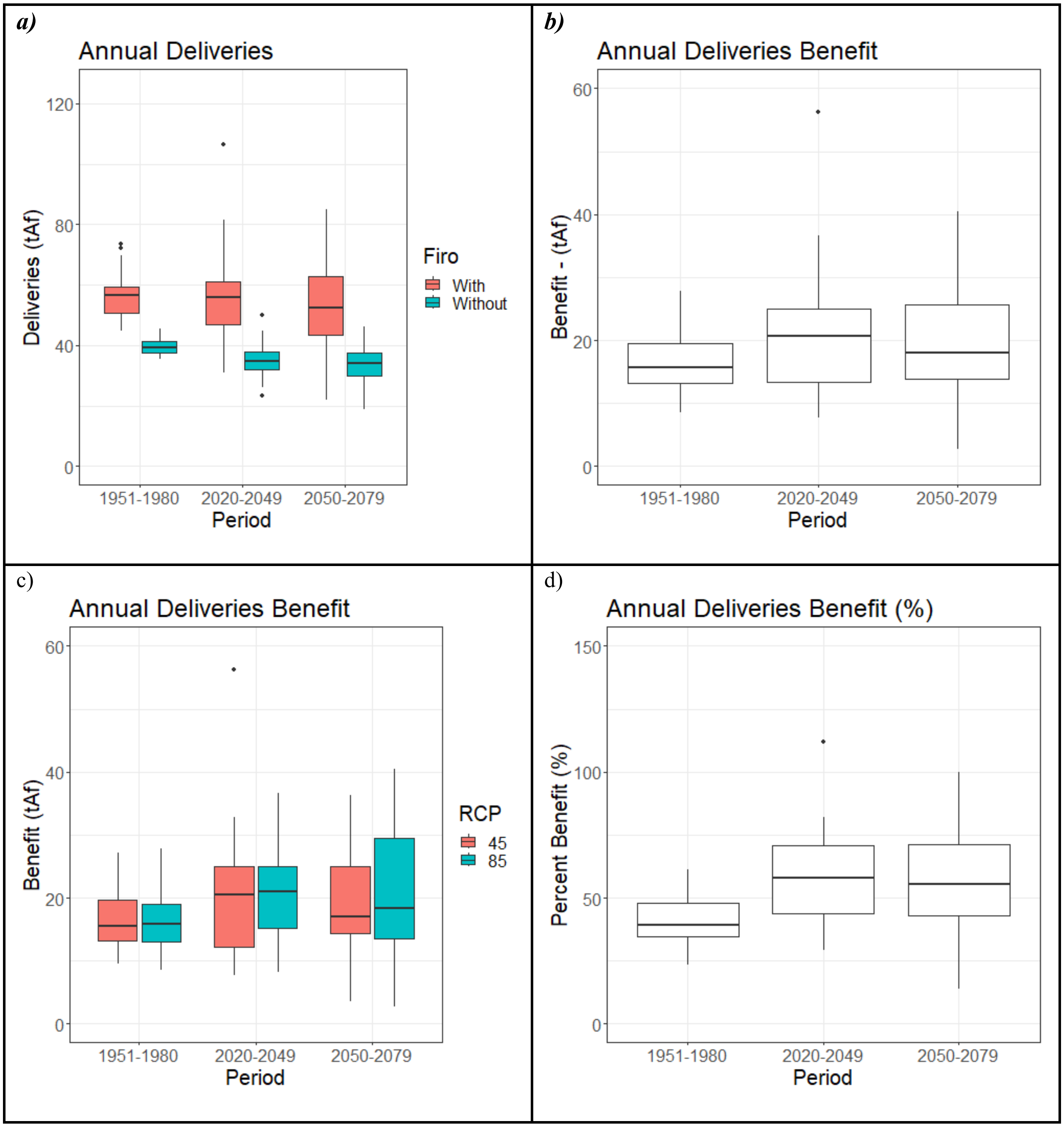


Figure 4-2 –COSD Deliveries Benefit of FIRO under Climate Change. a – average annual deliveries for each 30-year period with and without FIRO operations, b – Difference in average annual deliveries with FIRO and deliveries without FIRO. c - Difference in deliveries with FIRO and deliveries without FIRO grouped by RCP. d– Percent difference in operations in reference to without FIRO operations.

Deliveries (TAF)	**1951-1980 (BL)**	**2020-2049**	**2050-2079**
With Firo	115	125.5	119
Without Firo	97.75	105.9	103.2
Benefit	17.25	19.6	15.8

Table 4-3 – Median values for change in average annual Deliveries with and without FIRO for COSD (horizontal lines in box plots) for metrics in Figure 4-2. Percent of the 58 climate scenarios where there is FIRO benefit.

Full System Releases

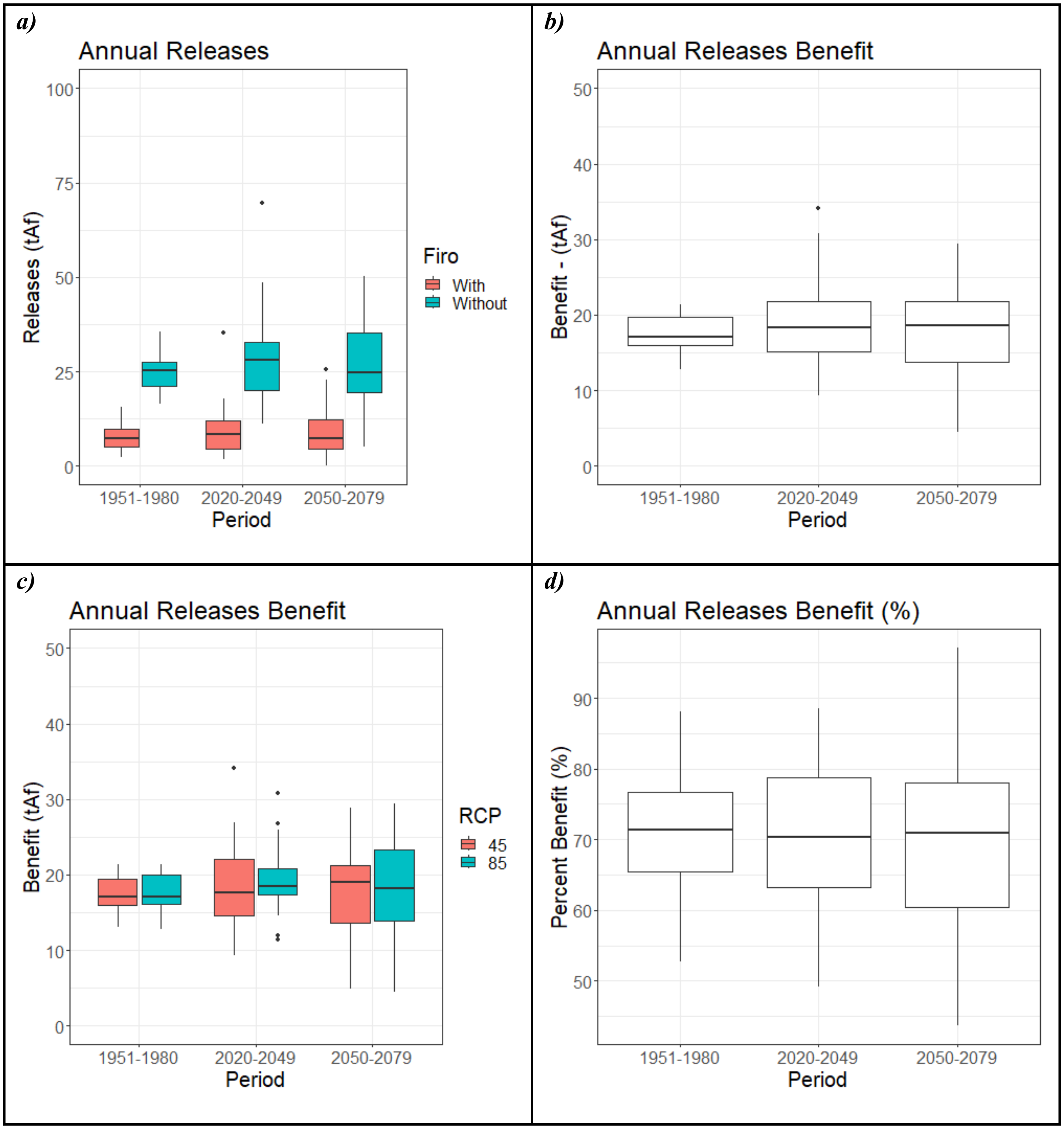


Figure 4-3 – COSD Releases Benefit of FIRO under Climate Change. a – average annual deliveries for each 30 year period with and without FIRO operations, b – Difference in average annual deliveries with FIRO and deliveries without FIRO. c - Difference in deliveries with FIRO and deliveries without FIRO grouped by RCP. d– Percent difference in operations in reference to without FIRO operations.

Releases	**1951-1980 (BL)**	**2020-2049**	**2050-2079**
With Firo	98.4	97	89.7
Without Firo	115.8	117.2	105.7
Benefit	17.4	20.2	16

Table 4-4 – Median values for change in average annual releases with and without FIRO for the City (horizontal lines in box plots) for metrics in Figure 4-3.

For COSD's Reservoir System, appreciable FIRO benefit is observed across all time periods as seen by an increase in Deliveries, and a reduction of Releases by approximately 15-20% in the median scenarios.

For system deliveries, we see a median benefit of 17.25 TAF per year on average in the baseline period , a slight increase in FIRO benefit in the 2020-2049 period to 19.6 TAF in 2020-2049, and a slight decrease to 15.8 TAF in 2050-2079. Although in some scenarios there is some slight reduction to the Potential FIRO benefit, in no scenario or time period is there no benefit or a negative impact on Deliveries.

For Releases, a median reduction by over 15 TAF annually is observed for each scenario and each period. This benefit increases in the future periods where wet weather events are projected to become more prevalent.

We will see that these benefits of increased Deliveries and reduced Releases are due nearly entirely to just the changing operations at El Capitan and Hodges and so we will focus our analysis in future sections on these reservoirs.

El Capitan

El Capitan Deliveries

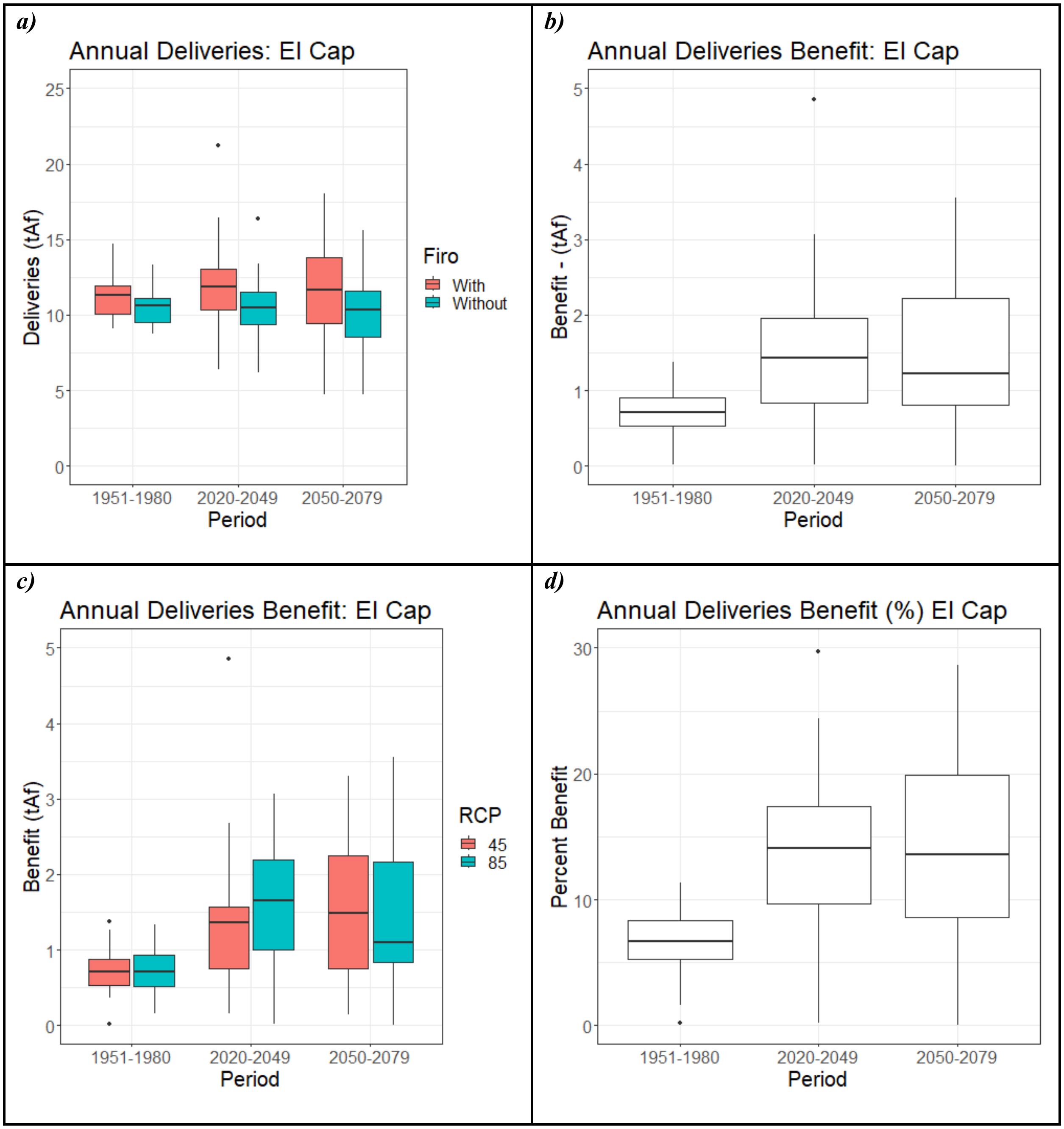


Figure 4-4 – El Capitan Deliveries benefit of FIRO under Climate Change. a– average annual deliveries for each period with and without FIRO operations, b – Difference in average annual deliveries with FIRO and deliveries without FIRO. c- Difference in average annual deliveries with FIRO and without FIRO grouped by RCP. d – Percent difference in operations in reference to without FIRO operations

Deliveries	*1951-1980 (BL)*	*2020-2049*	*2050-2079*
With Firo	11.3	11.9	11.7
Without Firo	10.6	10.5	10.3
Benefit	.7	1.4	1.4

Table 4-5 – Median values for change in average annual deliveries with and without FIRO for El Capitan (horizontal lines in box plots) for metrics in Figure 4-4.

El Capitan Releases

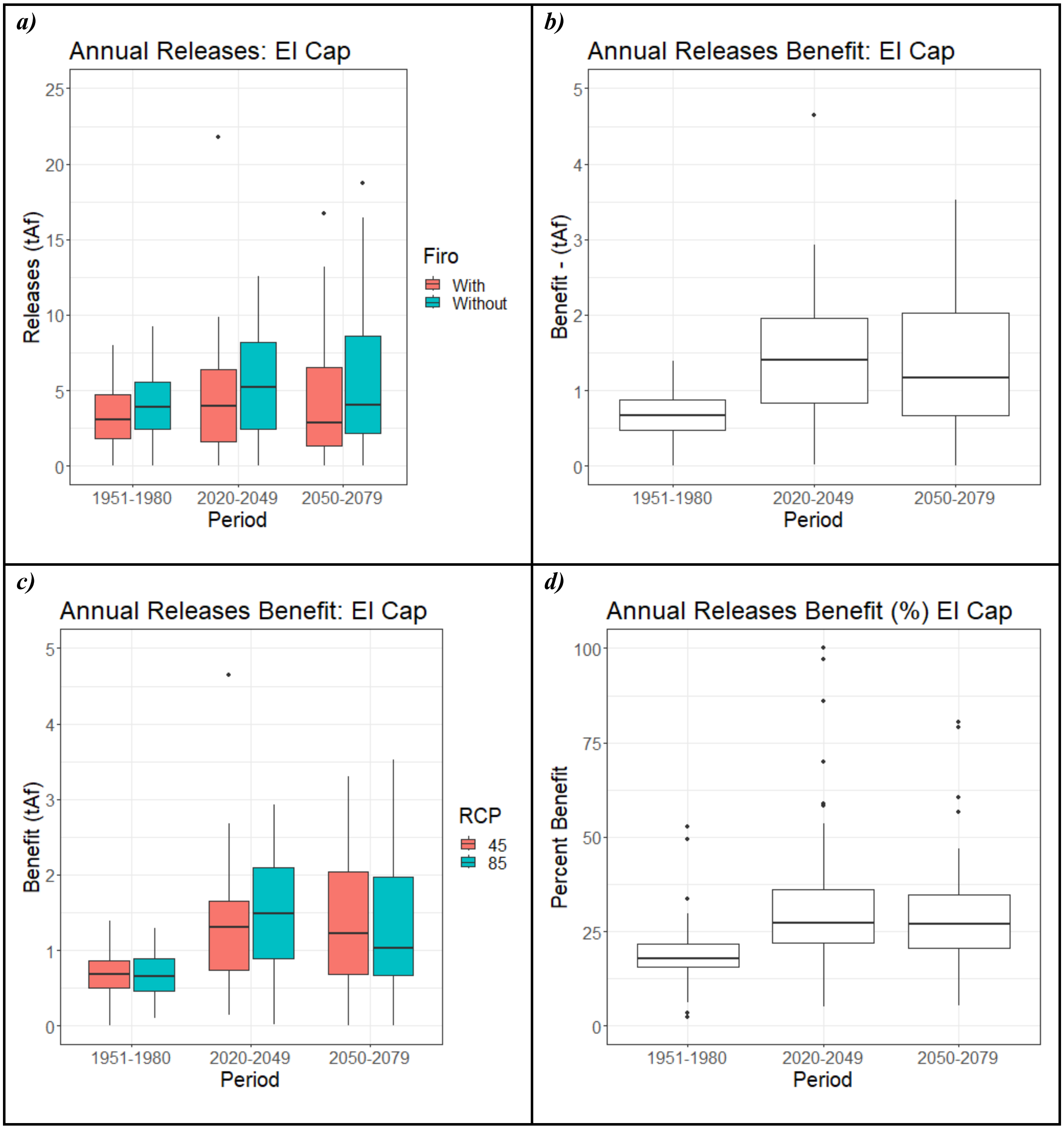


Figure 4-5 – El Capitan Releases Benefit of FIRO under Climate Change. a – average annual deliveries for each period with and without FIRO operations, b – Difference in average annual deliveries with FIRO and deliveries without FIRO. c- Difference in average annual deliveries with FIRO and without FIRO grouped by RCP. d – Percent difference in operations in reference to without FIRO operations

Deliveries	1951-1980 (BL)	2020-2049	2050-2079
With Firo	3.1	3.9	2.9
Without Firo	3.9	5.4	4.1
Benefit	.8	1.5	1.2

Table 4-64 – Median values for change in average annual releases with and without FIRO for El Capitan (horizontal lines in box plots) for metrics in Figure 4-5

For El Capitan, we notice an appreciable benefit from FIRO in the baseline period (median of .8 TAF per year) in both Releases and Deliveries. At El Capitan, the magnitude of the benefit in one of these metrics is approximately the same as the other. That is to say, all of the reduced releases are due to increased deliveries because of FIRO ahead of exceeding the level restriction. In the 2020-2049 period, we notice a doubling of the median FIRO benefit. There is also an improvement from the baseline in the 2050-2079 period, though slightly less than the increase in the 2020-2049 period. As shown in Figure 4-5 (c) and 4-6 (c), there are only modest differences between RCPs in terms of FIRO benefit. Furthermore, this difference appears to align with the modest differences in annual average streamflow between RCPs shown in Figure 4-1.

The increased IQR as shown in Figures 4-4 and 4-5 indicate a growing uncertainty in the FIRO benefit from current conditions into the future. This can be attributed to the increased divergence of the GCMs in more distant futures.

Under all the climate change simulations, at least a slight FIRO benefit is observed, and so the implementation of FIRO is never maladaptive for El Capitan. This result should however be interpreted in the context of the historical period as examined previously in section 3. In the prior section, no FIRO operations were triggered and though the climate change analysis here examines more variability than present in the timeseries available for section 3, it is possible that the climate change hydrology is overstating the potential future benefit of FIRO in the future. However, as configured for this study, FIRO operations never result in increased water releases via blowoff, only increased deliveries to water treatment plants when elevation requirements are projected to be violated. Therefore, in the worst case scenario poor FIRO operations simply collapse to operations as normal and there are no additional water releases.

Hodges

Hodges Deliveries

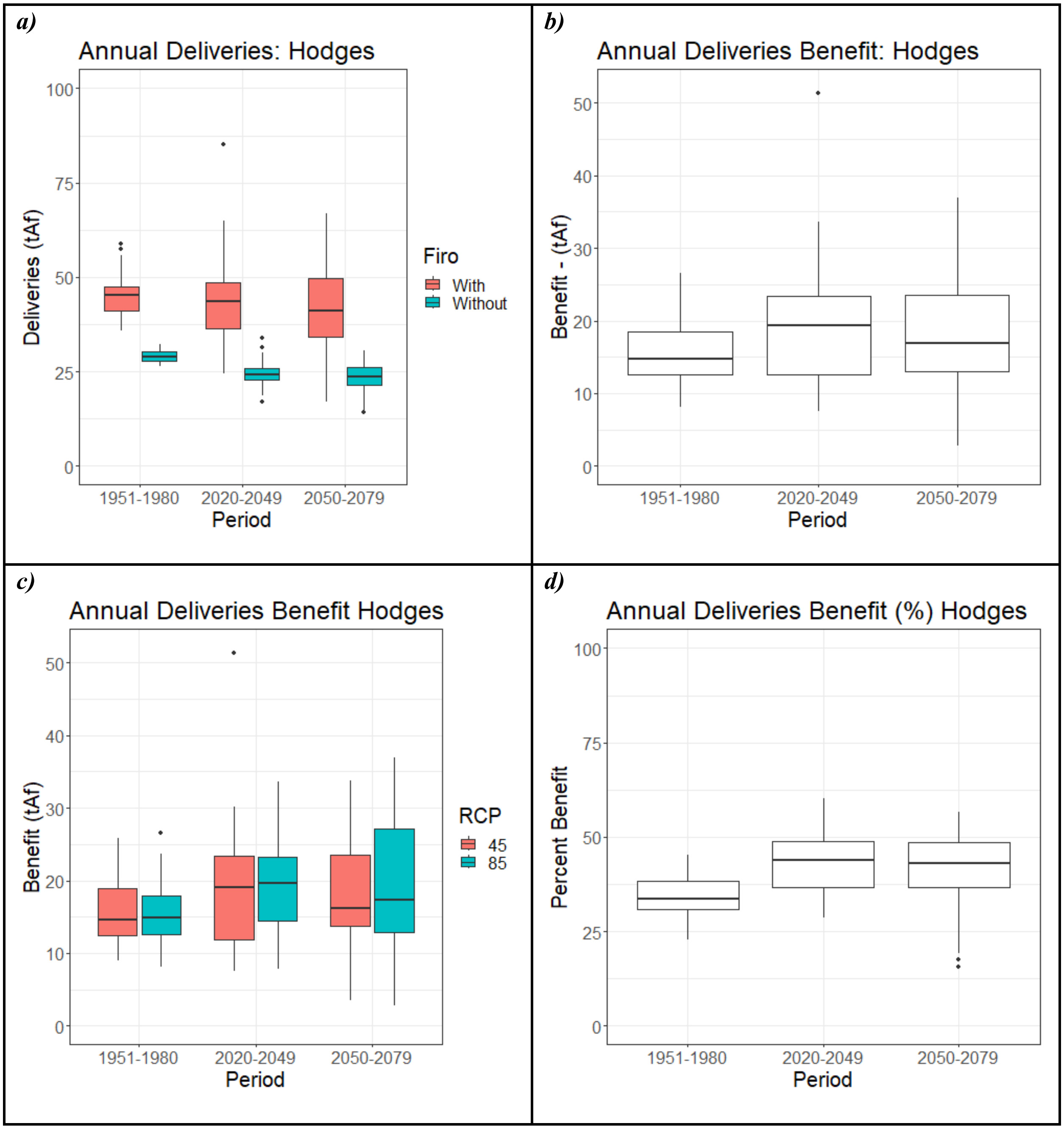


Figure 4-6 – Hodges Deliveries Benefit of FIRO under Climate Change. a – average annual deliveries for each period with and without FIRO operations, b – Difference in average annual deliveries with FIRO and deliveries without FIRO. c - Difference in average annual deliveries with FIRO and without FIRO grouped by RCP. d – Percent difference in operations in reference to without FIRO operations

Deliveries	1951-1980 (BL)	2020-2049	2050-2079
With Firo	45.1	43.5	41
Without Firo	29	24.3	23.6
Benefit	16.1	19.2	17.4

Table 4-7 – Median values for change in average annual deliveries with and without FIRO for Hodges (horizontal lines in box plots) for metrics in Figure 4-6

Hodges Releases

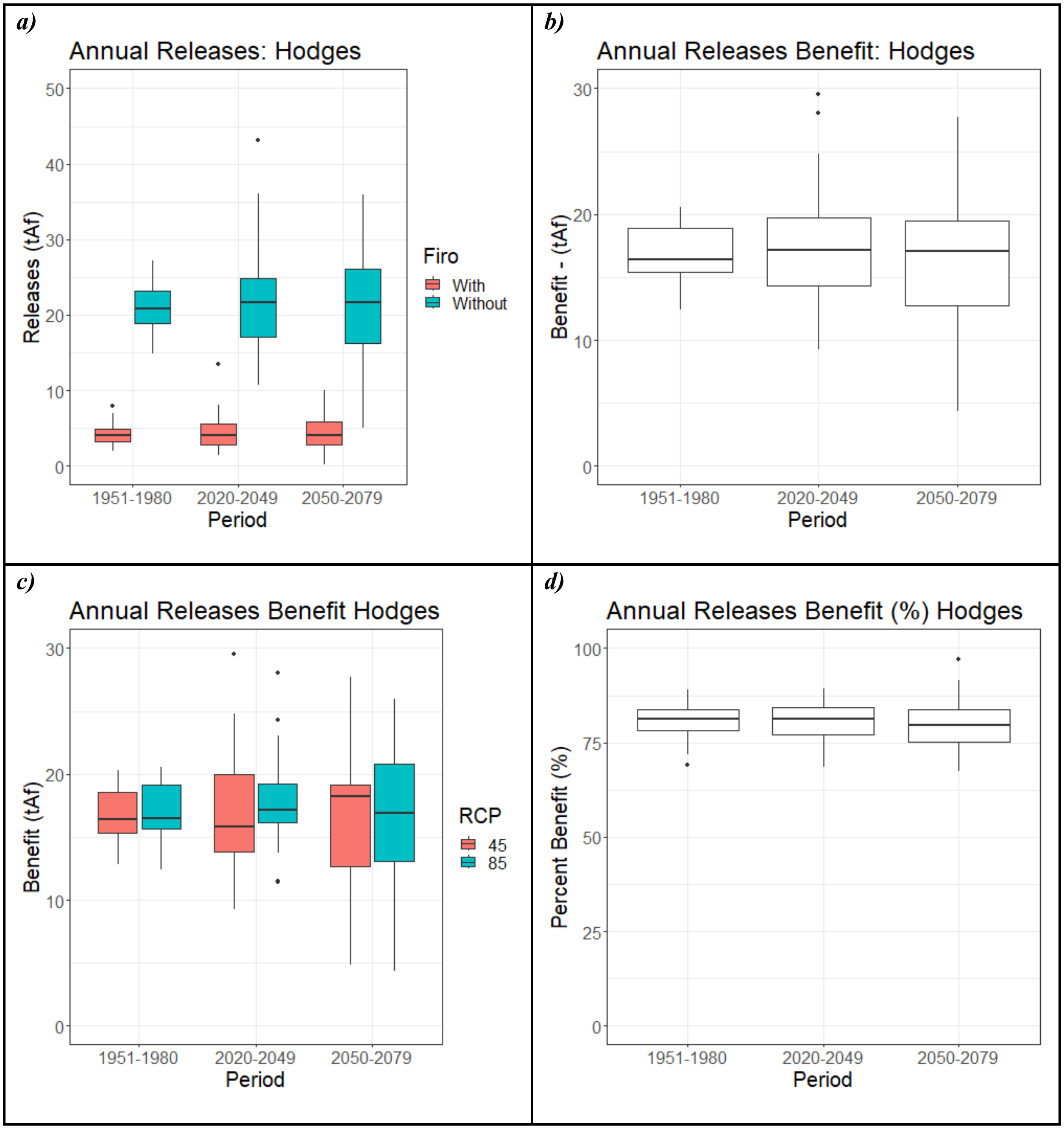


Figure 4-7 – Hodges Releases Benefit of FIRO under Climate Change. a – average annual deliveries for each period with and without FIRO operations, b – Difference in average annual deliveries with FIRO and deliveries without FIRO. c - Difference in average annual deliveries with FIRO and without FIRO grouped by RCP. d – Percent difference in operations in reference to without FIRO operations

Deliveries	Baseline 1951-1980	2020-2049	2050-2079
With Firo	4	4.1	4.1
Without Firo	20.8	21.6	21.6
Benefit	16.8	17.5	17.5

Table 4-8 – Median values for change in average annual releases with and without FIRO for Hodges (horizontal lines in box plots) for metrics in Figure 4-7.

For Hodges, we notice a substantial benefit from FIRO in the baseline period for median Deliveries (16.1 TAF) and Releases (16.8 TAF). In the 2020-2049 period, we notice a modest increase of the median FIRO benefit for both metrics. There is also an improvement from the baseline in the 2050-2079 period though less than the increase in the 2020-2049 Period.

The increased IQR as shown in Figures 4-6 and 4-7 indicate a growing uncertainty in the FIRO benefit from current conditions into the future. This can be attributed to the increased divergence of the GCMs in more distant futures.

Under all of the Climate Change Simulations, an appreciable FIRO benefit is observed. In the lowest performing case we see a FIRO Benefit of approximately 2 TAF annually for both Deliveries and Releases

4.1.4 Correlation of FIRO benefit with Streamflow Characteristics

Here we briefly present some results for the correlation of Streamflow Characteristics with FIRO benefit at El Capitan and Hodges. Within this section we will only examine those streamflow characteristics which show strong correlation between FIRO benefit and Deliveries and/or Releases:

1. Annual Average Streamflow (AAS)
2. Wet Weather Events (WWE)
3. Percent of Annual Inflow from Wet Weather Events (WWP)

A complete set of figures for all of the streamflow characteristics are included in Appendix B.

For this section, only a preliminary qualitative correlation is examined by comparing the quartiles (0-25%, 25-50%, 50-75%, 75-100%) of each of the stream flow characteristics with the FIRO benefit observed in each period. For example, Figure #4-8illustrates the full range of FIRO benefit for El Capitan Deliveries during the 2020 Period alongside the FIRO benefit from just those climate change simulations belonging to each quartile of the distribution seen in the Projected Annual Average Streamflow. From this we see that for the futures with the lowest amount of AAS (0-25), we have the smallest FIRO benefit, though still a median increase of approximately 9%. In contrast, in projections with the greatest AAS (75-100) we have the largest FIRO benefit.

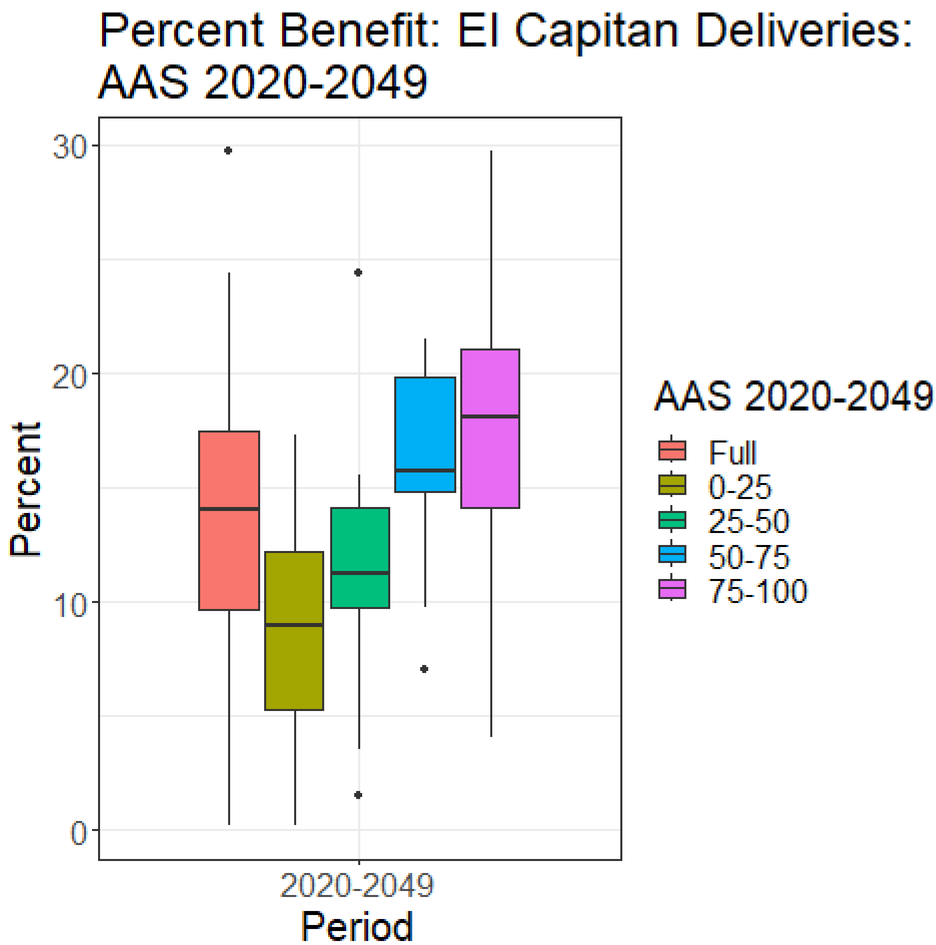
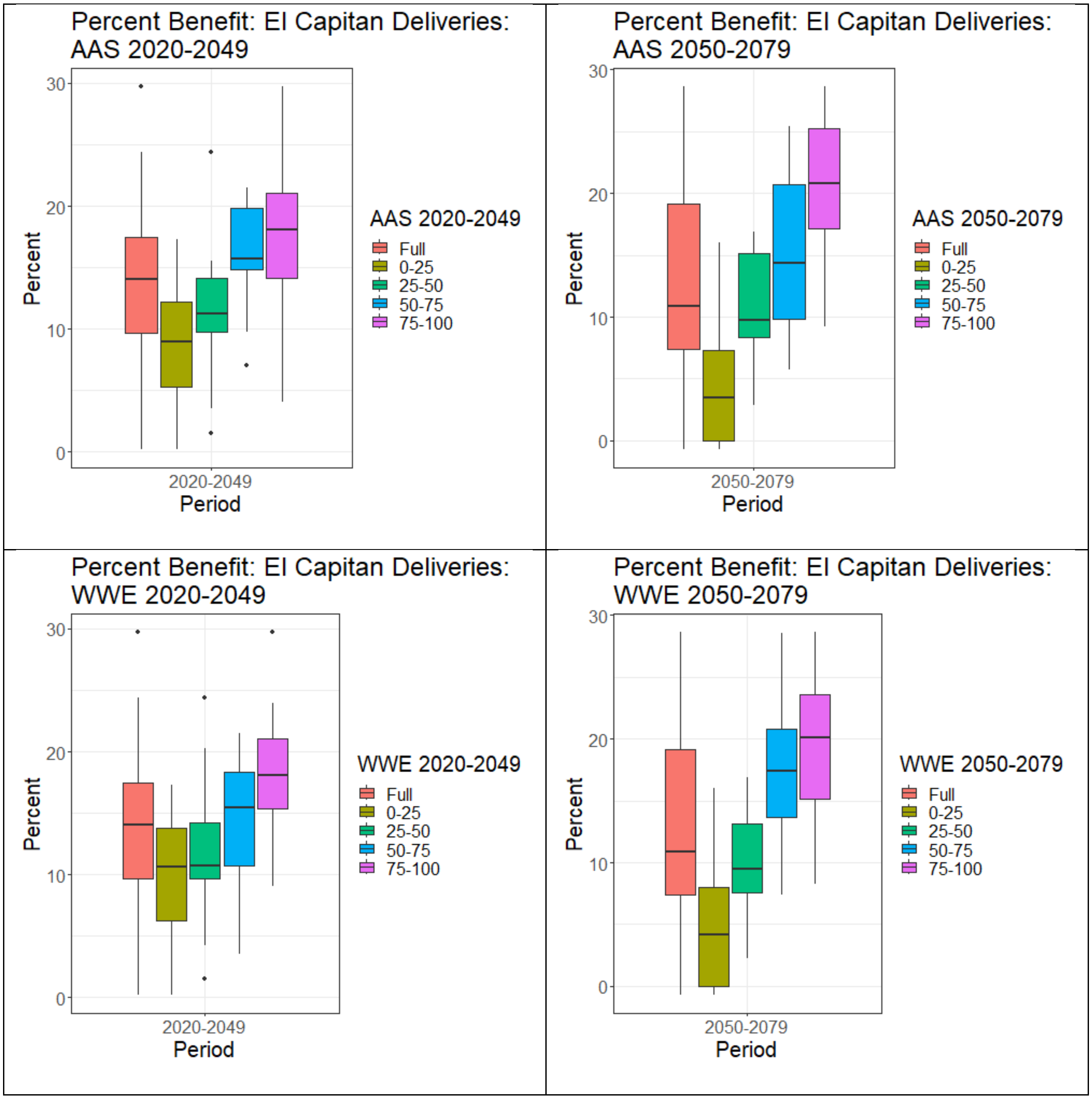


Figure 4-8 – Correlation between Annual Averaged Streamflow (AAS) and FIRO Benefit for the 2020-2049 Climate Period.

El Capitan


Percent Benefit: El Capitan Deliveries: AAS 2020-2049
Percent
Period
2020-2049
AAS 2020-2049
Full
0-25
25-50
50-75
75-100
Percent Benefit: El Capitan Deliveries: AAS 2050-2079
Percent
Period
2050-2079
AAS 2050-2079
Full
0-25
25-50
50-75
75-100
Percent Benefit: El Capitan Deliveries: WWE 2020-2049
Percent
Period
2020-2049
WWE 2020-2049
Full
0-25
25-50
50-75
75-100
Percent Benefit: El Capitan Deliveries: WWE 2050-2079
Percent
Period
2050-2079
WWE 2050-2079
Full
0-25
25-50
50-75
75-100
0
10
20
30

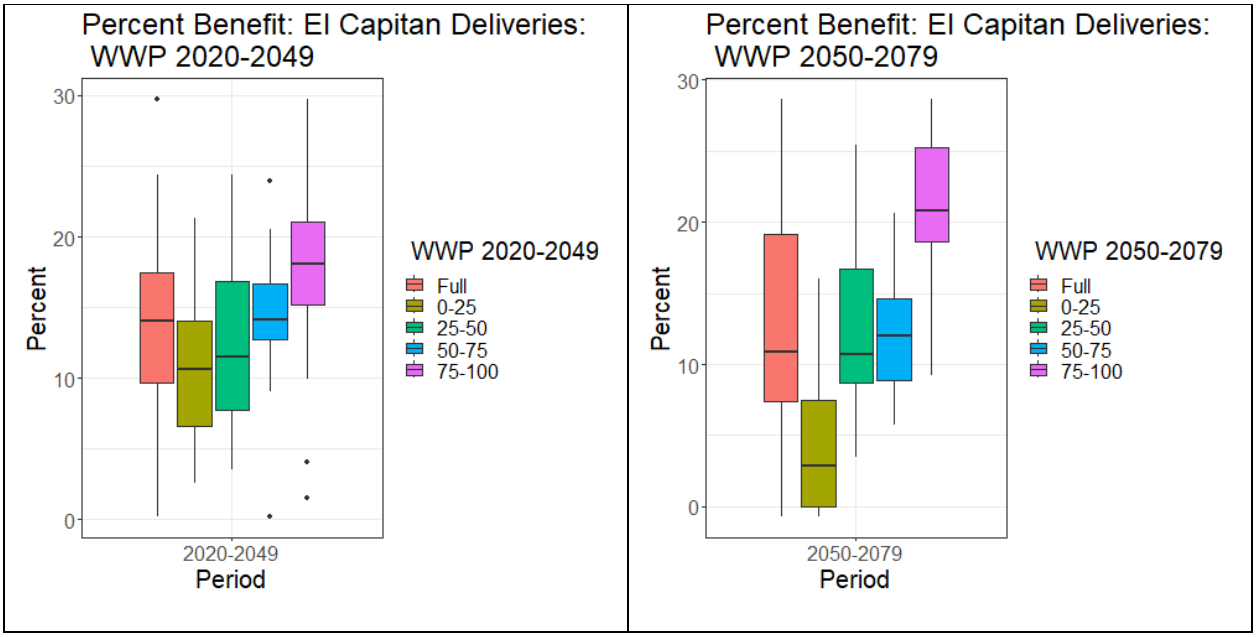
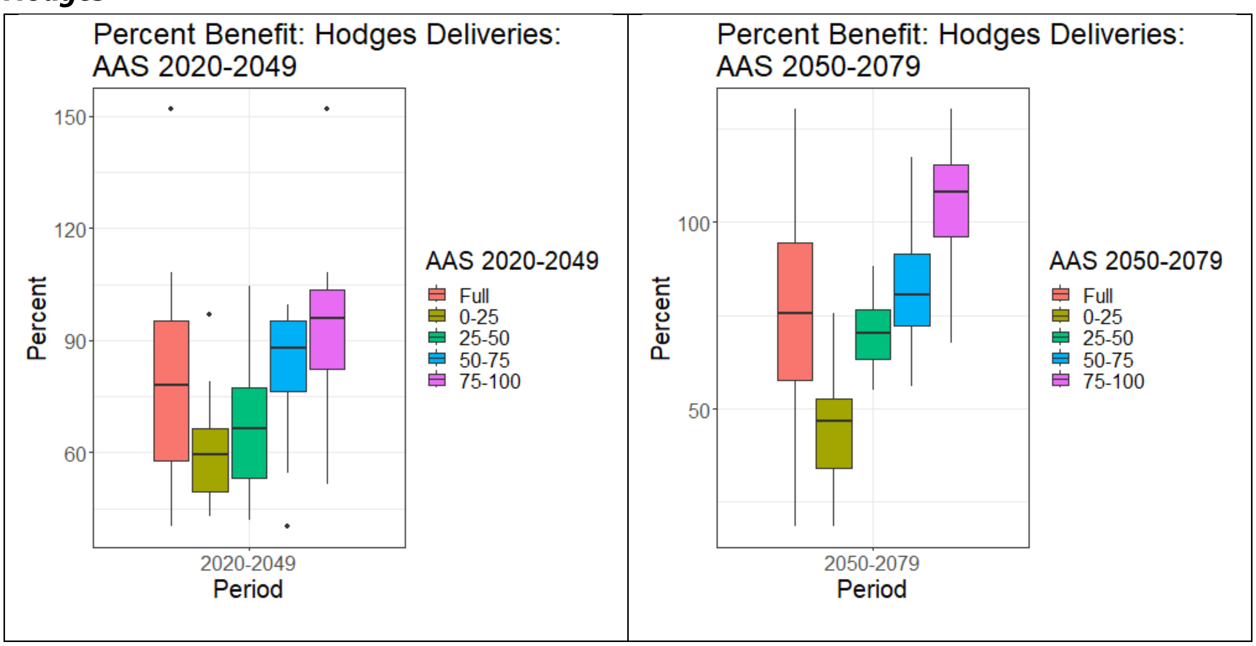


Figure 4-9 – Correlation between El Capitan Deliveries and Selected Streamflow Characteristics: Annual Average Streamflow (AAS), Wet Weather Event count (WWE), and percent of inflow from wet weather events (WWP).

Hodges



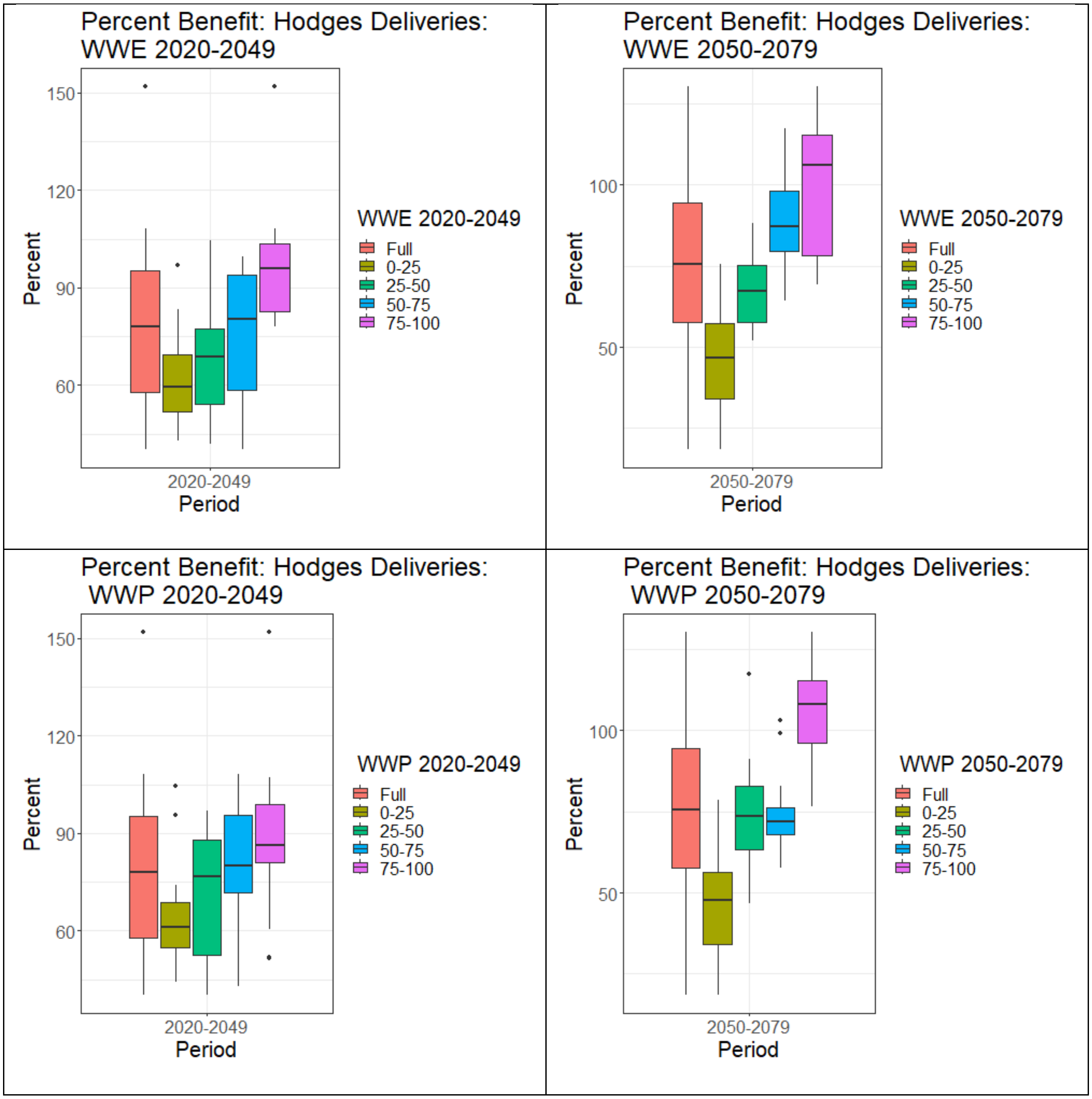


Figure 4-10 – Correlation between Hodges Deliveries and Selected Streamflow characteristics: Annual Average Streamflow (AAS), Wet Weather event count (WWE), and percent of inflow from wet weather events (WWP).

At both El Capitan and Hodges we see a similar correlation with streamflow. With Increased AAS, or an increase in the number of Wet Weather Events, the potential benefit of FIRO increases. This result is consistent with the results seen using the period of record where FIRO benefit is limited in dry years simply by there being no risk of exceeding reservoir elevation restrictions and thus no FIRO operations are triggered. However, during wet years, or years with a large number of high inflow events, FIRO operations may result in nearly a 20% increase to El Capitan Deliveries, and approximately 85% increase for El Capitan Deliveries.

4.1.5 Sensitivity of FIRO Benefit to different operations scenarios

In addition to the above examination of the potential future performance of FIRO under climate change scenarios, we examined a number of operational changes and their potential interactions with FIRO. In this section we will examine the benefit of FIRO under these operational scenarios:

1. Forecast horizon
    a. Operations were modeled reflecting a change in the Forecast Horizon used when determining FIRO releases from the baseline 10 days, to 6 and 3 days.
2. Modifications to El Capitan's Pipeline capacity
    a. Reductions in El Capitans Pipeline capacity were examined from it's current value of 50 MGD to 40,30,20 MGD
3. Changing level restrictions at El Capitan
    a. Year round level restrictions at El Capitan were examined to simulate potential future operating scenarios and their impact on FIRO capabilities. This elevation limit is such that if the reservoir ever exceeds this elevation, releases must be made. In addition to the baseline value of 700 feet, 680,690,710, and 720 were examined
4. Restrictions to El Capitan Deliveries due to water quality concerns.
    a. In discussion with COSD, a number of timer periods were determined to simulate the operational impacts of restrictions on the reservoir due to Water Quality concerns. In the baseline runs examined above, no restrictions were simulated. The time periods determined were two week or full month periods in February, March, and April.

Forecast Horizon

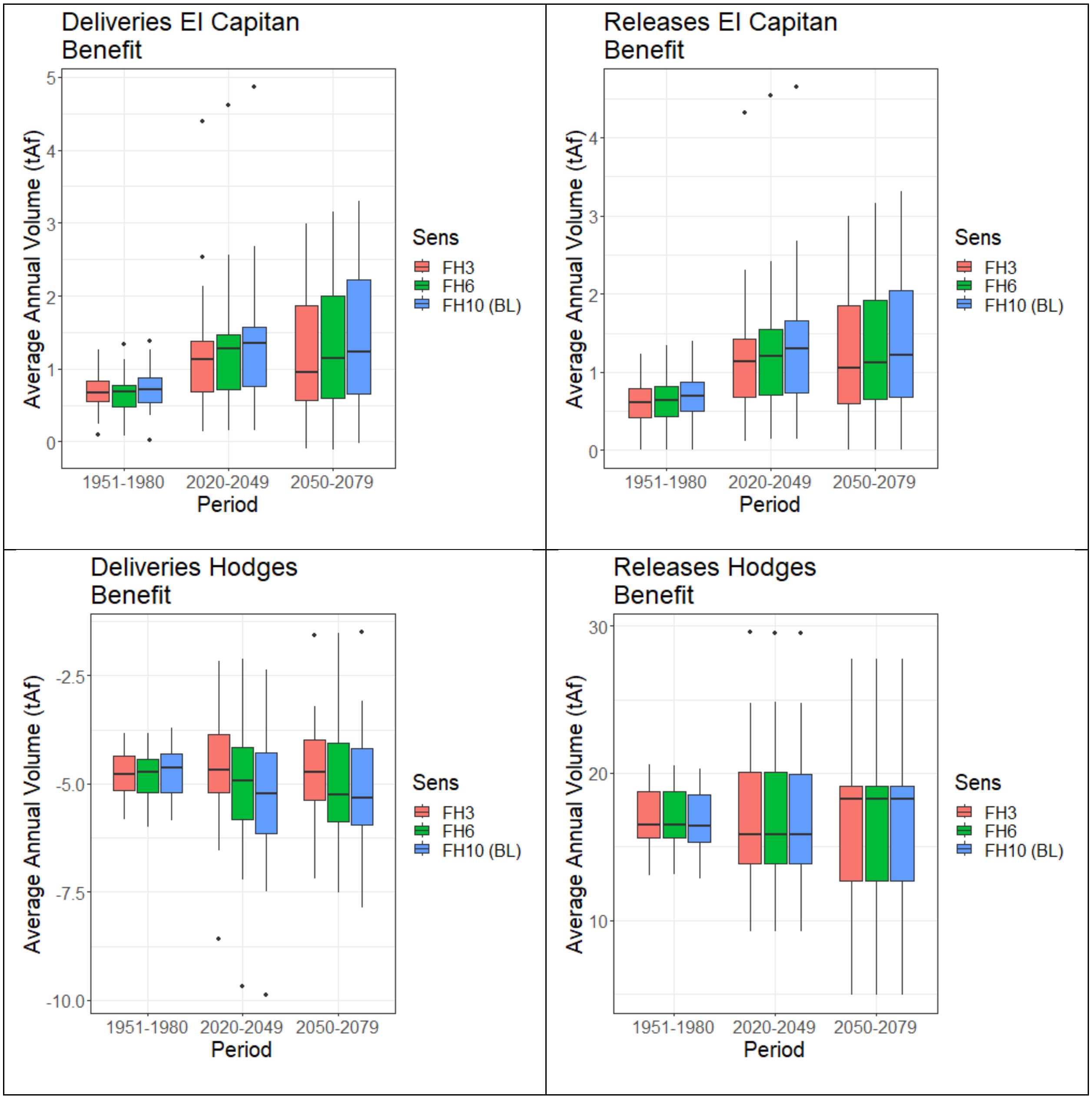


Figure 4-11 – Sensitivity of El Capitan and Hodges Deliveries to changing Forecast Horizon

As shown in Figure 4-11, with a reduced forecast horizon we observe a decline in FIRO benefit at El Capitan (top row). This is expected as the Forecast Horizon is the limiting factor in how much water can be drawn out of the reservoirs before a high inflow event. For El Capitan (Figure 4-11, top row), each additional day corresponds to the pipeline limit of 50 MGD. This result is simply that with decreasing forecast horizon by *n* days, there is a reduction of *n**50 *MGD* in the potential deliveries made prior to releasing water as a result of violating the elevation restriction. For Hodges, we appear not to see much sensitivity to the forecast horizon indicating that the rate at which water can be transferred out of Hodges is not the limiting factor.

El Cap Pipeline Capacity

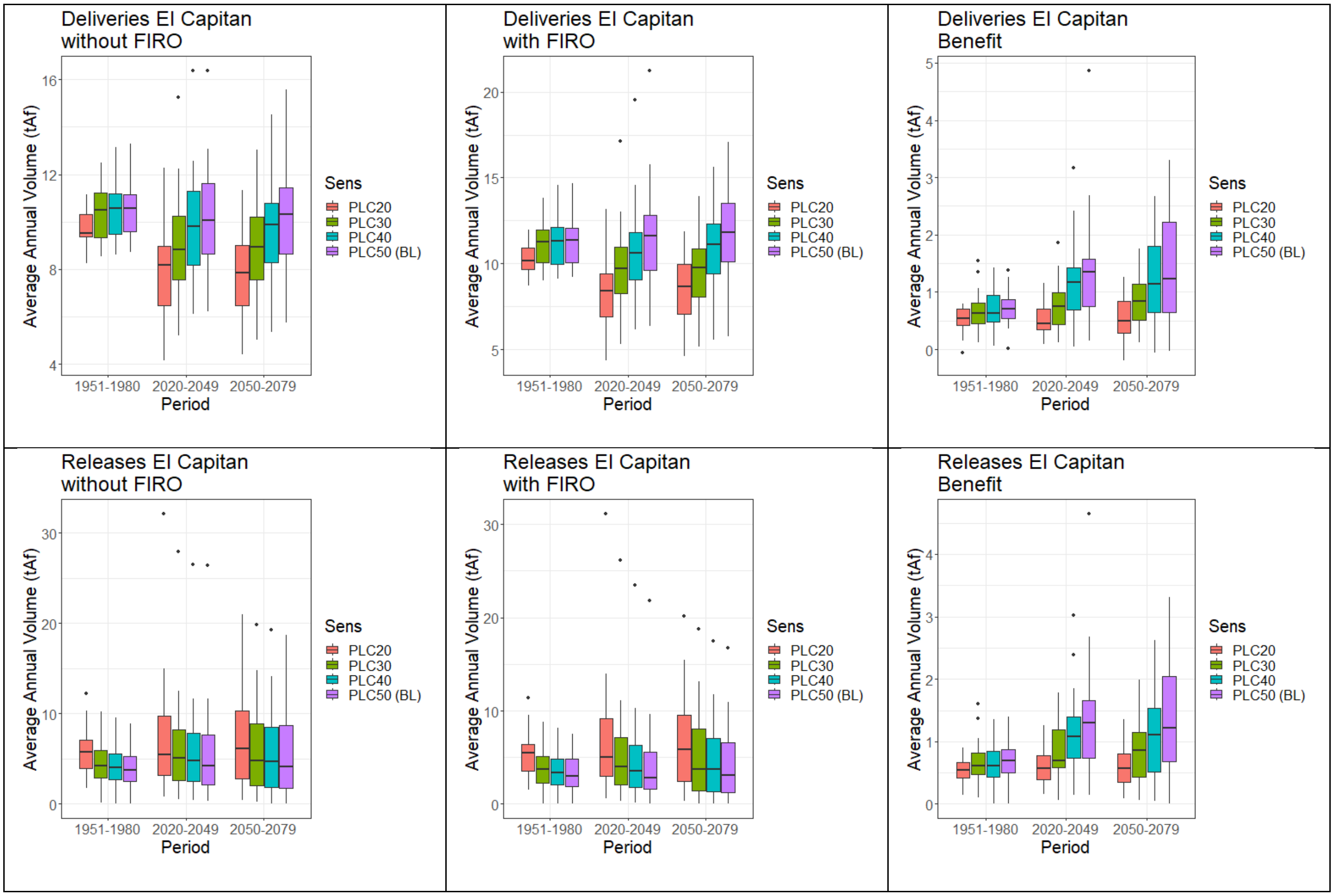


Figure 4-12 – Sensitivity of El Capitan Deliveries and Releases to changing Pipeline Capacity at El Capitan. PLC stands for Pipeline Capacity and the value corresponds to the capacity in MGD e.g. PLC 20 indicates a Pipeline capacity of 20 MGD.

For Changing Pipeline Capacity (PLC) at El Capitan, we examine capacities of 20, 30, 40 and 50 MGD (PLC20, PLC30, PLC40, and "baseline" respectively). As shown in Figure 4-12, we observe reduced Deliveries and Releases with lower pipeline capacity for both existing operations and with FIRO. Under all operating scenarios FIRO benefit was observed with a reduction in the net benefit corresponding to the reduced outflow capacity.

El Capitan Level Restriction

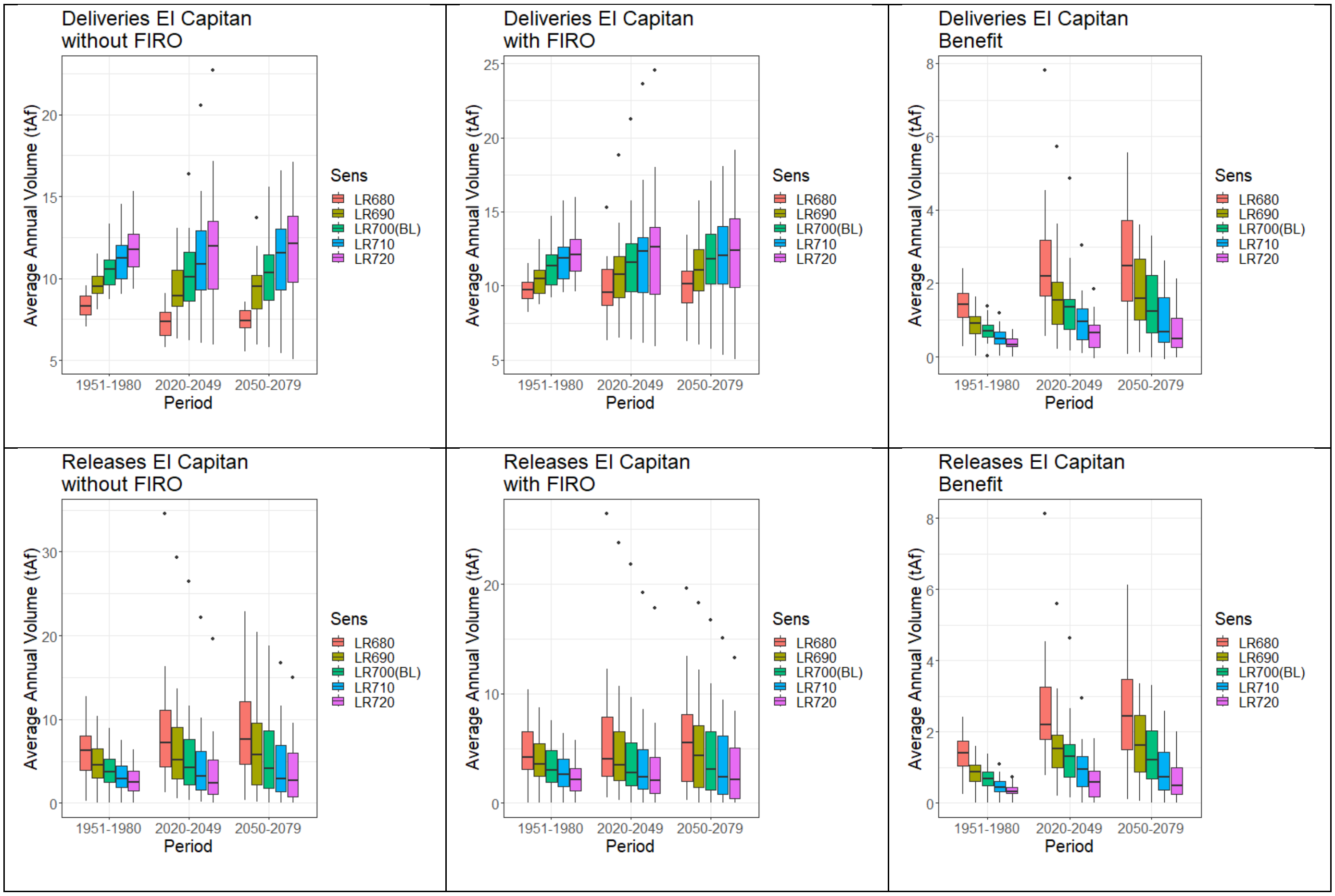


Figure 4-13 – Sensitivity of El Capitan Deliveries and Releases to changing year-round Level Restrictions at El Capitan. LR stands for Level Restriction and values indicate said restriction in Feet. E.g. LR 690 Corresponds to a Level Restriction of 690 ft.

Under changing Level Restriction (LR) scenarios, we see an increase in Deliveries and a reduction in Releases at higher level restrictions in both current operations and with FIRO. With higher level restrictions, we also observe a decrease in FIRO benefit. This is due to an overall reduction in the need for FIRO operations as a result of the increased capacity of the reservoir. The increased capacity of the reservoir results in fewer violations of the elevation requirement and this fewer instances of Releases. At low level restrictions, e.g., LR680, FIRO operations occur more often due to the reduced capacity, and so the benefit from FIRO is larger.

Water Quality

The Water Quality Scenarios do not permit deliveries at specific windows each water year as follows:

- LR1: No deliveries for the first 14 days of February
- LR2: No deliveries for the first 14 days of March
- LR3: No deliveries for the first 14 days of April

- LR4: No deliveries for the month of February
- LR5: No deliveries for the month of March
- LR6: No deliveries for the month of April

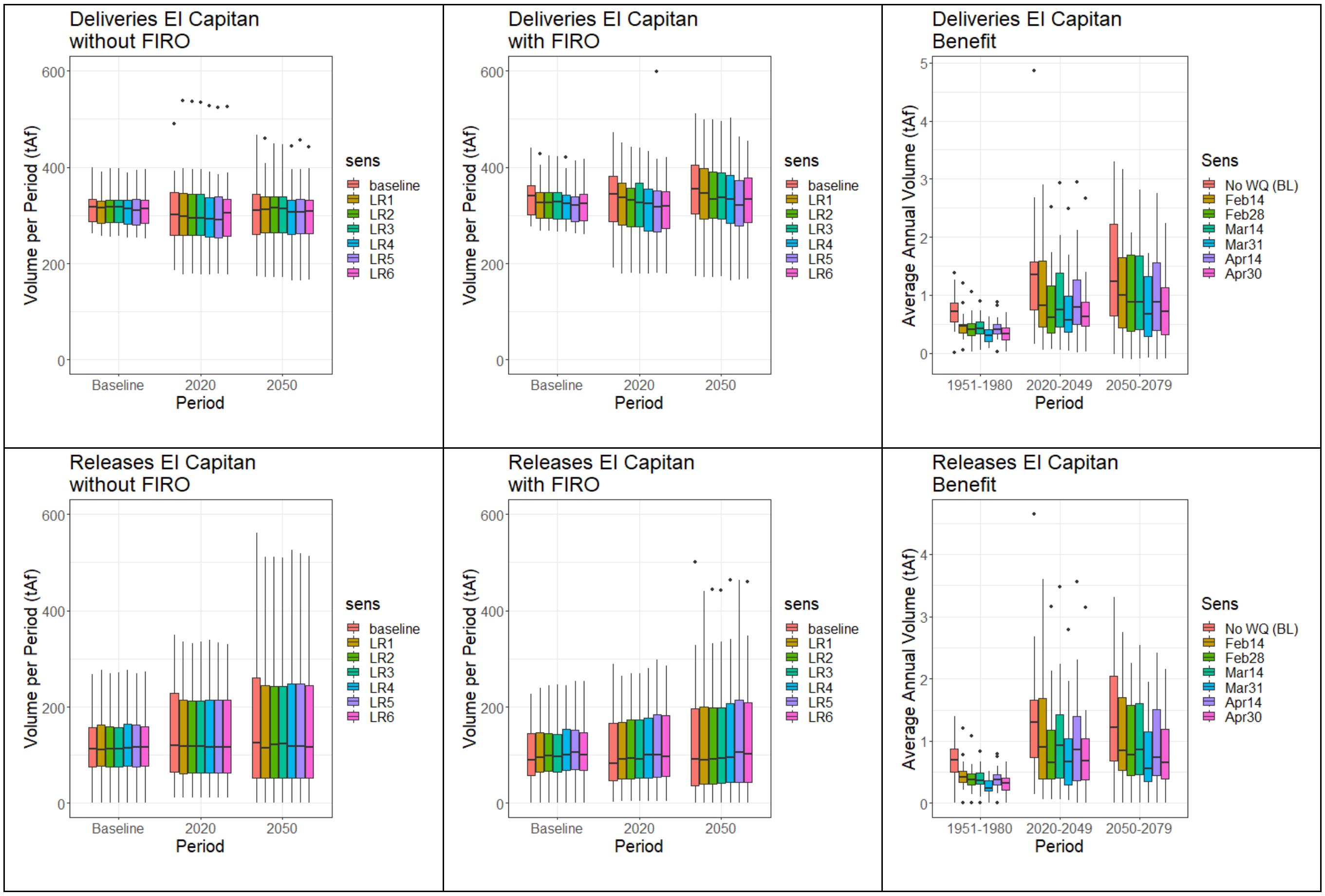


Figure 4-14 – Sensitivity of El Capitan Deliveries and Releases to changing Water Quality restrictions at El Capitan.

As seen in Figure 4-14, there is some slight reduction in Deliveries and Releases in the without FIRO scenario. The FIRO benefit declines under all WQ scenarios, with the restrictions in March and April (LR2,3,5,6) showing a further impact on Deliveries than restrictions in February. Overall, there is only a modest impact to operations, and a modest benefit from FIRO under all WQ scenarios.

4.2 Next Steps to Assess Feasibility of FIRO of COSD Reservoirs

The work documented in this report represents a preliminary exploration into the potential benefits of FIRO for the COSD reservoir system with a consideration of possible climate futures and the sensitivity to selected system parameters included. Additional steps are warranted to assess the feasibility of FIRO more comprehensively for COSD reservoirs and ultimately implement FIRO in the City's daily operations. The first step will be for SDPUD to test the SDFIROSim model created by this project. A user interface is being developed (to be finalized by the culmination of the current project at the end of May 2023) to facilitate the testing. In addition to the testing of SDFIROSim in SDPUD's actual operations, other formal steps can be initiated to make progress towards the goal of incorporating FIRO into the official operation of COSD reservoirs.

The recommended steps for assessing the feasibility of FIRO of COSD reservoirs include a Preliminary Viability Assessment (PVA), Water Operations Strategy document, Final Viability Assessment (FVA), and coordination with responsible agencies (e.g., California Department of Water Resources – Division of Safety of Dams) with the authority to ensure adequate flood control goals are met. The PVA will provide an evaluation of the viability of FIRO as a strategy to improve water supply reliability for COSD while not impairing flood risk management at a minimum (and potentially improving the flood control operations). The PVA will also consider the ability of FIRO to meet water quality objectives. The outcomes of the PVA will include: 1) a determination of whether FIRO is viable enough to take more concrete steps towards implementing the approach into SDPUD's actual operations; 2) a Water Operations Strategy document that will give a more complete accounting of how FIRO can be implemented into all aspects of the system's reservoir operations than the results given by the current project's conclusions documented herein. If the PVA determines that FIRO is viable, then an FVA will be initiated based on recommendations from the PVA. The FVA will address any remaining aspects of the operations that need to be more fully assessed before formal incorporation of FIRO into the SDPUD operation of the COSD reservoirs can be achieved. Results of the FVA will be used in the final step of coordination/approval with/from agencies responsible for flood safety and ensuring regulatory compliance is met.

Abbreviations and Acronyms

AAS	Annual Average Streamflow
af	Acre-feet
AGGI	Annual Greenhouse Gas Index
AORC	Analysis of Record Calibration
BCSD	Bias Correction and Spatial Downscaling
cfs	Cubic feet per second
CHPS	Community Hydrologic Prediction System
CMIP5	Coupled Model Intercomparison Project 5
CNRFC	California-Nevada River Forecast Center
COSD	City of San Diego
CT	Central Timing
CWASim	County Water Authority Simulation Model
DWR	California Department of Water Resources
DYC	Total number of dry years in the 30-year period
DYL	Average length of periods of consecutive dry years
°C	degrees Centigrade
°F	degrees Fahrenheit
ECMWF	European Centre for Midrange Weather Forecasts
ERA5	5th generation ECMWF atmospheric reanalysis of global climate
FIRO	Forecast-Informed Reservoir Operations
FVA	Final Viability Assessment
GCM	Global Circulation Model
GEFS	Global Ensemble Forecast System
GHG	Greenhouse gas
HAS	Hydrometeorological Analysis and Support
HEFS	Hydrologic Ensemble Forecast Service
IQR	Interquartile range
IPCC	Intergovernmental Panel on Climate Change
LR	Level Restriction
MAT	Mean areal temperature
MEFP	Meteorological Ensemble Forecast Processor
MEFPPE	Meteorological Ensemble Forecast Processor Parameter Estimator
MGD	Million gallons per day
NOAA	National Oceanic and Atmospheric Administration
MAP	Mean areal precipitation
PC	Percent change
PRISM	Parameter-elevation Relationships on Independent Slopes Model
PVA	Preliminary Viability Assessment
QPE	Quantitative Precipitation Estimates

QPF	Quantitative Precipitation Forecasts
RCP	Representative Concentration Pathway
RMSE	Root mean squared error
RSNWELEV	Rain-Snow Elevation Model
SAC-SMA	Sacramento Soil Moisture Accounting Model
SDFIROSim	San Diego Forecast-Informed Operations Simulation Model
SDPUD	San Diego Public Utility District
SNOW-17	Snow Model
TAF	thousand acre-feet
USGCRP	United States Global Change Research Program
VIC	Variable infiltration capacity
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WTP	Water Treatment Plant
WY	Water year
WWE	Wet weather events
WWP	Percent of annual inflow due to WWE inflow
WQ	Water quality
ZELV	Mean areal freezing level

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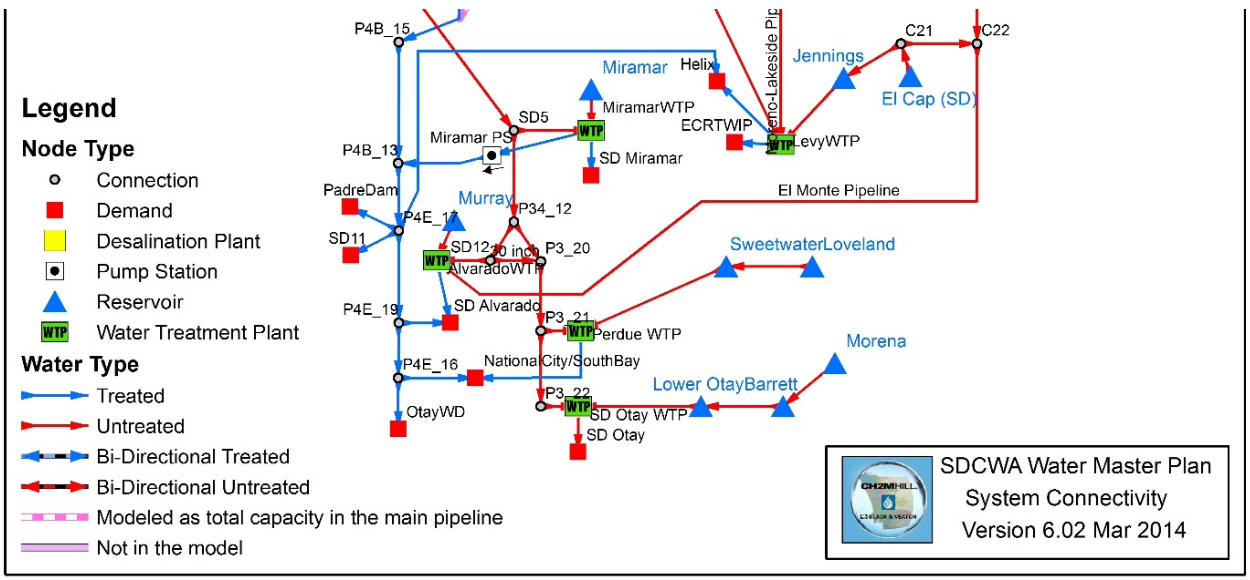
Appendix A – Notes on CWASim Documentation

Basin Study Model South Container review notes

This review is based on the baseline 2015 current climate scenario of the Basin Study Model. The review focuses on the City of San Diego's portion of the system.

In the South Container, there are 10 reservoir containers, 12 demand containers, 1 tank container, 5 water treatment plants (WTP).

Schematic:



Morena/Barret/Lower Otay System

Reservoirs:

Morena/Barret/Lower Otay Reservoirs

Operations description in the documentation:

The Morena, Barrett, and Lower Otay reservoirs have a combined usable capacity of 138 TAF. They can supply untreated water to the Lower Otay WTP. Morena reservoir spills into Barrett based on City of San Diego practices captured in the rule curve, and Morena reservoir is recharged with local runoff. The Lower Otay reservoir can be filled with releases from Barret or

MWD water from the aqueduct. MWD will fill only Zone 2 of the Lower Otay reservoir and only after Barret has released into it.

Operations equations in the model:
Morena+Barret+Lower Otay Combined capacity=50200+37900+49849=137949af

Morena

Maximum storage: IN_MaxStorage.Max_MOR=50,200 af
Minimum storage: MinSto =654af
Max release capacity: MaxRel= 20500cfs=
Inflow:
XL_ISHYD(MonthHydrology,5)*ClimateScen_Res_Inflow(5,Month,Climate_Scenario_Index)
Outflow Evaporation+Releases+Flood_Morena
Flood: max(0cfs,min(MaxRel,(STO_Morena-MinSTO)/1day,(ZS.z1+ZS.Unused)/1day)-Releases) z1=7432af
Release water to Barett: Request= STO_BAR.inRequest
Loss: A_MOR.Releases*0.12
Barrette

Maximum storage: IN_MaxStorage.Max_BAR=37,900 af
Minimum storage: MinSto = 4520af, 6500af in the input Excel spreadsheet, inconsistent with input spreadsheet
Max release capacity: MaxRel= 19 MGD
Inflow: IN+Mor_Bar+STO_MOR.Flood,In which IN =
XL_ISHYD(MonthHydrology,2)*ClimateScen_Res_Inflow(2,Month,Climate_Scenario_Index),
Mor_Bar= STO_MOR.Releases_2-STO_MOR.Losses
Outflow Evaporation+Releases+Flood_Barret
Flood: max(0cfs,min(60000cfs,(STO_Barret-MinSTO)/1day,(ZS.z1+ZS.Unused)/1day)-Releases) z1=3338af
Release water to Lower Otay from May 1 till Lower Otay full: Requested=
if(BAR_LOTcheck=true,STO_LOTA.Barret,0cfs)
Releases=max(0cfs,min((0*ZS.z8+0*ZS.z7+0*ZS.z6+0*ZS.z5+0*ZS.z4+ZS.z3+ZS.z2+ZS.z1+ZS.Unused)/1day,MaxRel,Requested,(STO_Barret-MinSTO)/1day))
Lower Otay

Maximum storage: IN_MaxStorage.Max_LOT=49,849 af

Minimum storage: MinSto = 3730af

Max release capacity: MaxRel= 50000cfs

Inflow: MWDFill+Bar_LOT+IN+PURE. In which IN =
XL_ISHYD(MonthHydrology,6)*ClimateScen_Res_Inflow(6,Month,Climate_Scenario_Index),
MWDFill =A_P3_22.LOtayFill, Bar_LOT =STO_BAR.Releases_2-STO_BAR.Total_Losses

Outflow Evaporation+Releases+Flood_LowerOtay

Flood: Flood_LowerOtay = max(0cfs,min(MaxRel,(STO_LowerOtay-MinSTO)/1day,(ZS.z1+ZS.Unused)/1day)-Releases), z1=4612af

Otay's release goes to Otay_WTP only

STO_LowerOtay.Withdrawal_Rate= WTP_Local + WTP_WA + flood,

In which, WTP_Local=WTP_OTY.Pure_2= AREQ_WTP.Local= min(STO_LOTA.STO_AV4REL,STO_LOTA.Local_LOTY/1day,DEM_SDOTY.REQS[1],STO_LOTA.MaxRel), STO_LOTA.STO_AV4REL= max(0cfs,min(ZS.z2+ZS.z1+ZS.Unused,(STO_LowerOtay-MinSTO))/1day)*STObyyr1[LOTA],

The Lower Otay Reservoir release is equal to Otay Treatment Plant's water request. This request is calculated based on previous inflow to the treatment plant, the required delivery from SD Otay demand unit.

TWP_WA=WTP_OTY.AREQOtay= AREQ_WTP.WA= min(STO_LOTA.WA_LOTAY/1day,STO_LOTA.STO_AV4REL)

Flood= Flood_LowerOtay= max(0cfs,min(MaxRel,(STO_LowerOtay-MinSTO)/1day,(ZS.z1+ZS.Unused)/1day)-Releases)

Otay WTP

Operations description in the documentation:

The Otay WTP has baseline capacity of 40 mgd (61 cfs) and can receive untreated water from Lower Otay reservoir. The WTP supplies SD Otay and Cal-Am, as described in Section 4.1.1. It can also utilize MWD untreated supplies.

Operations equations in the model:

WTP_Capacity[Otay]=34 MGD, inconsistent with model documentation of 40 MGD! However, it was 34 MGD in the Basin Study report.
Otay WTP receives raw water from Otay reservoir and Pipeline 3 (P3_22):
StoReleases=STO_LOTA.Releases_For_Demand+A_P3_22.Del_OTYTunnel7 (0) and
P5Inflow=A_P3_22.DEL_sdotay2
STO_LOTA.Releases_For_Demand= A_LOTA.WTP_Local+A_LOTA.WTP_WA, in which:
A_LOTA.WTP_Local= WTP_OTY.Pure2= AREQ_WTP.Local
A_LOTA.WTP_WA= WTP_OTY.AREQOtay= AREQ_WTP.WA
Delivery of treated water to SD Otay and Cal-Am:
DEM_SDOtay.Del_S1=WTP_OTY.Local+WTP_OTY.Pure

WTP_OTY.Local =A_WTP.WA_LOTA= min(STO_LOTA.WTP,DEM_SDOTY.REQS[1]), STO_LOTA.WTP= STO_LOTA.A_LOTA.WTP_WA
WTP_OTY.Pure=A_WTP. Local_LOTA= min(STO_LOTA.WTP_Pure,DEM_SDOTY.REQS[1]), STO_LOTA.WTP_Pure= STO_LOTA.A_LOTA.WTP_Local
The delivery from Otay Water Treatment Plant equals to Lower Otay Reservoir's actual release.
DEM_SDOtay.Del_S2=WTP_OTY.MWD= A_WTP. MWD= min(DEM_SDOTY.REQS[2],A_P3_22.DEL_sdotay2)
DEM_SDOtay.Del_S7=WTP_OTY.SV= A_WTP.SV=0

Demand

The demand logic is set up to have 7 sources of water. These are prorized as follows:

Source1 : Water released from local storage (Will be treated at local WTP)
Source2 : MWD Raw water (Will be treated at local WTP)
Source3 : TOVWTP Treated Water (Will request Pipeline 5 water)
Source4 : MWD Treated Water (Pipeline 4 or 1&2 water)
Source5 : Desalt CP
Source6 : Desalt Carlsbad
Source7 : San Vicente

San Diego Otay (DEM_SDOTY)

Operations description in the documentation:

San Diego Otay is located in the southern part of the system and is a portion of the City of San Diego demands. The agency historical average daily delivery is 1 cfs, ranging from approximately 4cfs to 58 cfs. San Diego Otay receives local water from the Barrett, Lower Otay, and Morena reservoirs and untreated water via the Second Aqueduct. The untreated water supplied to San Diego Otay is treated at the San Diego Otay WTP. Configured, but not currently modeled, is the ability for San Diego Otay to receive MWD treated water via the treated water pipeline. The agency capability to meet deliveries under baseline conditions is limited by San Diego Otay WTP's capacities. The model is configured to allow San Diego Otay to receive treated water from MWD, however it is not a baseline assumption. San Diego Otay could physically have the ability to receive both Carlsbad and Camp Pendleton desalinated water via P4; however this is currently not configured in the model.

Operations equations in the model:

Only 2 sources of water is modeled for SD Otay

DEM_SDOtay.Del_S1=WTP_OTY.Local+WTP_OTY.Pure

WTP_OTY.Local =A_WTP.WA_LOTA= min(STO_LOTA.WTP,DEM_SDOTY.REQS[1]), STO_LOTA.WTP= STO_LOTA.A_LOTA.WTP_WA= WTP_OTY.AREQOtay

WTP_OTY.Pure=A_WTP. Local_LOTA= min(STO_LOTA.WTP_Pure,DEM_SDOTY.REQS[1]), STO_LOTA.WTP_Pure= STO_LOTA.A_LOTA.WTP_Local = WTP_OTY.Pure_2
DEM_SDOtay.Del_S2=WTP_OTY.MWD= A_WTP. MWD= min(DEM_SDOTY.REQS[2],A_P3_22.DEL_sdotay2)

DEM_SDOtay.Del_S7=WTP_OTY.SV= A_WTP.SV=0

REQS=vector(max(0,IN_Excel.Switches[row,SD_Otay])*max(0cfs,DEM*AS[row]-(if(SOT[1]<SOT[row],S1_prv,0cfs)+if(SOT[2]<SOT[row],S2_prv,0cfs)+if(SOT[3]<SOT[row], S3_prv,0cfs)+if(SOT[4]<SOT[row],S4_prv,0cfs)+if(SOT[5]<SOT[row],S5_prv,0cfs)+if(SOT[6] <SOT[row],S6_prv,0cfs)+if(SOT[7]<SOT[row],S7_prv,0cfs)+if(SOT[8]<SOT[row],S8_prv,0cfs)+if(SOT[9]<SOT[row],S9_prv,0cfs)+if(SOT[10]<SOT[row],S10_prv,0cfs))))

Row=1-7, corresponding to the 7 sources of water
AS (Active Source) is the supply and agency switch table in the input.xlsx spreadsheet.
DEM=DEM1+addtDEM
DEM1=SD_Otay=min(MeterCapacities[SD_Otay],Demands[SD_Otay]+CalAm) * S_swt
Demands[SD_Otay] =DailyShape*vector(AnnualDemands[row]/(LeapYear*1d+365d))
AnnualDemands[row]= AdjustedDem= max(vector(0af),GrossDEM-CONSAdj-GW_Supply_1-RCY_Supply_1)= 10543af -929-24-389=9201af
GrossDEM =max(vector(0af),((DFMScale)*XLDemand_Climate_Adjusted))
XLDemand_Climate_Adjusted[SD_Oty]=10543af
AddtDEM is computed from shortage
Question: Cal-American (City of Coronado) got turned off at SD_Otay, should be put back on.

El Capitan/Jennings System

El Capitan Reservoir

Operations description in the documentation:

The El Capitan reservoir has a usable capacity of 113 TAF. It can supply untreated water to the Alvarado and Levy WTPs. The reservoir is recharged with local runoff only and can be released to keep Lake Jennings at a specified level.

By contract Helix Water District is entitled to draw its stored water from the El Capitan reservoir at a maximum rate of 20 mgd (30.85 cfs). No accounts are simulated on the El Capitan reservoir.

Operations equations in the model:

Maximum storage: IN_MaxStorage.Max_ElCap=112,807 af
Minimum storage: MinSto =2820af
Max release capacity: MaxRel=75000cfs ?
Inflow: IN+IN_ELCAP_FROM_SV_actual, in which IN is excel input: (XL_ISHYD(MonthHydrology,3)*ClimateScen_Res_Inflow(3,Month,Climate_Scenario_Index))+ XL_ISHYD(MonthHydrology,11), IN_ELCAP_FROM_SV_actual=STO_SV.toIntertieElCap is the intertie delivery, not modeled in baseline models,

XL_ISHYD(MonthHydrology,11) is the inflow input from Helix, no values

Outflow: max(0cfs,Flood_ElCap-Requested intertieReqOut_ElCap) + max(0cfs,Requested+IntertieReqOut_ElCap-Flood_ElCap)

Flood: Flood_ElCap =min((ZS.z1+ZS.Unused)/1day,MaxRel) z1=62074af

Supply water to Levy WTP, Alvarado WTP and Lake Jennings:
Request=WTP_Levy.ElCap+WTP_Alvarado.ElCap+STO_JEN.ForebayRequest

Delivery table

Priority	**Label**	**Demand**
0	evap	Evap
1	toAlvarado	WTP_Alvarado.ElCap
2	toLevy	WTP_Levy.ElCap
3	toJennings	STO_JEN.ForebayRequest
4	STO_JEN.ForebayRequest	SV_Elcap_Intertie_Req.IN_SV_FROM_ELCAP
5	Intertie_GW	SV_Elcap_Intertie_Req.IN_GW_FROM_ELCAP
6	flood	Flood_ElCap

The rate of 20 MGD to Helix is implemented at WTP_Levy container using the element of MaxHelix: min(MaxHelix,max(0cfs,STW1*STO_ElCAP.Spl_toLevy)), MaxHelix=20MGD

Miramar Lake

Operations equations in the model:

Maximum storage: IN_MaxStorage.Max_MIR =6050 af?
Minimum storage: MinSto =1130af?

Max release capacity: MaxRel=105MGD ?
Inflow: IN+A_Rancho_SD5.DELMirFB+STO_HOD.WA+PURE, in which IN is 0,
PURE is: if(ZS.z2>=0.95*ZoneCapcity.z2,0MGD, Mir_Pure_Selector)

Pure Water San Diego

Phase 1: 33,600 AF/y (30 mgd) from North City Advanced Water Reclamation Plant to Miramar Reservoir by the year 2021. (This option can be set on the WTPSO dashboard)

Outflow: min(REQ_OUT,REL_Lim)+Evap, REQ_OUT= max(0cfs,Flood_Miramar-Requested)+max(0cfs,Requested-Flood_Miramar), REL_Lim= min((0*ZS.z8+0*ZS.z7+0*ZS.z6+0*ZS.z5+0*ZS.z4+0*ZS.z3+ZS.z2+ZS.z1+ZS.Unused)/1day, MaxRel)

Flood: =0af

Supply water to Miramar Water Treatment Plant:

STO_Miramar.Withdrawal_Rate=

Priority	**Name**	**Demand**
1	Evaporation	Evap
2	WTP_Pure	WTP_Miramar.Mir_Pure
3	WTP	WTP_Miramar.AREQMiramar
4	Flood	Flood_Miramar

Levy WTP

Operations description in the documentation:

The Levy WTP has baseline capacity of 106 mgd (164 cfs) and can receive untreated water from Lake Jennings, El Capitan, and San Vicente Reservoir via the Moreno-Lakeside Pipeline. The WTP supplies Helix and ECRTWIP. Levy WTP will request water from first aqueduct only after the Moreno Lakeside pipeline is operating at full capacity or during San Vicente reservoir filling operations.

The Water Authority now owns 36 mgd (56 cfs) of the Levy WTP's capacity. When ECRTWIP's demand of 56 cfs is being requested this represents full use of the Water Authority 36 mgd. The ECRTWIP agencies involved, Lakeside Water District, Otay Water District, and Padre Dam MWD, buy this amount from the Water Authority via the Levy WTP, as long as some other *conditions are met. The remainder of the Levy WTP capacity (70 mgd) belongs to Helix, which is assumed to be sufficient to supply their peak demand.*

Operations equations in the model:

Inflow:

StoReleases+P5Inflow, in which:

StoReleases= STO_ElCAP.toLevy+STO_JEN.Releases_2+STO_SV.toLevyMorLks(no value)+STO_SV.toLevy1 (A_SV1.tolevy1)

P5Inflow=
A_xover_Disag.xoverHelix+A_Rancho_SD5.DEL_Helix+A_Rancho_SD5.DEL_ECRTWIP

Request:

Treated Water Request= STOrelswitch*if(~LoopCount=SOT[1],min(WTP_capacity_1[Levy]-Inflow_prv,DEM_HWD.REQS[1]+STW1*DEM_ECRTWIP.REQS[1]),Loc_REQ_prv)

Request is divided into:

Priority	Label	Demand
1	ElCap	min(MaxHelix,max(0cfs,STW1*STO_ElCAP.Spl_toLevy))
2	SV	min(MorenoLakeside_capWE,STO_SV.splt_toLevy)
3	Jennings	min(STO_JEN.STO_AV4REL,DEM_HWD.REQS[1]+STW1*DEM_ECRTWIP.REQS[1])

Delivery Table:

Priority	Label	Demand
1	Local	min(DEM_HWD.REQS[1]+STW1*DEM_ECRTWIP.REQS[1],STO_ElCAP.toLevy+STO_SV.toLevy1+STO_JEN.Releases_2)
2	MWD	min(DEM_HWD.REQS[2]+DEM_ECRTWIP.REQS[2],P5Inflow)
3	MorenoLakeside	min(WTP_Out_Levy,STO_SV.toLevyMorLks)

Alvarado WTP

Operations description in the documentation:

The Alvarado WTP has baseline capacity of 200 mgd (309 cfs), can receive untreated water straight from the aqueduct, from Lake Murray, or from San Vicente and El Capitan reservoirs via the El Monte Pipeline. The WTP supplies the San Diego Alvarado Area.

The WTP can receive water from Murray's seasonal pool, Seasonal storage at El Capitan (via El Monte Pipeline), seasonal storage at San Vicente (via El Monte Pipeline), and San Vicente Carryover storage (Via Aqueduct). The first three sources are under the same source priority (locally stored water) and the order of preference is based on the fullest reservoir, on a percentage basis. The other two sources, MWD untreated and San Vicente carryover is based on the priority, as discussed in Section 4.2, the user set for those sources.

Operations equations in the model:

Inflow:
Inflow= StoReleases+Imported
StoReleases =STO_MUR.Actual_Releases+ElMonte_S+A_SD12.Del_AlvTunnel7
Imported= A_SD12.DEL_Alvarado2
Request:
Treated Water Request= if(~LoopCount=SOT[1],min(min(TPCapacity,ElMonteCap)-Inflow_prv,DEM_SDALV.REQS[1]),Loc_REQ_prv)
Request is divided into:

Priority	Label	Demand
0	Murray_Pure	if(~LoopCount=SOT[1],min(STO_MUR.PURE,DEM_SDALV.REQS[1],STO_MUR.STO_AV4REL,STO_MUR.MaxRel),AreaQPURE_prv)
SOT[1]+1-STO_MUR.Pfull	Murray1	if(~LoopCount=SOT[1],min(DEM_SDALV.REQS[1],STO_MUR.STO_AV4REL),AreaQMUR_prv)
SOT[1]+1-STO_GWBasin.Pfull	GW1	if(~LoopCount=SOT[1],min(ElMonteCap-ElMonte_prv,min(DEM_SDALV.REQS[1],STO_GWBasin.Spl_toAlvarado)),AreaQGW_prv)*GW_ExtractionOn

SOT[1]+1-STO_ElCAP.Pfull	ElCap1	if(~LoopCount=SOT[1],min(ElMonteCap-ElMonte_prv,min(DEM_SDALV.REQS[1],STO_ElCAP.Spl_toAlvarado)),AreaQElCap_prv)
SOT[1]+1-STO_SV.Pfull_CitySeasonal	SV1	if(~LoopCount=SOT[1],max(0cfs,min(DEM_SDALV.REQS[1],ElMonteCap-ElMonte_prv,STO_SV.splt_toAlvarado_2)),AreaQSV_prv)

Delivery Table*:*

Priority	**Label**	**Demand**
0	Pure	min(DEM_SDALV.REQS[1],STO_MUR.PURE,STO_MUR.STO_AV4REL,STO_MUR.MaxRel)
1	Murray_MWD	min(DEM_SDALV.REQS[1],STO_MUR.WTP,STO_MUR.STO_AV4REL,STO_MUR.MaxRel)
1	Local_GWSto	STO_GWBasin.toAlvarado
1	Local_ElCap	STO_ElCAP.toAlvarado
1	Local_Seasonal_SV	Out_ElMonte_x
2	MWD	min(DEM_SDALV.REQS[2],MWD_U_REQ)
3	Carryover_SV	A_SD12.Del_AlvTunnel7

Treated Water Request= if(~LoopCount=SOT[2],min(min(TPCapacity-Inflow_prv,SD12_cap-UntreatedTotal.SD12_div_prv),DEM_SDALV.REQS[2]),MWD_U_REQ_prv)

San Vicente Carryover Request= if(~LoopCount=SOT[7],min(min(TPCapacity-Inflow_prv,SD12_cap-UntreatedTotal.SD12_div_prv),DEM_SDALV.REQS[7]),SV_DEL_prv)*STO_SV.TunnelLogic

Miramar WTP

Operations description in the documentation:

The Miramar WTP has baseline capacity of 215 mgd (333 cfs), can receive untreated water straight from the aqueduct, from Lake Miramar, or from San Vicente. The WTP can supply directly the San Diego Miramar Area, plus it could pump treated water (via Miramar pump *station) to the SD 11 area, and also theoretically to Padre Dam MWD, and Otay Water District, although this latter capability is unused. The WTP can receive water from MWD, from Miramar Reservoir seasonal pool, from seasonal storage at San Vicente (Via Tunnel and aqueduct), and from San Vicente Carryover storage (Via Tunnel and Aqueduct). The first two sources are under the same source priority (locally stored water), as discussed in Section 4.2, and the order of preference is based on the most full reservoir, on a percentage basis. Use of the other two sources, MWD untreated and San Vicente carryover is based on the priority the user set for those sources.*

Operations equations in the model:

Inflow:

Inflow= StoReleases+Imported

StoReleases = STO_MIR.WTP+A_Rancho_SD5.DEL_Mirtunnel7+A_Rancho_SD5.DEL_MiramarSV1+STO_HOD.City+STO_MIR.WTP_Pure

P5Inflow= A_Rancho_SD5.DEL_Miramar+A_Rancho_SD5.DELMirTK

Miramar Can Supply the Following Demands: SD Miramar, Padre Dam, Otay WD, SD11, Del Mar

Request:

Loc_Req= if(~LoopCount=SOT[1],min(TPCapacity-Inflow_prv,DEM_SDMIR.REQS[1]+DEM_DM.REQS[1]),Loc_REQ_prv)

WMD_U_REQ=if(~LoopCount=SOT[2],min(TPCapacity-Inflow_prv,DEM_SDMIR.REQS[2]+DEM_DM.REQS[2]+min(DEM_OWD.REQS[2]+DEM_PD.REQS_1[2]+DEM_SD11.REQS[2],MiramarPS_cap-MiramarPS_prv)),min(Inflow_prv,MWD_U_REQ_prv))

SV_REQ= if(~LoopCount=SOT[7],min(TPCapacity-Inflow_prv,DEM_SDMIR.REQS[7]+DEM_DM.REQS[7]+min(DEM_OWD.REQS_1[7]+DEM_PD.REQS_1[7]+DEM_SD11.REQS[7],MiramarPS_cap-MiramarPS_prv)),SV_DEL_prv)*STO_SV.TunnelLogic

Delivery is divided into:

Priority	Name	Demand
SOT[1]	MIR_PURE	min(DEM_SDMIR.REQS[1],STO_MIR.WTP_Pure,STO_MIR.STO_AV4REL,STO_MIR.MaxRel)

SOT[1]	MIR_SV1	min(DEM_SDMIR.REQS[1],STO_SV.toMiramar1+STO_HOD.City)
SOT[1]	MIR_MIR	min(DEM_SDMIR.REQS[1],STO_MIR.WTP,STO_MIR.STO_AV4REL,STO_MIR.MaxRel)
SOT[1]	DM_SV1	min(DEM_DM.REQS[1],STO_SV.toMiramar1+STO_HOD.City)
SOT[1]	DM_MIR	min(DEM_DM.REQS[1],STO_MIR.WTP)
SOT[2]	MIR_MWD2	min(DEM_SDMIR.REQS[2]+DEM_PD.REQS_1[2]+DEM_OWD.REQS[2]+DEM_SD11.REQS[2]+DEM_DM.REQS[2],P5Inflow)
SOT[7]	MIR_SV_7	min(DEM_SDMIR.REQS[7]+DEM_PD.REQS_1[7]+DEM_OWD.REQS_1[7]+DEM_SD11.REQS[7]+DEM_DM.REQS[7],A_Rancho_SD5.DEL_Mirtunnel7)
99	TankSto	TK_MIR.IdleCap/1day

SD Miramar demand

Operations description in the documentation:

San Diego Miramar is located in the southern part of the system and is a portion of the City of San Diego demands. San Diego Miramar's historical average daily delivery is 133 cfs, ranging from approximately 44 cfs to 225 cfs. It receives local water from the San Vicente Reservoir via the San Vicente Pump Station and San Vicente Tunnel; and untreated water to its own WTP via the Second Aqueduct. San Diego Miramar has the ability to receive treated MWD or Water Authority water via Pipeline 4B, so this is setup in the model: but is currently not active as it is not typical for it to do so. SD Miramar has access to the San Vicente Regional Carryover/Seasonal storage via the tunnel and Second Aqueduct.

San Diego Miramar could physically receive both Carlsbad and Camp Pendleton desalinated water via Pipeline 4B, however this configuration is not currently being modeled, as noted above.

Operations equations in the model:

DEL_Tank= TK_MIR.Releases

Tank is used to store Treated Water. Tank is filled whenever there is Extra Raw Water Supply and idle WTP capacity.

Request for Local Raw Water Sources =WTP_Miramar.MIR_MIR+WTP_Miramar.SV1+WTP_Miramar.MIR_PURE_2
Request for MWD Raw water from Pipeline5 to be locally treated= WTP_Miramar.sv_SDMiramar2
San Vicente carryover pool treated at Local WTP= WTP_Miramar.sv_SDMiramar

SD11 Demand

Operations description in the documentation:

San Diego SD 11 is located in the southern part of the system. SD 11 is a portion of the City's total demands which was separated out along with 4 other portions of the City. This was done based on the need to have separate nodes in the model splitting out the city's WTPs, reservoirs, widespread demand, etc. The historical average daily delivery is 33 cfs, ranging from approximately 14 cfs to 77 cfs. San Diego 11 does not have a "Local Reservoir" release source. However, the SD 11 connection can receive treated water from the Miramar WTP that originally came from the Miramar reservoir or San Vicente reservoir. SD 11 has access to the San Vicente Regional Carryover/Seasonal storage via treated water from Miramar WTP.

SD 11 is limited to supply its demands by untreated water supply delivered to the Miramar WTP, by the Miramar pump station capacity with a the baseline delivery set to 85 cfs, and by treated water available from the treated water aqueduct. The model is configured to allow SD 11 to receive both Carlsbad and Camp Pendleton desalinated water via P4.

Operations equations in the model:

1.Request for Local Raw Water Sources=0
2.Request for MWD Raw water from Pipeline5 to be locally treated= A_P4E_17.DEL_SD112
3.Request for TOVWTP treated water= A_P4E_17.DEL_SD113
4.Request for MWD treated water P4= A_P4E_17.DEL_SD114
5. Request for MWD treated water P4= A_P4E_17.DEL_SD115=0
6. Request for MWD treated water P4= A_P4E_17.DEL_SD116
7. San Vicente carryover pool treated at Local WTP= A_P4E_17.DEL_SD117=0

Demand
Helix
The document says:
Helix Water District
Helix is located in the southern part of the system. The Agency historical average daily demand is 73 cfs, ranging from approximately a low of 33 cfs to as much as 115 cfs. Helix demands are supplied by Levy Water treatment Plant.

The baseline system analyses assume that Helix will prefer to use water sources in the following order:

- *Helix-owned water stored in El Capitan Reservoir (Zones 1,2,3) or Lake Jennings (zones 1,2 and 3 with specific rules); or Water-Authority owned water in San Vicente Reservoir (Zones 1,2). The reservoir zones will be discussed in more detail in Section 4.1.2.*
- *MWD Untreated water*

And then, only under the unusual conditions that treated water purchases might be needed, described in more detail following this list:

- *TOV WTP*
- *MWD Treated water*

And finally, in the event that its use is authorized:

- *San Vicente Carryover Pool (zone 3): During years that total San Vicente Reservoir is above 70 percent of total storage capacity, i.e. years in which there is ample stored water available, this order is flipped and the Carryover pool is used right after all the other storages and before purchasing MWD untreated water.*

As shown in the order list above, even though it is undesirable, there are special conditions under which Helix will have to request and receive treated water from the TOV WTP or MWD. These conditions are:

- *Condition (a): The San Vicente Pipeline/Tunnel is operating in the east-to-west direction, during the time period defined by the user. This time period would be during the San Vicente Reservoir "storage-use-by-pumping" period. The default assumes that this happens every year for the May to September period, or throughout any allocation year, on the assumption that an allocation year will require use of the SV carryover pool, and therefore SV will be releasing water and not filling. The east-to-west flow direction prevents Levy WTP from receiving* <u>*any*</u> *water from the Second Aqueduct. The model overrides this condition if the San Vicente Reservoir seasonal and carryover pools are empty, in which case it allocates the possibly-limited Second Aqueduct supplies as required to most equally meet demands.*
- *Condition (b): Condition (a) plus there is not sufficient Water Authority owned water available in storage to supply all of the Levy WTP demands. The model assumes that Helix is also capable of receiving 40 cfs of untreated water flow to Levy WTP from its connection on the First Aqueduct*

– see Condition (d).

- *Condition (c): Condition (a) plus either the San Vicente Pump Station or the Moreno-Lakeside pipeline are operating at maximum capacity and flows are not enough to supply Levy demands.*
- *Condition (d): Condition (a) plus the first aqueduct connection and pipeline are operating at maximum capacity, 40 cfs, and this is still not enough to supply the Levy WTP demands.*

Helix drawing water from ElCap: indirectly

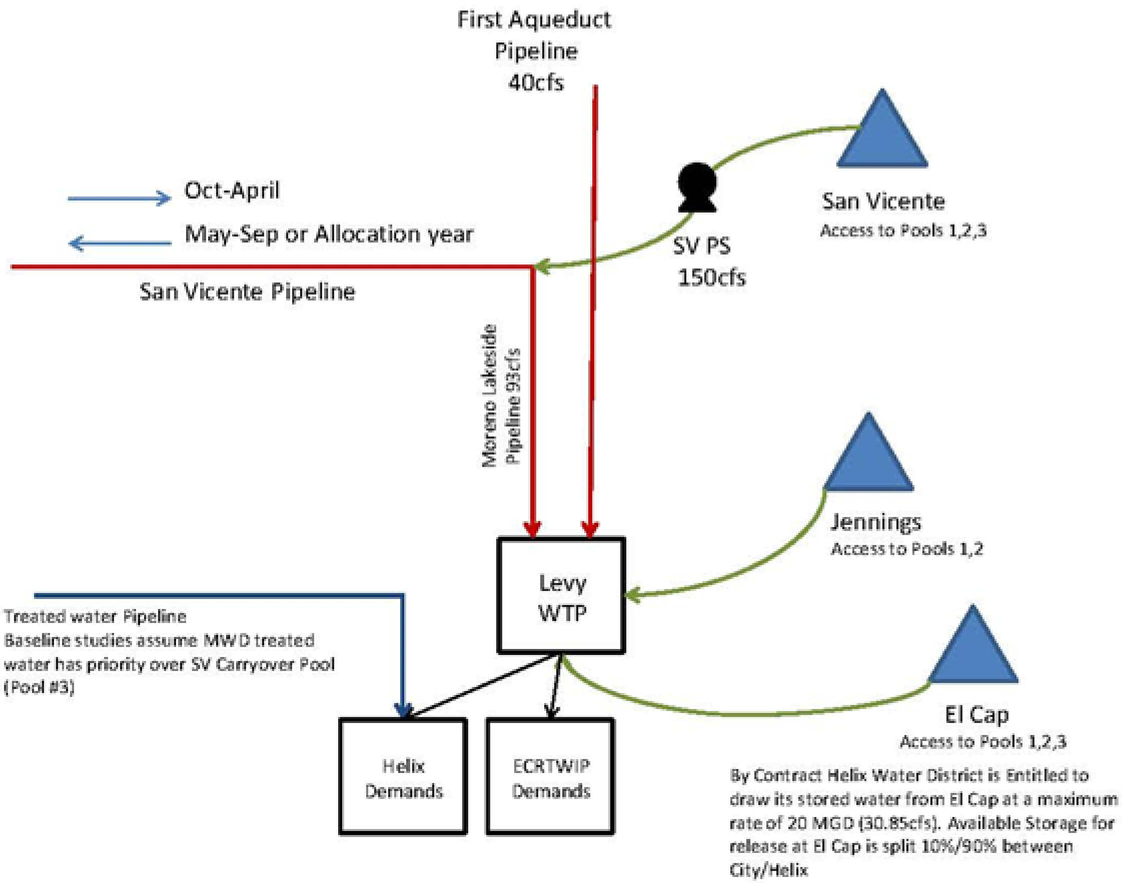
Note from the Helix demand container:

Helix demands:

Helix is the only place in the system that can get Raw MWD water from two different places (Tunnel and Lakeside-Moreno pipeline). Helix can receive water from the First aqueduct OR from the tunnel, not both at the same time step

Helix demand 30676af=34840-4071 (conservation)-93(groundwater) to be met:
1.Request for Local Raw Water Sources: WTP_Levy.S1_HLX
2.Request for MWD Raw water from Pipeline5 to be locally treated: WTP_Levy.S2_HLX
3.Request for TOVWTP treated water: A_P4E_17.DEL_Helix3
4.Request for MWD treated water P4: A_P4E_17.DEL_Helix4
7.San Vicente carryover pool treated at Local WTP: WTP_Levy.S7_HLX

Connectivity



SD Alvarado demand

Operations description in the documentation:

San Diego Alvarado, a portion of the City, is located in the southern part of the system and is a portion of the City of San Diego demands. The agency historical average daily delivery is 137 cfs, ranging approximately from 77 cfs to 196 cfs. It receives local water from San Vicente and El Capitan reservoir via the El Monte pipeline and untreated water service to its own WTP via the Second Aqueduct. San Diego Alvarado has the ability to receive treated MWD or Water Authority water via Pipeline 4B. SD Alvarado, like Miramar, has access to the San Vicente Regional Carryover/Seasonal storage via the tunnel and Second Aqueduct.

The model is configured to allow San Diego Alvarado to receive both Carlsbad and Camp Pendleton desalinated water via Pipeline 4B.

Operations equations in the model:

1.Request for Local Raw Water Sources=
WTP_Alvarado.Local_GWSto+WTP_Alvarado.Local_ElCap+WTP_Alvarado.Pure+
WTP_Alvarado.Local+WTP_Alvarado.Murray_MWD,
2. Request for MWD Raw water from Pipeline5 to be locally treated= WTP_Alvarado.MWD
3. Request for TOVWTP treated water= A_P4E_19.DEL_SDAlvarado3
4.Request for MWD treated water P4= A_P4E_19.DEL_SDAlvarado4
5.Request for MWD treated water P4= A_P4E_19.DEL_SDAlvarado5
6. Request for MWD treated water P4= A_P4E_19.DEL_SDAlvarado6
7. San Vicente carryover pool treated at Local WTP= WTP_Alvarado.SV_2

Sutherland Reservoir

Operations description in the documentation:

The Sutherland reservoir has a usable capacity of 32 TAF. It can supply the San Vicente reservoir and is limited by delivery capacity. Based on operating practices in March and April the delivery is zero and the remainder of the year it up to 50 cfs.

April through July there are no transfers from Sutherland to San Vicente. Other months the model will check if San Vicente storage is below 200,000 AF (user controlled in dashboard, set as 65,000 AF for calibration runs), if yes, then will do a maximum 50 cfs transfer to empty SUT Reservoir Zone2 until next March. A 7% loss between SUT and SANV is applied whenever there is flow between the two reservoirs. A rating curve of Sutherland releases as a function of storage was developed to avoid maximum of 50 cfs transfers all the time.

Operations equations in the model:

Maximum storage: IN_MaxStorage.Max_SUT = 31,960 af
Minimum storage: MinSto = 5590af
Max release capacity: MaxRel= 1000cfs (where to verify?)
Inflow:
XL_ISHYD(MonthHydrology,8)*ClimateScen_Res_Inflow(8,Month,Climate_Scenario_Index)
Outflow: Evaporation+Releases+Flood_Sutherland
Flood: Flood_Sutherland = min(ZS.z1/1day,MaxRel)
Releases=
min((ZS.z8+ZS.z7+ZS.z6+ZS.z5+ZS.z4+ZS.z3+ZS.z2+ZS.z1+ZS.Unused)/1day,MaxRel,Requested)

Requested= WTP_Bargar.Dixon+SUTToSV
Delivery table

A_SUT.Releases=

Priority	**Name**	**Demand**
1	toBargar	WTP_Bargar.Dixon
2	toSV	SUTToSV*(1-0.07)

SUTToSV =if(SUT_SVcheck=False or Month>=4 and Month<=7,0cfs,SUT_SV_flow(STO_Sutherland))

San Vicente Reservoir

Operations description in the documentation:

The San Vicente has a usable capacity of 273 TAF. The San Vicente reservoir has two main accounts to supply which are the Water Authority account and the City account. San Vicente operations can be controlled by several variables which the user decides. These are as follows:

- *Reservoir Filling:*

A) *Typically October through April, but user adjustable.*
B) *MWD untreated water can be sent to San Vicente reservoir only after all of the WTP demands are fulfilled. The Levy WTP can also receive MWD untreated water while the San Vicente reservoir is filling.*
C) *If the sum of the City seasonal storage plus the Water Authority storage, seasonal plus carryover, is equal to zero the San Vicente pipeline will switch to filling, independent of time period of the year.*
D) *The "Filling switch" could be changed to filling during the usual release period if San Vicente's carryover and Seasonal pools are empty. Helix has a special logic that it will get treated water from MWD only if the Carryover Pool at San Vicente is empty. This special condition overrides the global assumption of order of supplies for Helix. Helix will never get treated water as long as there is water in the San Vicente Water Authority carryover pool.*

- *Reservoir Releasing:*

– *Typically May through September, but user adjustable.*
– *The assumption is that San Vicente is releasing flows from the seasonal pool and the San Vicente pipeline will be flowing from east to west via operation of the San Vicente Pump Station. In addition, it is assumed that the MWD untreated water that could reach the*

Levy WTP from the First Aqueduct is limited by the First Aqueduct connection capacity of 40 cfs. In addition, there are gravity releases to Alvarado via the El Monte Pipeline.

- *Reservoir "No Filling" Condition*
    - *During an MWD allocation year the reservoir is switched to no-filling even during the months of October through April. The assumption is that there will not be enough water to fill the reservoir. This condition will still allow for the Levy WTP to be supplied with MWD untreated water by San Vicente reservoir and the first aqueduct.*

Operations equations in the model:

Maximum storage: IN_MaxStorage.Max_ElCap= 272,528 af

Minimum storage: MinSto = 5228 af

Max release capacity: MaxRel= 47008cfs (where to verify?)

Inflow: IN+StorageFill+Supply_fromEast+PURE+IN_SV_FROM_ElCap_actual, in which IN is excel input: XL_ISHYD(MonthHydrology,7)*ClimateScen_Res_Inflow(7,Month,Climate_Scenario_Index) , StorageFill= max(0cfs,Tunnel)+A_Crossover.SV+STO_SUT.toSV, Supply_fromEast= if(CRPC_Switch=1,277700*1af/yr,0af/yr),PURE=0, IN_SV_FROM_ElCap_actual=0= STO_ElCAP.Intertie_SV is the intertie delivery, not modeled in baseline models,

Outflow: Evaporation+Flood_SanVicente+Releases

Flood: Flood_SanVicente = max(0cfs,if(Month>=1,min(MaxRel,1*ZS.z1/1day),0cfs)-Requested-(IN_ELCAP_FROM_SV_actual+IN_GW_FROM_SV_actual))

Releases= max(0cfs,min((IN_Excel.STOZ_switch[SANV,8]*ZS.z8+IN_Excel.STOZ_switch[SANV,7]*ZS.z7+IN_Excel.STOZ_switch[SANV,6]*ZS.z6+IN_Excel.STOZ_switch[SANV,5]*ZS.z5+IN_Excel.STOZ_switch[SANV,4]*ZS.z4+IN_Excel.STOZ_switch[SANV,3]*ZS.z3+IN_Excel.STOZ_switch[SANV,2]*ZS.z2+IN_Excel.STOZ_switch[SANV,1]*ZS.z1+ZS.Unused)/1day,MaxRel,Requested+IntertieReqOut_SV))

Releases allocation

Priority	Name	Demand
1	Source1	min(WTP_Alvarado.AREQSV1,Avail_CitySeasonal)+min(A_SVPS.PStoLevy1,(Avail_WASeasonal)/1day)+min(A_SVPS.PStoMiramar1,Avail_CitySeas

		onal)+AccSplit_City_Intertie.Intertie_ElCap+AccSplit_City_Intertie.Intertie_GW
2	Source7	min(Avail_WASCarryover/1day,A_SVPS.PStoAlvTunnel7 +A_SVPS.PStoLevy7+A_SVPS.PStoMirTunnel7+A_SVPS.PStoOtyTunnel7 +A_SVPS.PStoSweTunnel7)

Source1 allocation

Priority	**Name**	**Demand**
SOT[1]	toAlvElMonte1	max(0cfs,min(Avail_CitySeasonal,WTP_Alvarado.AREQSV1))
SOT[1]	toLevy1	max(0cfs,min(A_SVPS.PStoLevy1,Avail_WASeasonal/1day))
SOT[1]	toMiramar1	max(0cfs,min(A_SVPS.PStoMiramar1,Avail_CitySeasonal))
SOT[1]+1	toIntertieElCap	min(~Remainder, AccSplit_City_Intertie.Intertie_ElCap)
SOT[1]+1	toIntertieGW	min(~Remainder, AccSplit_City_Intertie.Intertie_GW)

Source7 allocation

Priority	**Name**	**Demand**
SOT[7]+0.1+HLXPriority	toMirTunnel7	min(A_SVPS.PStoMirTunnel7,MC_sv[MIRW])
SOT[7]+0.2+HLXPriority	toAlvTunnel7	min(A_SVPS.PStoAlvTunnel7,MC_sv[ALV])
SOT[7]+0.3+HLXPriority	toSweTunnel7	min(A_SVPS.PStoSweTunnel7,MC_sv[SWT])
SOT[7]+0.4+HLXPriority	toOtyTunnel7	min(A_SVPS.PStoOtyTunnel7,MC_sv[SDO])
SOT[7]+0.5	toLevy7	A_SVPS.PStoLevy7

San Vicente Pump Station operation: SanVicentePS_cap

Priority	Name	Demand
SOT[1]	PStoLevy1	max(0cfs,min(Avail_WASeasonal/1day+Avail_CitySeasonal,WTP_Levy.SV))
SOT[1]	PStoMiramar1	max(0cfs,min(Avail_CitySeasonal,WTP_Miramar.AREQ_SV))
SOT[7]+HLXPriority	PStoMirTunnel7	max(0cfs,min(Avail_WASCarryover/1day,WTP_Miramar.SV_REQ))
SOT[7]+HLXPriority	PStoAlvTunnel7	max(0cfs,min(MC_sv[ALV],Avail_WASCarryover/1day,WTP_Alvarado.SV_REQ))
SOT[7]+HLXPriority	PStoSweTunnel7	max(0cfs,min(MC_sv[SWT],Avail_WASCarryover/1day,WTP_SWE.SV_REQ))
SOT[7]+HLXPriority	PStoOtyTunnel7	max(0cfs,min(MC_sv[SDO],Avail_WASCarryover/1day,WTP_OTY.SV_REQ))
SOT[7]	PStoLevy7	max(0cfs,min(Avail_WASCarryover/1day,WTP_Levy.SV_REQ))

Requested=
min(STO_AV4REL,min(Avail_CitySeasonal,WTP_Alvarado.AREQSV1+min(RanchoCap_S1,A_SVPS.PStoMiramar1))+min(Avail_WASeasonal/1day,A_SVPS.PStoLevy1)+min(Avail_WASCarryover/1day,min(RanchoCap_S7,A_SVPS.PStoAlvTunnel7+A_SVPS.PStoMirTunnel7+A_SVPS.PStoOtyTunnel7+A_SVPS.PStoSweTunnel7)+A_SVPS.PStoLevy7))

Reservoir filling: Fill up to Carryover pool, then fill discretionary giving priority to the storage that is less full

Filling amount=
max(0cfs,(IN+StorageFill+Supply_fromEast+PURE+IN_SV_FROM_ElCap_actual)-max(0af,(MinSTO-STO_SanVicente))/1day)

Priority	Name	Demand
1	CITYacc	min(IN+A_Crossover.SV+IN_SV_FROM_ElCap_actual+STO_SUT.toSV+PURE,max(0cfs,if(Portfolio>1and ResManag_Switch=1,RC_WACityAcc_OpOptimiz(4,

		Month),(RC_WACityAcc(4,Month))-CITY_acc)/1day))
1	WAacc	min(max(0cfs,Tunnel),max(0cfs,if(Portfolio>1and ResManag_Switch=1,RC_WACityAcc_OpOptimiz(1, Month),(RC_WACityAcc(1,Month))-WA_acc)/1day))
2+CITY_acc/MaxCity_Acc	CityAdditional	max(0cfs,(MaxCity_Acc-CITY_acc)/1day)
2+WA_acc/MaxWA_Acc	WAAdditional	max(0cfs,(MaxWA_Acc-WA_acc)/1day)
99	Flood	99999 cfs

How to fill emergency pool:

if(ZS.z4<ZoneCapcity.z4 or WA_Accounts.Emergency<RC_WA_ESP,1,99)

Hodges Reservoir

Operations description in the documentation:

The Hodges reservoir has a usable capacity of 27.6 TAF. The Hodges reservoir has three main accounts where water is stored, the Santa Fe/San Dieguito, City of San Diego, and Water Authority accounts.

The three parties operate storage and supply in the Hodges. The City of San Diego and SD/SF use it for local yield.

The Water Authority uses the reservoir for emergency storage and pumped storage hydro operations. There are minor nuanced details within the City/SD/SF agreement that can occur on occasion but would be difficult to model and would not add to the modeling results. Below are the capacities and supply splits and a general operating plan. Note the operating plan would normally change from year to year depending on agency needs and expected hydrology but the general assumptions would remain the same.

- Storage capacities:

SF/SD - 5,000 AF (may exceed if capacity is available) - dead storage 305 = net useable: 4,695 AF City - 5,000 AF (may exceed if capacity is available) - dead storage 1,691.3 = net useable: 3,308.7 AF SDCWA - 20,000 AF (max storage) - dead storage 3,992.7 = net useable: 16,007.3 AF

- Reservoir Filling:

The reservoir can be filled with local runoff or aqueduct water. The Runoff going into the reservoir is split equally between Santa Fe/San Dieguito and the City of San Diego until the maximum in one account is reached, then the runoff will go 100% to the account that is not full yet.

Imported water from the aqueduct is split equally between the City of San Diego and the Water Authority. Aqueduct water is modeled as water transferred from Olivenhain reservoir.

- Reservoir Evaporation/Losses and spills

Reservoir spills will be shared equally between the Santa Fe/San Dieguito and City of San Diego accounts for the amount above their maximum storage capacity.

Evaporation losses are shared as follow:

City of San Diego - 16.7% of total evaporation. Water Authority - 66.6% of total evaporation Santa Fe/San Dieguito - 16.7% of total evaporation

The storage is operated with the rule curve where zone 2 represents the total usable storage in the three accounts.

Operations equations in the model:

Maximum storage: IN_MaxStorage.Max_HDG = 33600 af

Minimum storage: MinSto = 5989 af

Max release capacity: MaxRel= Restrict_Hodges_Volume =6.245 MGD

Inflow: IN+Oliv_Hod_Logic.IN_HOD+STO_SUT.Flood, IN= XL_ISHYD(MonthHydrology,4)*InflowScale*ClimateScen_Res_Inflow(4,Month,Climate_Scenario_Index),

Outflow: min(REQ_OUT,REL_Lim)+Evap

Flood: min((ZS.z1+ZS.Unused)/1day,MaxRel)

Release requests: WTP_Badger.Hodges+STO_SAND.ForebayRequest+WTP_Miramar.AREQ_SDG+min(STO_MIR.HOD,Acc_AVAIL[SDCWA]/1day)

The following operation plan is taken from the model:

Water Authority Sales Forecast Model Assumptions for Storage in Lake Hodges

Background

Three parties operate storage and supply in the Hodges. The City of San Diego and SD/SF use it for local yield. The City can place imported but for this modeling effort do not plan on doing so. The Water Authority uses the reservoir for emergency storage and pumped storage hydro operations. The assumptions within in this write-up represent the operations for modeling purposes. There are minor nuanced details within the City/SD/SF agreement that can occur on occasion but would be difficult to model and would not add to the sales forecast result. Below are the capacities and supply splits also described is a general operating plan. Note the operating plan would normally change from year to year depending on agency needs and expected hydrology but the general assumptions would remain the same.

Hodges Operations

Storage capacities:

SF/SD - 5,000 AF (may exceed if capacity is available) - dead storage 305 = net useable: 4,695 AF

City - 5,000 AF (may exceed if capacity is available) - dead storage 1,691.3 = net useable: 3,308.7 AF

SDCWA - 20,000 AF (max storage) - dead storage 3,992.7 = net useable: 16,007.3 AF

Runoff:

SF/SD - 50%

City - 50%

Spill:

SF/SD - 50% above storage capacity

City - 50% above storage capacity

Imported fill capacity:

City - 100%

SDCWA - 100%

SF/SD -0%

Evaporation/Losses:

City - 16.7% of total evap.

SDCWA - 66.6%

SF/SD -16.7%

Operating Plan

Operations are based on SDCWA plan, but must maximize local yield. Therefore the modified plan approach would be as follows:

- Reduce storage to between El 296 and El 290 by Jan 1 of each year (about 40-36% of total capacity). Do not go lower than 36% of total capacity for pumped storage operations.
- Keep the reservoir at a maximum of 40% of total capacity through beginning on March by drafting first to SF/SD then the City.
- Water Authority starts filling May 1st, note WA could start earlier if reservoir level below 40%.
- SF/SD and the City take water from the reservoir anytime their pools are full or high runoff occurs.
- Local water stored in City and SF/SD account is taken out June through September.
- Water Authority imported water is taken August through December.

City of San Diego

Operations description in the documentation:

The Water Authority member agency, City of San Diego, has been separated into five unique sub-agencies as will be described below for each City of San Diego sub-agency. The City of San Diego demands were split as shown by percentage of total demand in Table 4-1. The percent split was derived based on the historical percent split of the specific City of San Diego connections which are also shown. Because of the size of this member agency's demand as well as the fact that it is very spread out within the Water Authority system it allows for a more accurate representation of the City of San Diego's deliveries, water treatment plants, and pipeline configurations.

TABLE 4-1

City of San Diego Sub-Agency Percent Split

Number	Sub-Agency	Percent of Total City Demand (%)	City of San Diego Connections
1	San Diego 11	13	SD11
2	San Diego Miramar[1]	45	SD5A+SD5B+SD5C
3	San Diego Alvarado	30	SD12, SD18/21+SD19+ SD23TA+SD23TB
4	San Diego North	7	SD10+SD14+SD15
5	San Diego Otay[2]	5	SD6A+SD7+SD20
	Total	**100**	

Notes:

[1] See section on City Del Mar demands which discusses how Del Mar demands are linked with these demands

[2] See section on Cal-AM demands which discusses how CAL-AM demands are linked with these demands

San Diego North

Operations description in the documentation:

San Diego North, a portion of the City, is located in the southern part of the system and is a portion of the City of San Diego demands. The agency historical average daily delivery is 21 cfs ranging from approximately 4 cfs to 59 cfs. San Diego North receives treated MWD and Water Authority TOV WTP water via P4.

The agency capability to meet deliveries under baseline conditions is limited by MWD supplies, specifically P5 capacities. The model is configured to allow San Diego North to receive both Carlsbad and Camp Pendleton desalinated water via P4.

Cal-AM

Operations description in the documentation:

The City of Coronado is served water by the Cal-American water company, a private entity which is not a member agency of the SDCWA. Additionally, the City of Coronado is not a member agency of MWD, and therefore cannot legally receive MWD water. The Cal-American company does receive water service from the City of San Diego's Otay WTP, but it only receives water from the City of San Diego's local storage pool derived from local rainfall, an arrangement which existed prior to the existence of SDCWA. While the City of San Diego, which is an MWD and SDCWA agency, can deliver its own local water from any local rainfall source to the company serving areas lying outside the MWD area, and can then buy MWD water for its own needs. The City of San Diego cannot simply buy MWD water, however, treat it at their Otay WTP and deliver it to Coronado. In the model, the annual Coronado demand is determined by the user, based on historical output of the San Diego Otay WTP. Coronado demands are included in the demand node for the SD Otay area, and an agency average daily demand pattern was applied to the annual demands. The model can supply Cal-Am with local water stored at Lower Otay reservoir or WA from San Vicente's carryover pool. Any shortage to Cal-Am, which could occur due to lack of local rainfall or lack of WA San Vicente carryover pool, is reported as a shortage in this combined demand node, however, the Cal- Am shortages are removed from the overall system shortage calculations. Because this "excess" included demand is outside the SDCWA service area, the demand total in the model does not exactly match the 2010 UWMP; for purposes of cross-checking with the UWMP when demands in the model are totaled up, the resulting total model demand is adjusted to account for the excess. Cal-Am demands were turned off in the STDFM model.

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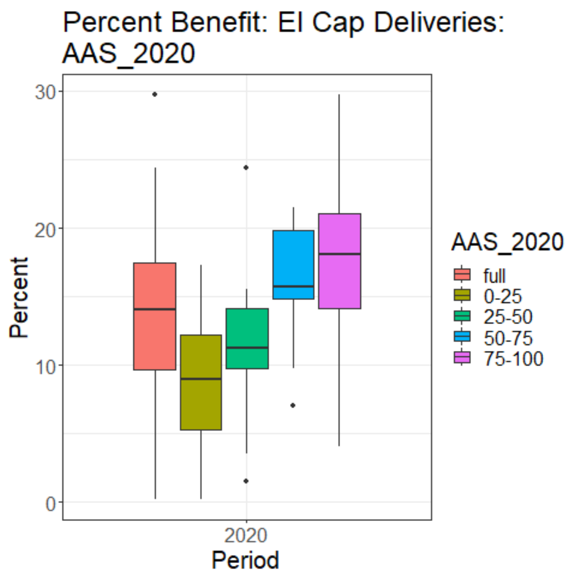
Appendix B – Supplementary Climate Change Plots

Streamflow Correlation

El Capitan – Deliveries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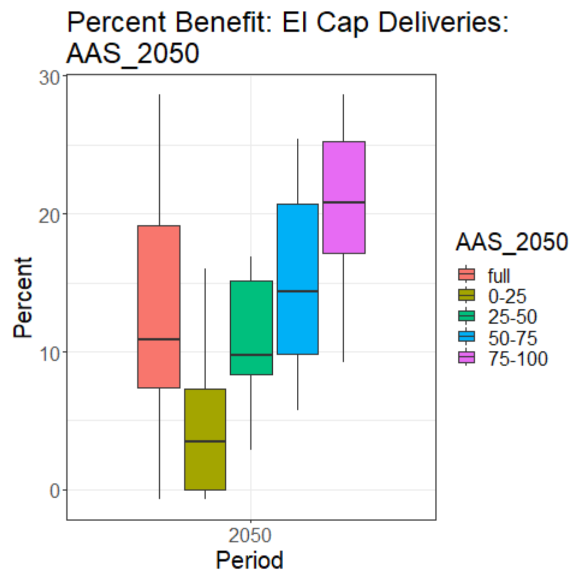
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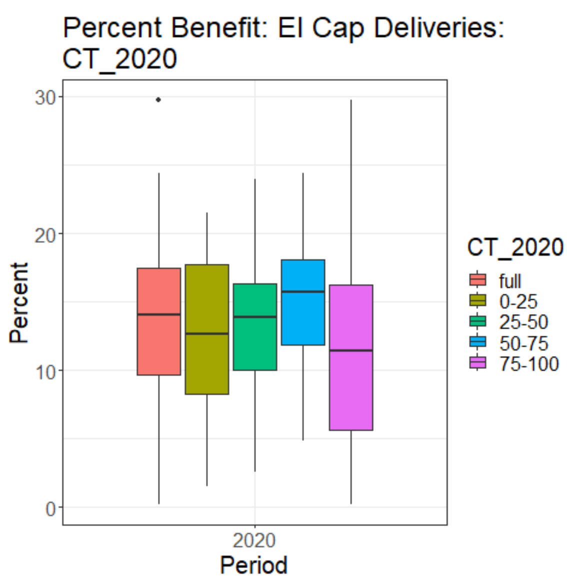
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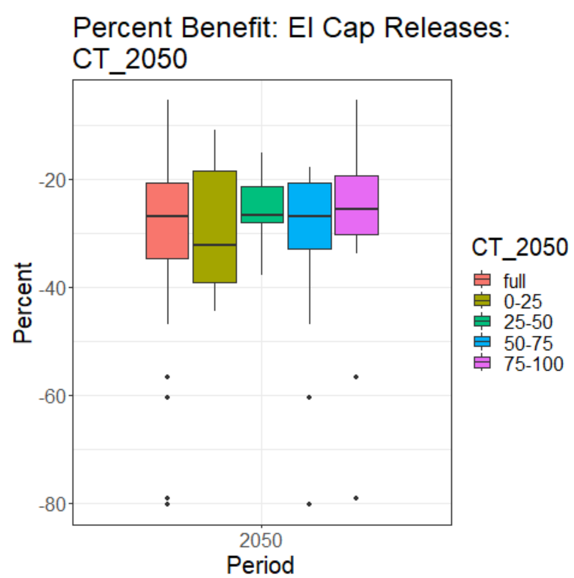
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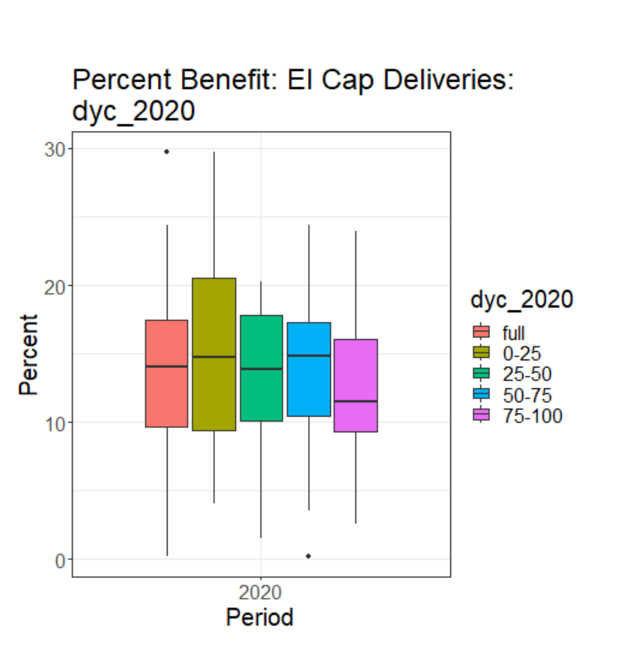
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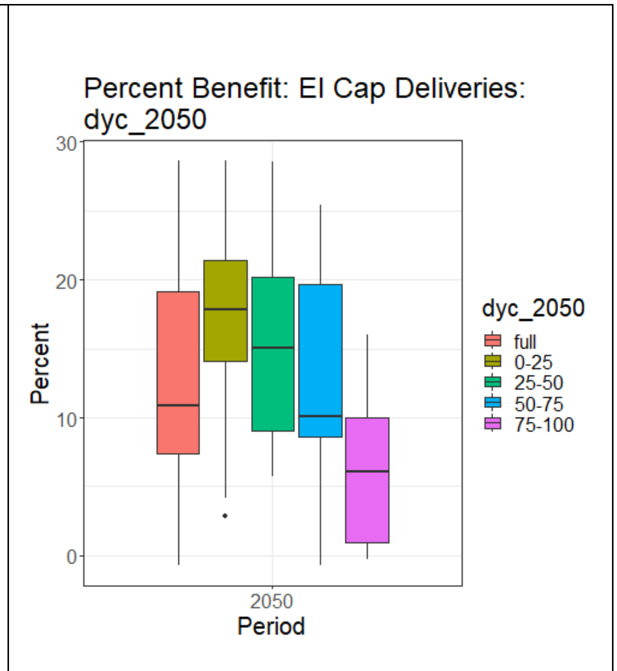
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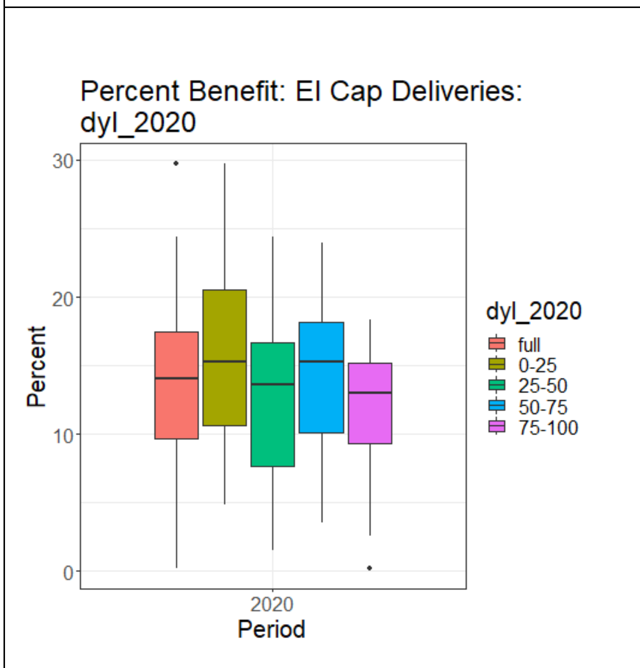
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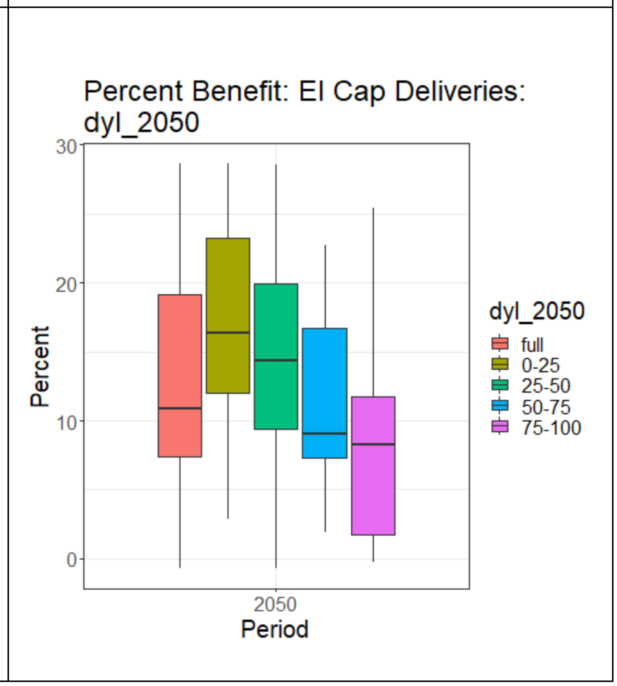
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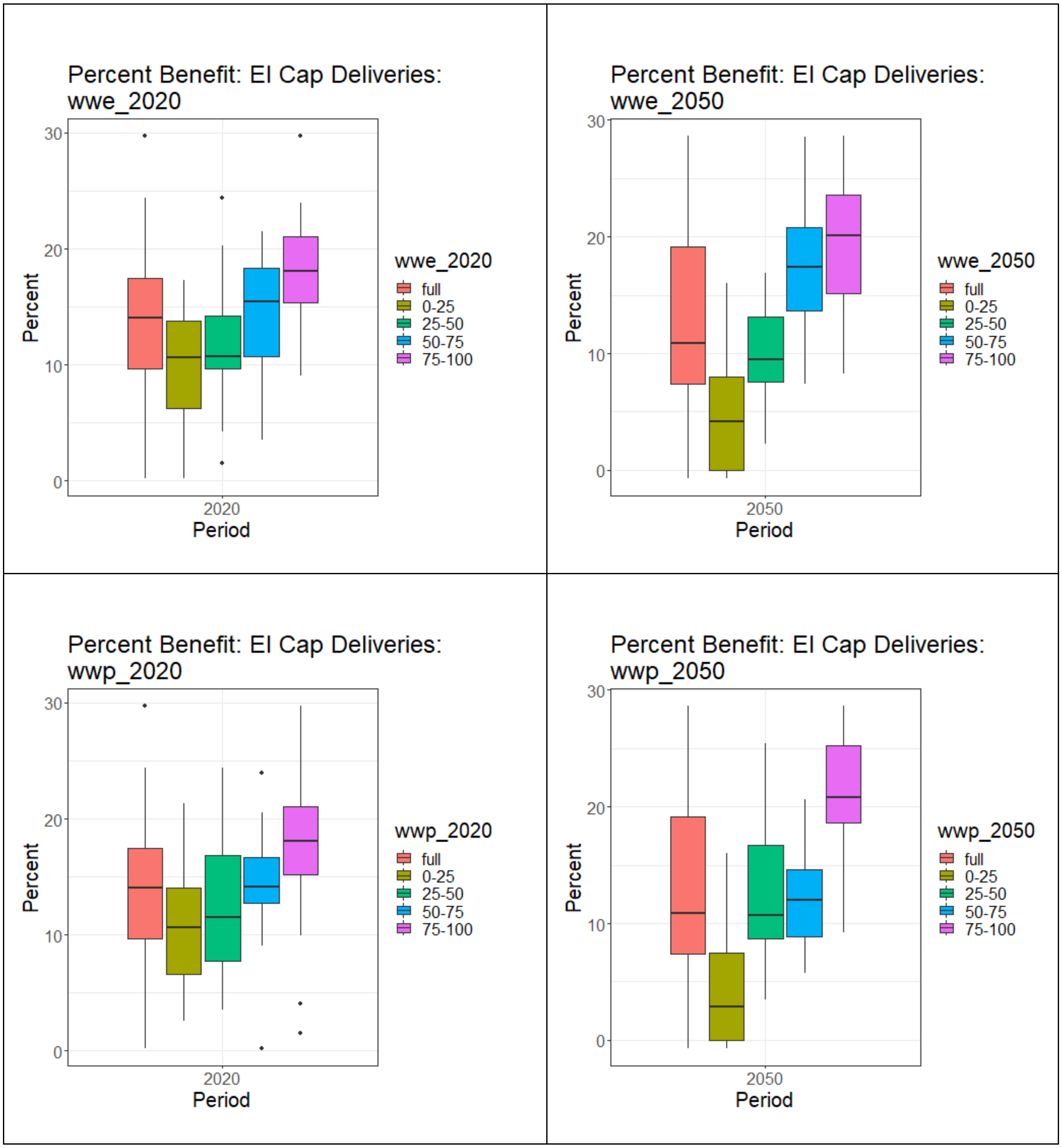
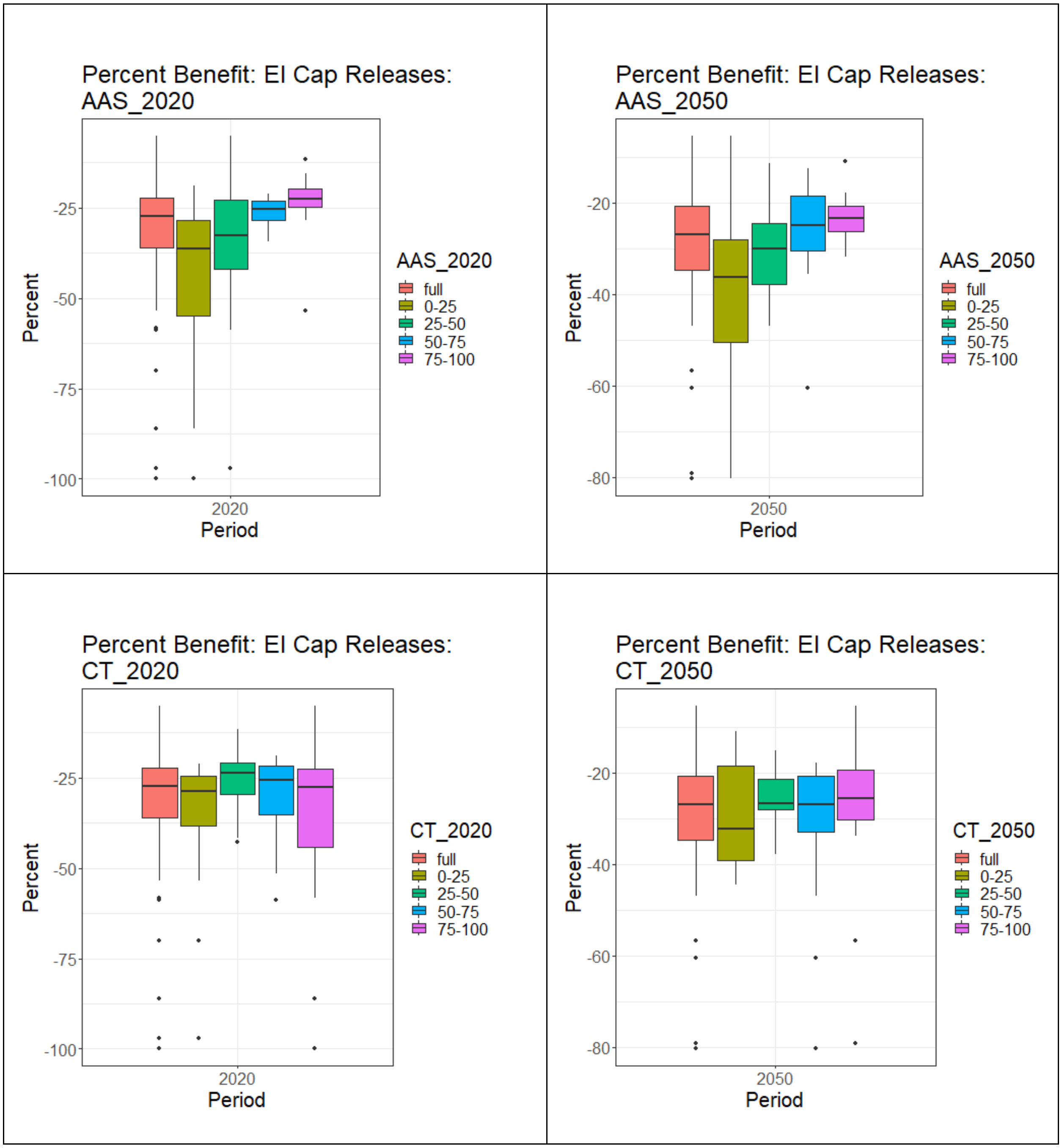


El Capitan – Releases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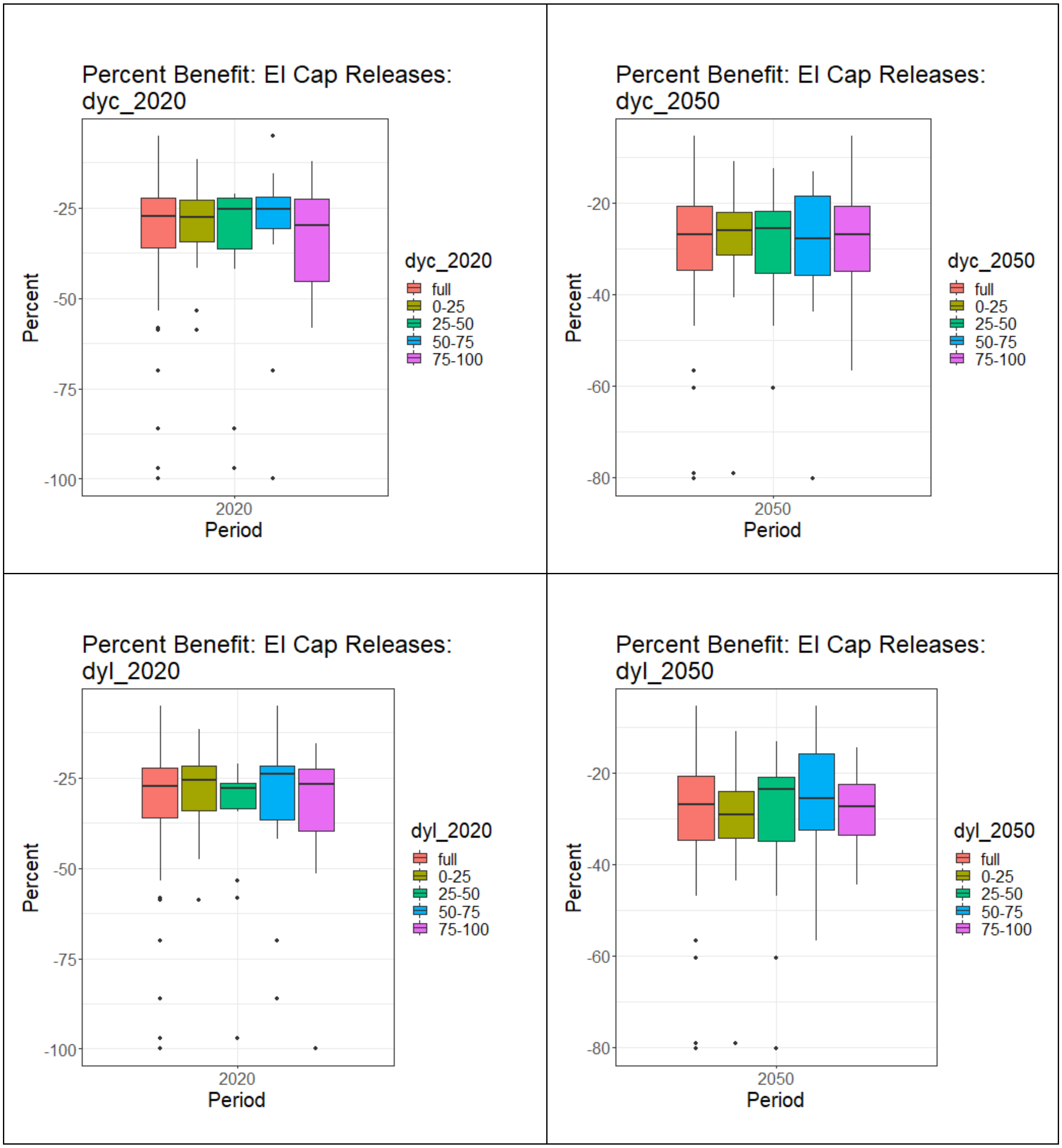
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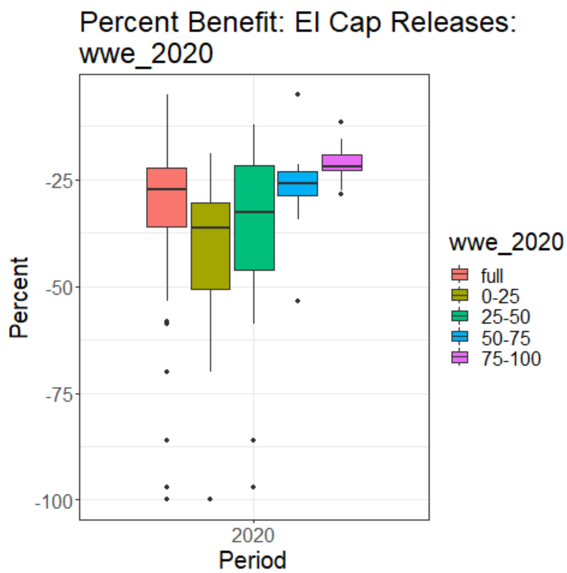
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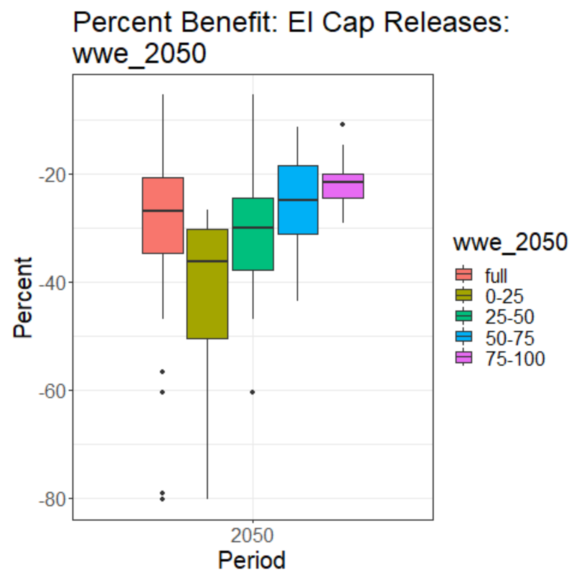
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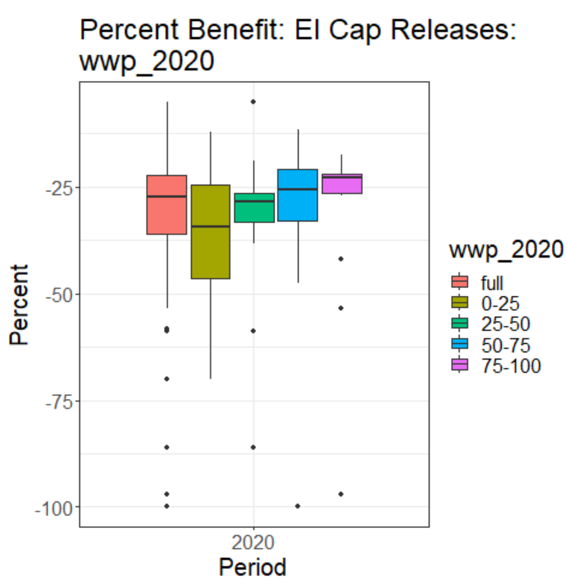
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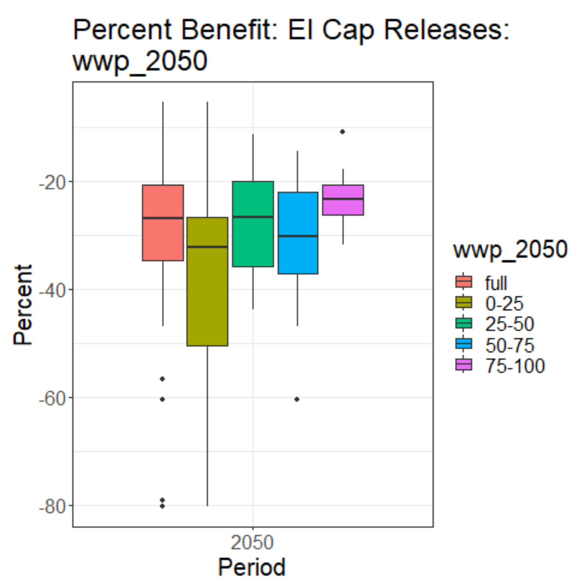
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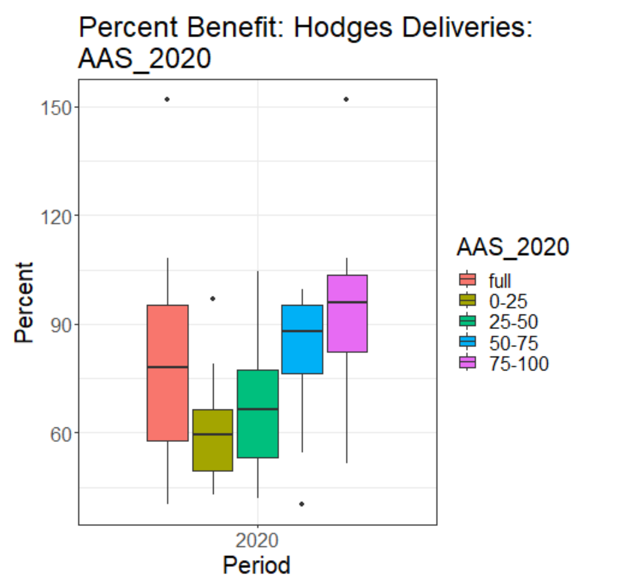
Hodges – Deliveries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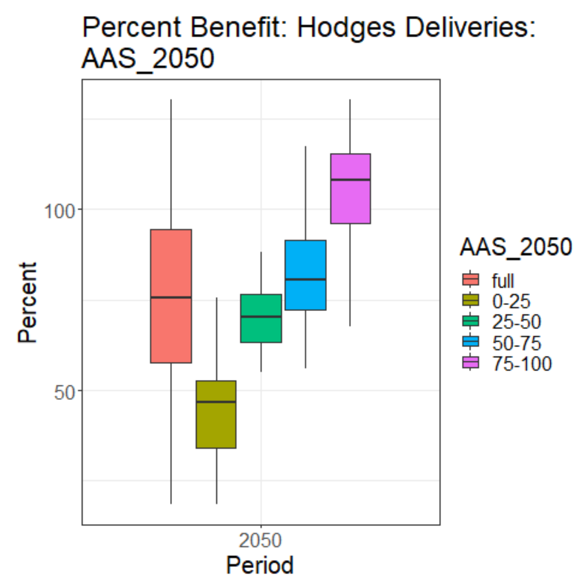
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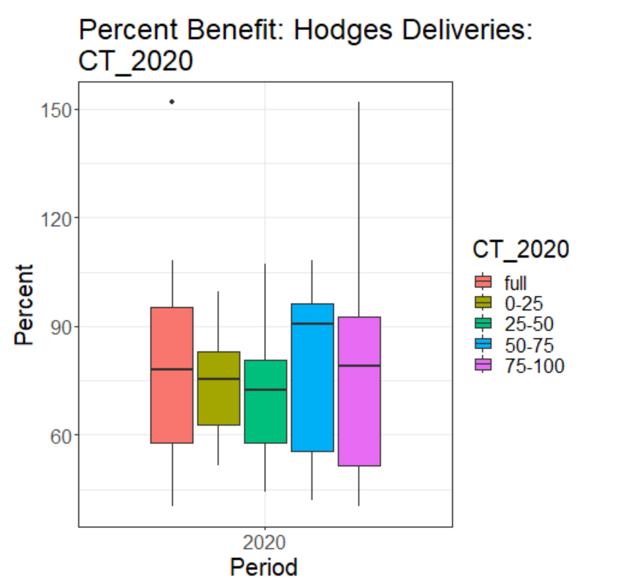
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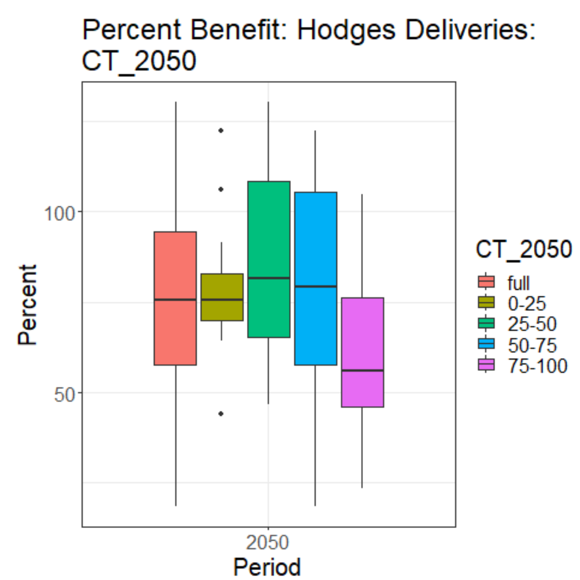
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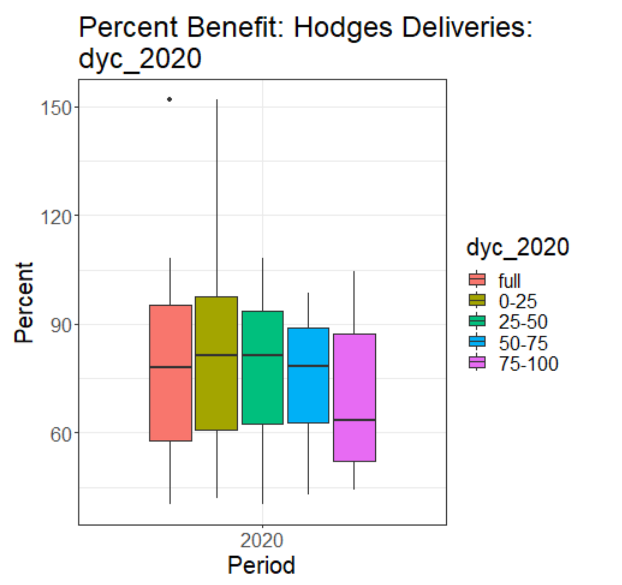
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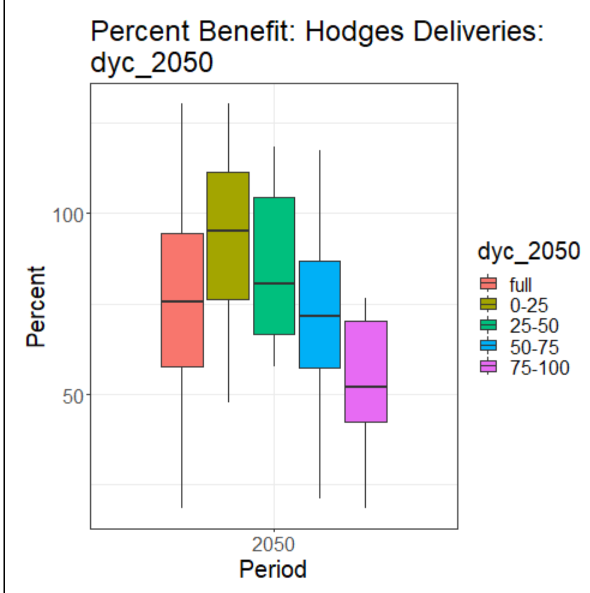
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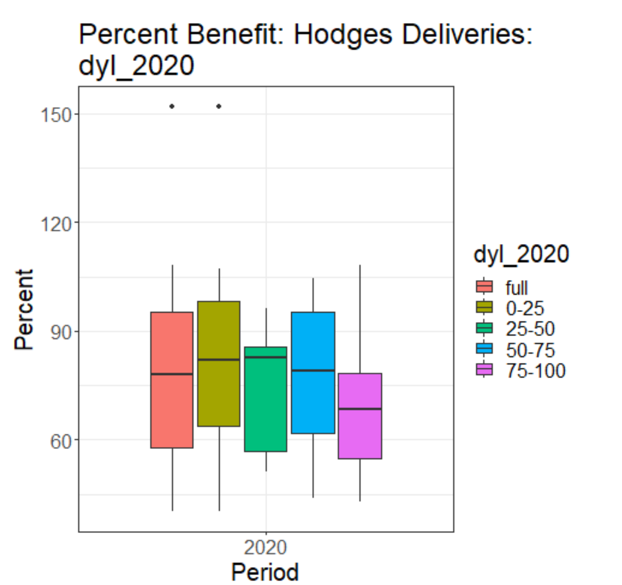
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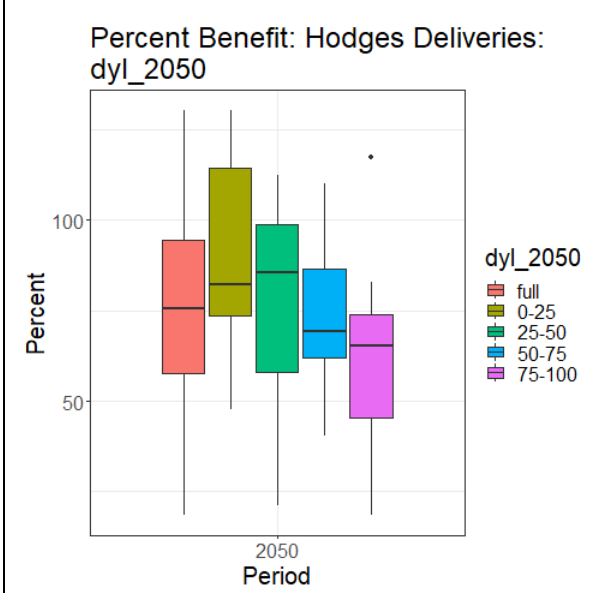
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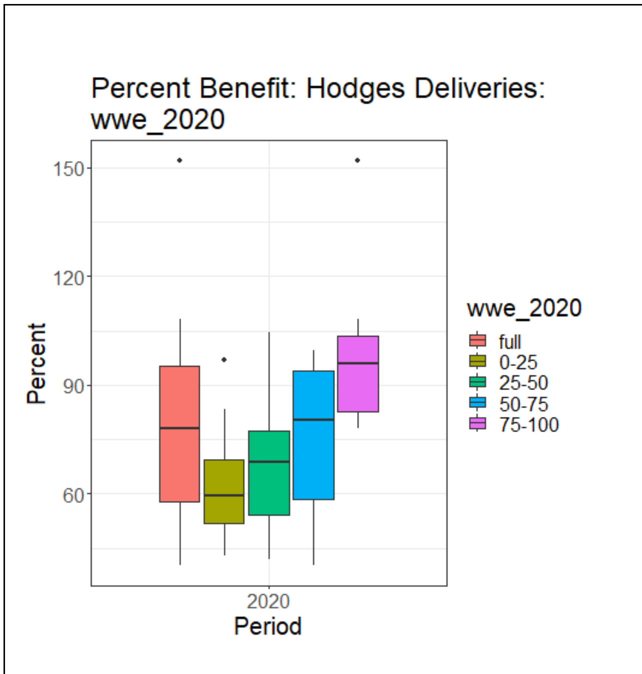
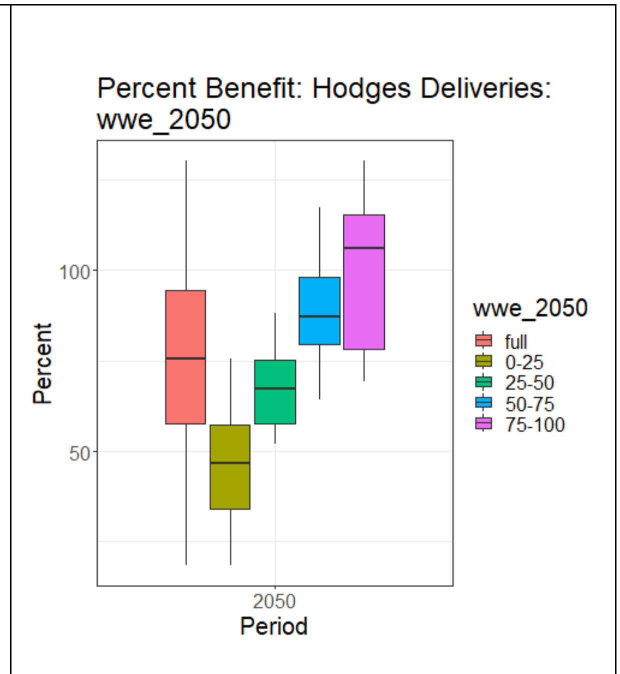
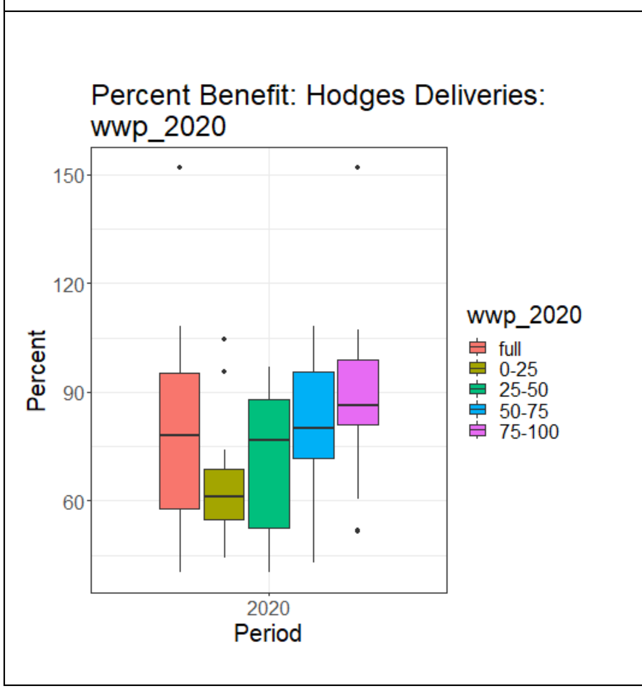
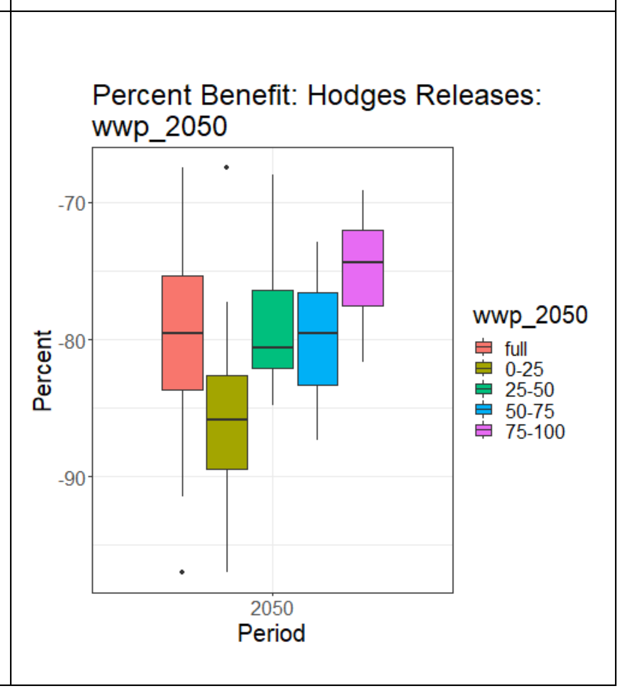
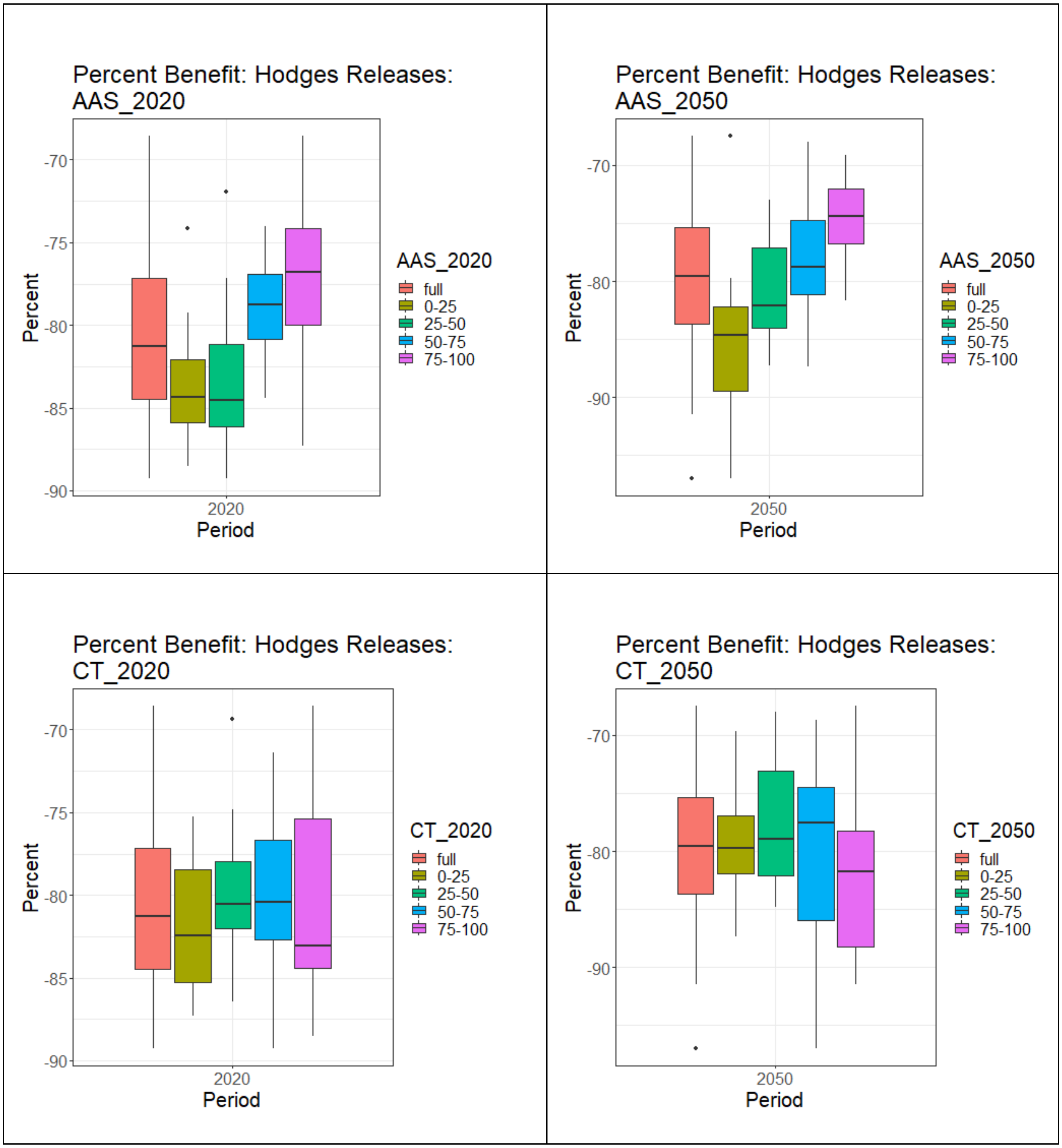








Hodges – Releases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Percent
Period
2020
AAS_2020
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25-50
50-75
75-100
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2050
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CT_2020
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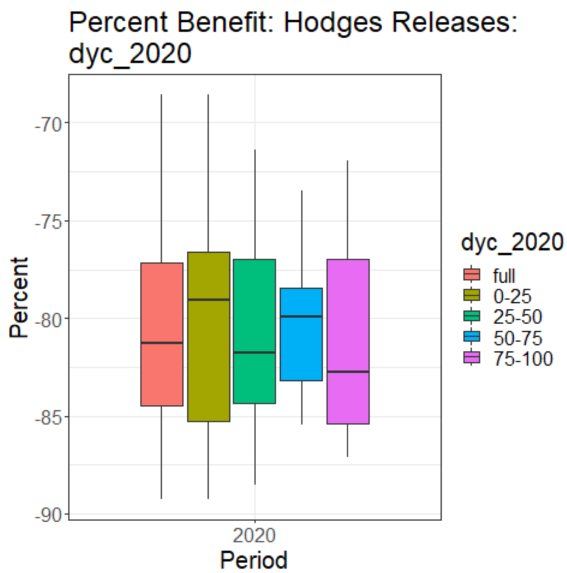
CT_2050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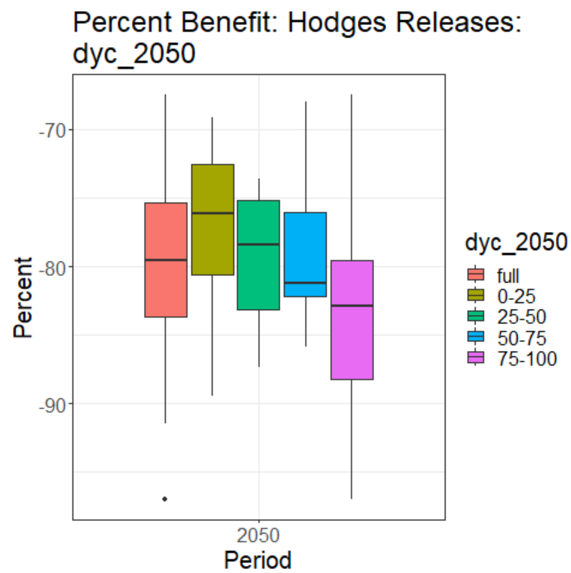
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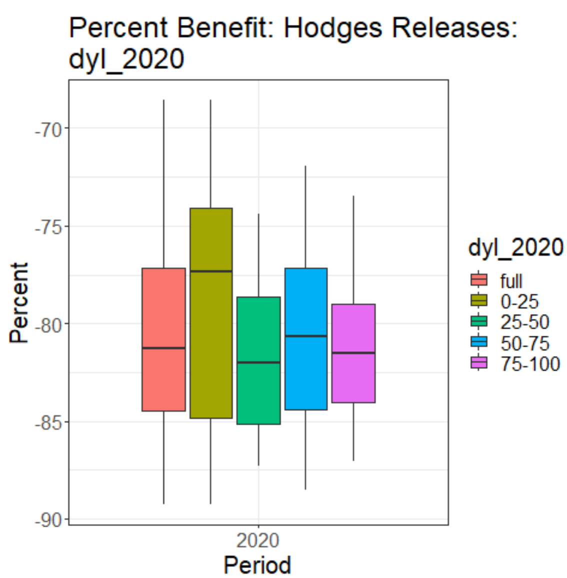
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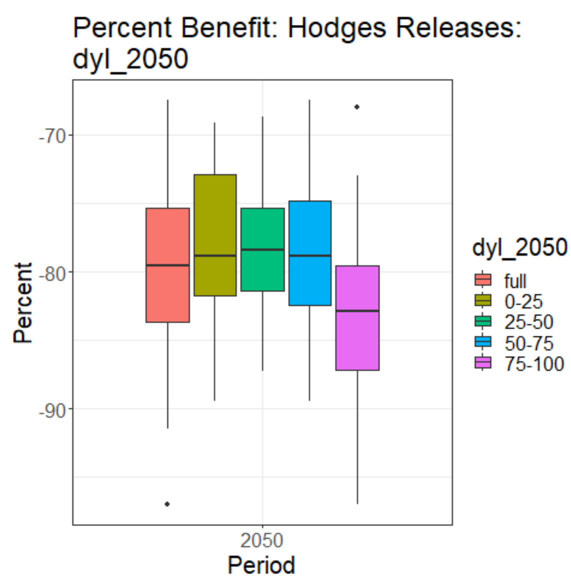
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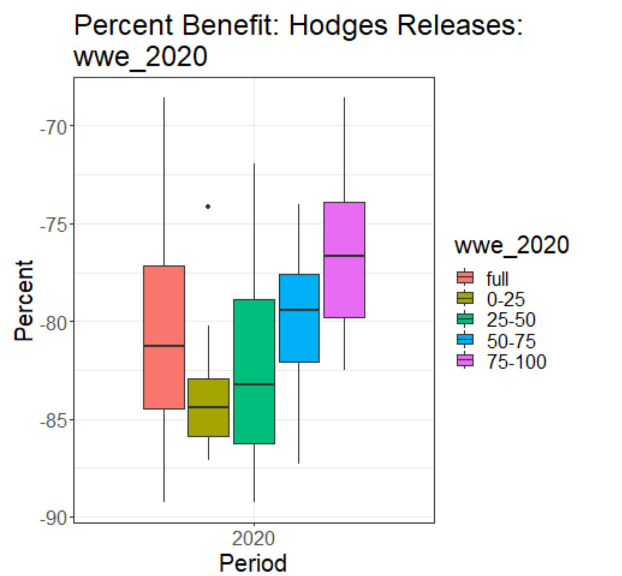
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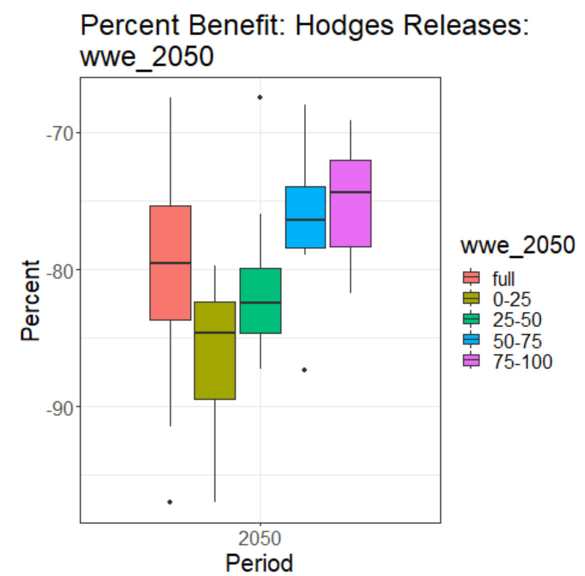
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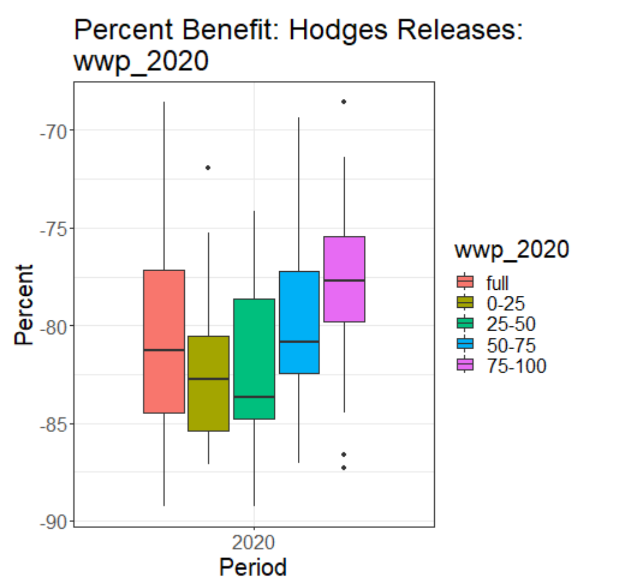
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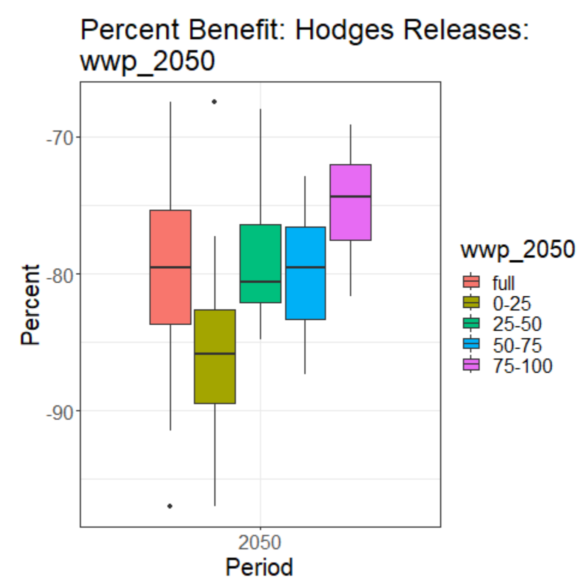
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2050
Period
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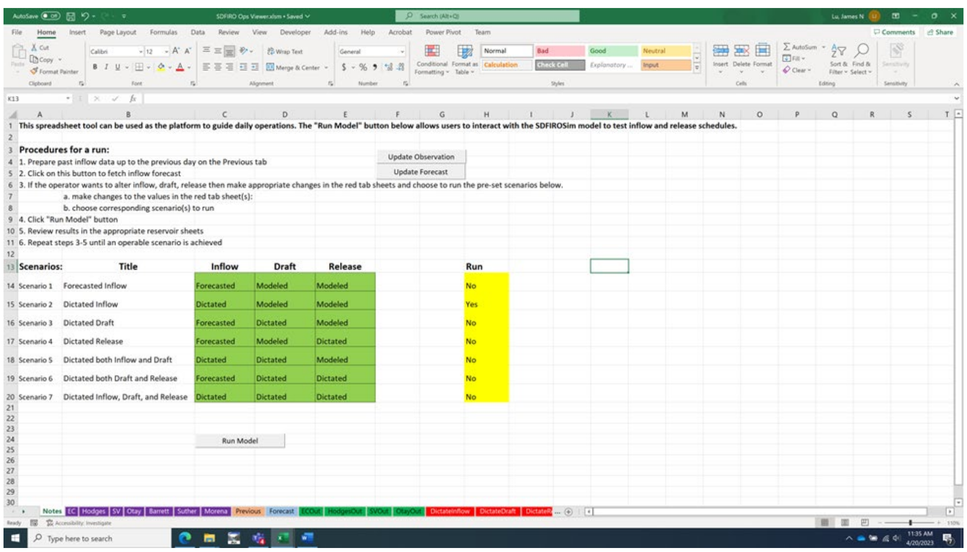
full
0-25
25-50
50-75
75-100

Appendix C – Instructions of the SDFIROSim real-time operation platform

Description

Reclamation staff has been studying the benefit of implementing FIRO operation in the City of San Diego Reservoirs. One outcome of the study is the SDFIROSim model. The model is a GoldSim model with daily time step, used successfully both in the climate impact analysis and historical simulations with different datasets. A platform is also developed for the city operators to leverage the power of the model in their daily operation practices.

The platform is Excel based, providing access to the model through automation. Observation and forecast update and model runs can be done with a click of a button. A screen shot of the main interface is shown below:



Assumptions

For the purpose of daily operations, there are some changes to the baseline SDFIROSim Model. First, the mode run start time was changed from 1/1/2013 to 1/1/2022 to shorten the run time. As a result, the initial reservoir status should also be changed to reflect the new starting date. Second, the end time is changed to 10 days beyond the run date. Also, a few model elements are added or changed based on the condition of the scenarios. For example, the logic for the draft request was changed for scenarios that with preset draft schedules.

System requirement

The tool is development under Windows 10, Microsoft Excel for Microsoft 365 environment. A successful operation of the tool will also need the GoldSim software Version 14.0 installed at C:\Program Files (x86)\GTG\

Installation

1. Create a folder and copy the following files to this folder:

SDFIRO Ops Viewer.xlsm

SDFIROSim-s1.gsm

SDFIROSim-s2.gsm

SDFIROSim-s3.gsm

SDFIROSim-s4.gsm

SDFIROSim-s5.gsm

SDFIROSim-s6.gsm

SDFIROSim-s7.gsm

Input_inflow.xlsx

Input_draft.xlsx

Input_release.xlsx

Input_runoff.xlsx

Input_demand.xlsx

Output.xlsx

SDBS_Metric_Output.xlsx

ECOutput.xlsx

HodgesOutput.xlsx

SVOutput.xlsx

OtayOutput.xlsx

2. Create a subfolder and name it "Data". This folder stores CNRFC forecast data.

Operating procedures

1. Update observation. At this time, the function of automatically updating observed data is under development. Users need to update the input_runoff.xlsx file up to the day before the operation. This is a simple spreadsheet file contain observed reservoir inflow timeseries. The first column is calendar date starting from January 1, 2013 and the rest of it is observed runoff for Barrett, Morena, Sutherland, ElCapitan, Hodges, SanVicente, and Otay.
2. Update forecast. This is done by click on the "Update Forecast" button from the interface. The function will go to CNRFC website https://www.cnrfc.noaa.gov/deterministicHourlyProductCSV.php and grab the San Diego/Inland zip file and extract the data. The forecast is hourly and 10 days look-ahead. It will be aggregated into daily and populated into the "Forecast" worksheet.

Scenario selection. There are 7 preset scenarios for the operator to choose. Operators can choose any scenario by choose yes on the yellow cells in the interface.

Scenario 1: This is probably the first scenario which the operator will analysis. The model runs with the RFC forecast.

Scenario 2: The operator will choose this scenario to run if the forecast is not anticipated or the operator wants to see the results of different forecasts. The operator will give his own forecast data in the "DictateInflow" worksheet.

In the following scenarios the inflow is always forecasted if it does not involve "DictatedInflow".

Scenario 3: If the operator wants to know what would be the storage and release given a pre-determined draft schedule. The operator will give his draft schedule on the "DictateDraft" worksheet.

Scenario 4: If the operator wants to know what would be the storage and draft given a pre-determined release schedule. The operator will give his release schedule on the "DictateRelease" worksheet.

Scenario 5: This scenario is designed for testing with pre-determined inflow and draft schedules. The operator needs to produce the inflow and draft schedules on the "DictateInflow" and "DictateDraft" worksheets.

Scenario 6: This scenario is designed for testing with pre-determined draft and release schedules. The operator needs to produce the draft and release schedules on the "DictateDraft" and "DictateRelease" worksheets.

Scenario 7: This scenario is designed for testing with pre-determined inflow, draft, and release schedules. The operator needs to produce the inflow, draft, and release schedules on the “DictateInflow”, “DictateDraft”, and “DictateRelease” worksheets.

3. Run model. This is done by a click on the “Run Model” button. This process is automated. A windows batch file will be created and launched. The model will be run. Results will be populated in the output files for the reservoirs. The operator can go to the individual reservoir worksheet to view the results.
4. View results: On the individual reservoir worksheets, there is a chart with 4 variables shown: inflow, release, draft, and storage. The storage in acre-feet is read from the vertical axis on the right. The rest are discharges in cfs and read from the vertical axis on the left. The operator can toggle scenarios using the dropdown box. The lines can be turned on and off with the checkboxes. A screenshot of the El Capitan worksheet is shown below: