Stevens Creek Reservoir – Forecast Informed Reservoir Operation (FIRO) Phase One Report

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Prepared for SCV Water District

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Acknowledgments

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Executive Summary

The Santa Clara Valley Water District (Valley Water) is seeking to improve reservoir operations to maximize utilization of reservoir capacity via the use of Forecast Informed Reservoir Operations (FIRO) under current and future climate conditions. Stevens Creek Reservoir (SCR) was selected as a pilot study reservoir to test this approach. The goal is to create a prediction-oriented, near real-time control reservoir modeling support system that can help Valley Water better manage reservoirs for multiple objectives, including water supply, flood control, and ecosystem support. The project has three phases, and this report provides a summary of Phase One, which includes developing a linked modeling system for the contributing watersheds and SCR, conducting FIRO experiments, and assessing the potential benefits of applying FIRO for water supply and flood control purposes.

A watershed model (a refined version of Watershed Dynamic Model, WDM) was developed for the SCR watershed to estimate inflow. It predicts inflow volume with an average of less than 4% relative error during the simulation period. It also performs well in predicting high flow events during the calibration and validation periods. A reservoir water budget model is developed to simulate reservoir storage by given reservoir operation rules. A baseline scenario, which strictly follows the current reservoir operation rules, was created to assess the benefits of FIRO. Four FIRO scenarios, FS1(perfect hindcast + current flood control rules), FS2(perfect hindcast + ‘fill and spill’), MFS1(modeled inflow + current flood control rules), and MFS2 (modeled inflow + ‘fill and spill’), were created to be compared with the baseline scenario and evaluate the benefits of FIRO approach.

Three performance metrics (same as those used for the Lexington Reservoir FIRO analysis) were used to evaluate the benefit of FIRO: 1. average reservoir storage before large inflows; 2. reservoir peak outflow during spill events; 3. reservoir storage at the end of winter. In an ideal prediction situation (FS1 and FS2), both FIRO scenarios show larger benefits than the current operation. The FS1 scenario resulted in a similar water supply benefit versus the baseline scenario (2,122 ac-ft vs 2,175 ac-ft), and totally avoided the spill events. The FS2 scenario gained larger benefits than the baseline scenario from both water supply (2,320 ac-ft vs 2,175 ac-ft) and flood control (8 spill days vs 27 spill days). The FIRO scenarios with modeled inflow show either larger flood control benefits or water supply benefits than the baseline scenario. MFS1 sacrificed some water supply benefit (2,054 ac-ft vs 2,175 ac-ft) to achieve a larger flood control benefit (2 spill days vs 27 spill days) than the baseline scenario. MFS2 resulted in a similar flood risk (27 spill days vs 27 spill days) but a larger water supply benefit (2,322 ac-ft vs 2,175 ac-ft). Both scenarios performed as well as the baseline, indicating potential benefits despite prediction errors. MFS1 eliminated spill events with a lower water supply than the baseline, while MFS2 had a higher storage capacity with a "fill and spill" rule that increased flood risk. The study suggests that relaxed operation rules not as extreme as ‘fill and spill’ may achieve benefits on both ends. Reservoir operations resulting in lower flood risk and increased water storage are worth exploring for FIRO scenarios.

The study did not test the impact of precipitation forecast accuracy on FIRO effectiveness, but it is recommended to do so once the forecast data source is selected. A further test with a rainfall forecast product is recommended, along with the exploration of the accuracy of different precipitation products and recalibration of the watershed model periodically for FIRO analysis to improve watershed model estimation. Once the downstream watershed model is completed, the integrated upstream-reservoir-downstream modeling system can be used to develop an initial framework for multi-benefit reservoir flow management and explore the opportunities to couple this with downstream channel-floodplain modifications that support healthy ecosystems through physical and ecological processes and functions. The implementation of FIRO in practice requires consideration of additional operational details, such as the time it takes for the outlet to open fully and the maximum outlet flow rate, which may require direct monitoring. All of these operational details need to be taken into consideration when applying FIRO in reality.

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1. Background and Motivation

Santa Clara Valley Water District (Valley Water hereafter) maintains and operates a network of reservoirs for potable water supply and flood management. The current reservoir operation rules are relatively static and derived from historical data, which may not be able to maximize utilization of reservoir capacity under current and future climate conditions. Elsewhere in the state, the Forecast Informed Reservoir Operations (FIRO) project (https://cw3e.ucsd.edu/firo/) has provided an innovative way to enhance reservoir operations in several watersheds using ensemble weather forecast products and cutting-edge modeling systems. For example, the viability assessment at Lake Mendocino in the Russian River watershed showed large potential to improve water supply management by incorporating weather forecast information into decisions of conservation storage as well as pre-release for flood control purposes (Delaney et al., 2020, Weihs et al., 2020).

With a similar goal of improving reservoir operations, an existing regional watershed model (Zi et al., 2021, 2022) developed by the San Francisco Estuary Institute-Aquatic Science Center (SFEI-ASC) was downscaled to support reservoir operation management with a watershed-based approach. This project was designed to: 1) help Valley Water develop a linked watershed-reservoir modeling system; 2) provide benefit estimates of FIRO; 3) assess the uncertainties of watershed modeling based on FIRO and provide reservoir operation recommendations. The prediction-oriented, near real-time control reservoir modeling support system, once developed and validated, could help Valley Water better manage reservoirs for multiple objectives (i.e., water supply, flood control, and ecosystem support). By incorporating forecasted precipitation and inflow predictions, reservoir operations could be optimized to better meet water supply and other requirements based on predicted conditions.

The Stevens Creek Reservoir (SCR) was selected as a pilot study reservoir to test this approach after discussion with Valley Water based on their overall reservoir modeling plan. Valley Water holds water rights licenses for the Stevens Creek watershed, which allow water diversion and storage for irrigation and domestic uses. Like all Valley Water reservoirs, the dam operations are governed by rule curves developed to achieve specific objectives. One of the priority objectives is maintaining a reliable current and future water supply and water deliveries. Therefore, Valley Water aims to have water storage at the end of the rainy season (April 30th) be as high as possible. Since 1997, reservoir spill events have occurred in 1998, 2005, 2006, 2010, 2011, 2016, 2017, and 2019 at SCR.

Reducing flood risk for downstream areas is another major objective of reservoir operation. With increased urban development in flood-prone areas, particularly in the past 20 years, the potential for property damage from major flooding has also increased. The peak flow rates of flood releases and spill events are reduced by reservoir operations, with the goal of not exceeding the downstream flood capacity of Stevens Creek (5,000 cubic feet per second, cfs) (SCVWD, 2021).

Valley Water is proposing to implement the Fish and Aquatic Habitat Collaborative Effort (FAHCE) Settlement Agreement through a Fish Habitat Restoration Plan. One of the management objectives of the FAHCE Settlement Agreement is to restore and maintain a healthy steelhead population in the Stevens Creek watershed by providing suitable spawning and rearing habitat, adequate passage for migrating adult steelhead (into the watershed) and juvenile steelhead (out of the watershed), extended suitable time for spawning, and increased spatial distribution of suitable habitat through the Adaptive Management Program (AMP). To achieve these restoration objectives, FAHCE rule curves for winter base flow releases, spring pulse flow releases, summer base flow releases, and flow ramping were proposed for SCR (SCVWD, 2021). SCR reservoir operations therefore need to follow the requirements from the FAHCE Settlement Agreement.

Better reservoir inflow forecasts can support both flood preparations and water management for water supply and ecosystem needs. FIRO has the potential to improve reservoir operation rules using weather forecast data and hydrologic modeling results. This project assesses how streamflow predictions can improve reservoir operating rules and make water management more efficient in the face of extreme weather and climate events that typically lead to flooding or drought, while also providing other benefits such as ecosystem restoration.

This effort to update reservoir operations has three phases:

Phase 1: Develop a linked modeling system for the contributing watersheds (upstream of SCR) and SCR, and conduct FIRO experiments with a perfect inflow forecast and a modeled inflow forecast. The benefits of applying FIRO are then assessed for water supply and flood control purposes.

Phase 2: Extend the FIRO analysis to include the watersheds downstream of the reservoir and develop an initial framework for multi-benefit (i.e., water supply, flood control, and ecosystem support) reservoir flow management, and explore coupling this with downstream channel-floodplain modifications that address the needs of people and wildlife. Incorporate the downstream needs into the reservoir operation modeling and conduct the viability assessment to evaluate the benefits of adjusting reservoir operations based on future forecasts.

Phase 3: Develop a decision-support tool for online operations that provides a streamlined system for conducting the operation optimization, from data acquisition to modeling to reservoir operations support. The decision support tool will be customized for SCR and will have the capability to automatically generate modeling predictions and provide reservoir operation recommendations given optimized rules on a daily basis or even shorter intervals (with the same update frequency as weather forecasts).

This report provides a summary of the Phase 1 work, including the linked model system development, the FIRO scenarios and their performance results, and the benefit assessment.

2. Study Area

2.1. Watershed Description

The Stevens Creek watershed (29 square miles) is located in western Santa Clara County and ultimately drains to the southern end of San Francisco Bay.. Flows in Stevens Creek originate from the Santa Cruz Mountains and travel southeast along the San Andreas Fault for approximately 5 miles. The creek then travels northeast for approximately 3 miles, enters SCR, and then continues north for approximately 13 miles before discharging into San Francisco Bay. Figure 1 shows the contributing watersheds of SCR. The drainage areas contributing to SCR have an area of 17 square miles, over 80% of which is forest (Table 1). Over 41% of the drainage area has high permeability soil and low runoff potentials (Hydraulic Soil Group A or B).

Table 1. The distribution of land cover for Stevens Creek Watersheds (upstream of SCR).

Land Cover*	**Area (acres)**	**Percentage of total area**
Developed Area	638	6%
Forest	9327	81%
Grass	463	4%
Shrub	895	8%
Water	136	1%

* Land cover distribution is derived from the National Land Cover Database (NLCD 2019) product.

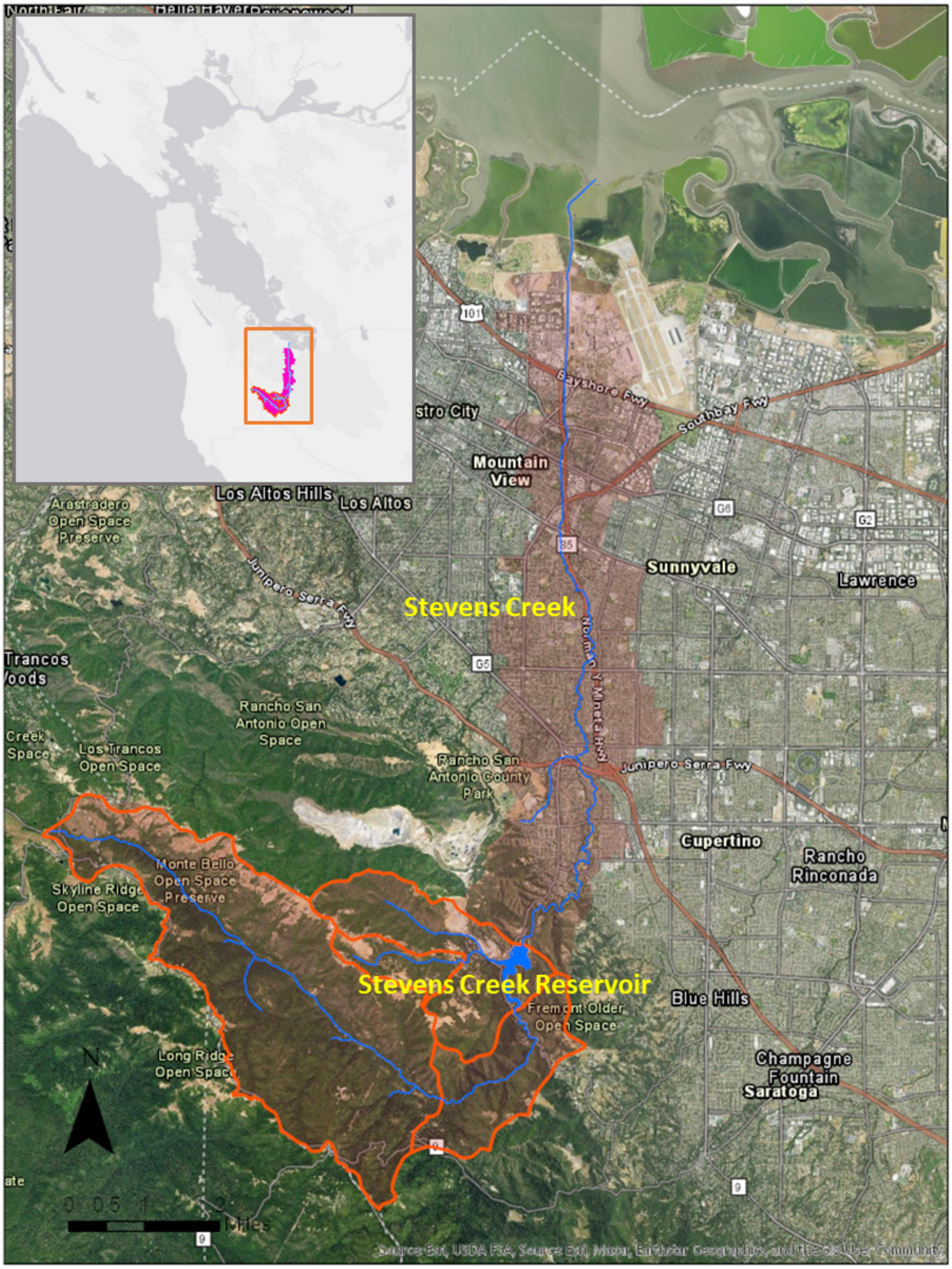

Figure 1. The Stevens Creek and its watershed (light orange background). Subwatersheds bounded by orange lines are upstream of Stevens Creek Reservoir (blue).

2.2. Reservoir Description

SCR is located on Stevens Creek, about two miles southwest of Cupertino. At the downstream end, SCR is impounded by SCR dam which is owned and operated by Valley Water. SCR dam is an earthfill structure that was constructed across Stevens Creek in 1935. The 195 -foot tall dam is 830 feet long and 40 feet wide at its crest. SCR has a maximum capacity of 3,056 acre-feet at the nominal spillway elevation of 535 feet with 92 acres of water surface area. SCR has an outlet pipe with a 50-inch diameter and 890-foot length that can release water downstream, controlled by a butterfly valve. The estimated downstream flood capacity is 5,000 cfs (SCVWD, 2021). The reservoir elevation-storage curve for SCR (Figure 2) enables conversion of reservoir stage to reservoir storage. The discharge rate of water above the spillway is determined by the elevation-discharge curve above SCR spillway (Figure 3).

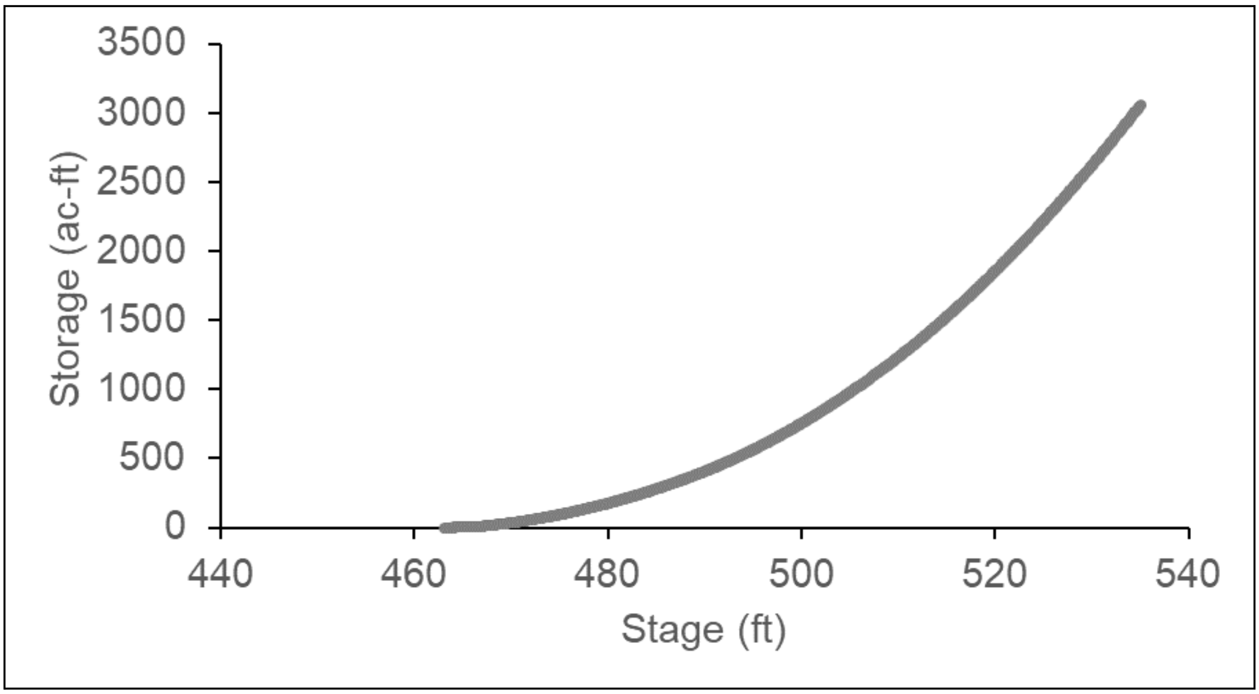

Figure 2: Elevation-Storage Curve for Stevens Creek Reservoir

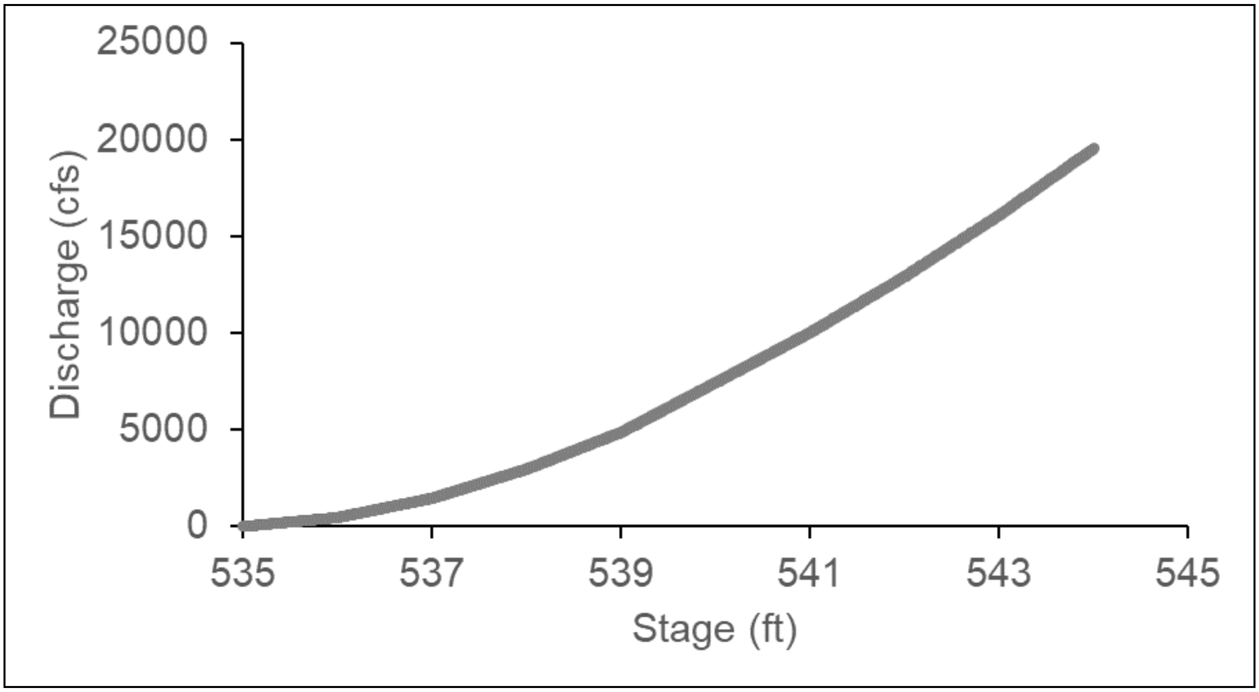

Figure 3: Elevation-Discharge Curve for water above Stevens Creek Reservoir Spillway

The flood control rule curve is designed to reduce spill events in reservoirs. In recent years, SCR operations have followed the 2019 flood control rule curve (Figure 4) which was modified from the 1997 flood control rule curve. The flood control rule curve limits the reservoir storage at the beginning of the rainy season to make sure that there is enough reservoir capacity to store flow from incoming storms and gradually increase the upper limit of reservoir storage as the probability of spill events reduces to eventually reach the reservoir capacity (3056 ac-ft) by April 30. SCR has a minimum capacity of 400 ac-ft to maintain suitable conditions for fish. The Winter Baseflow Rule Curves (WBRCs) for flow releases is 12 cfs from January 1 to April 30, and 3 cfs the rest of the year.

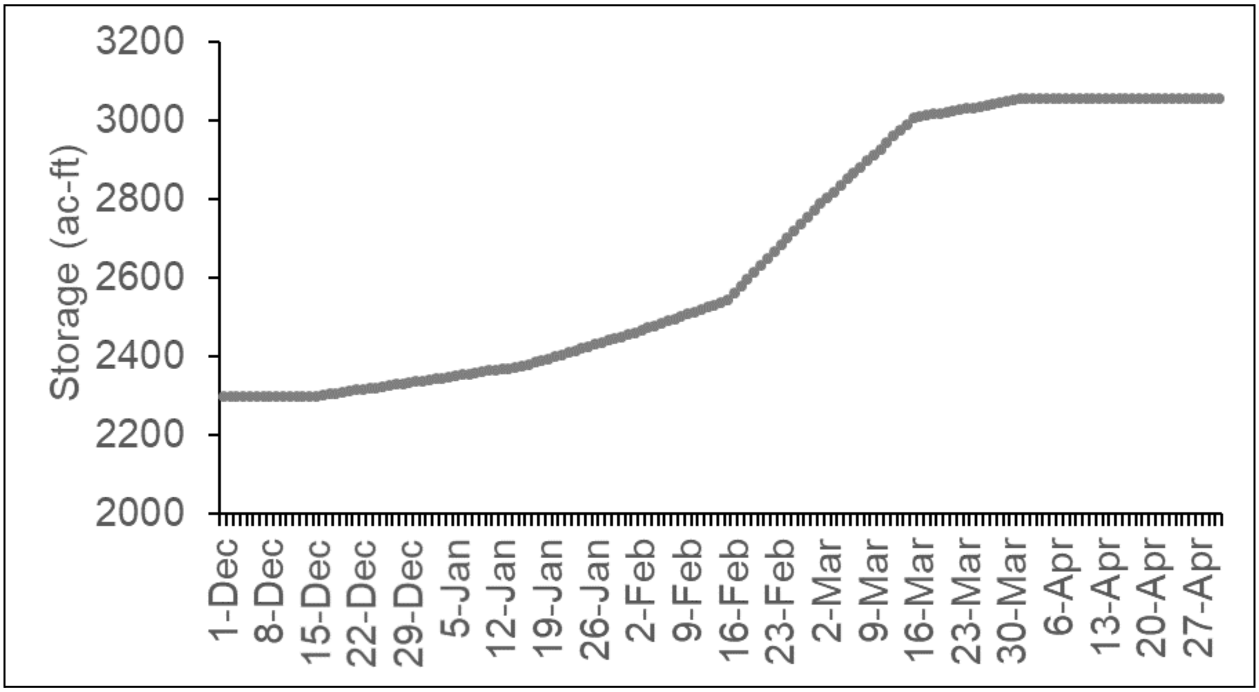

Figure 4: Flood control rule curve for Stevens Creek Reservoir. The storage of the reservoir is controlled to not exceed the storage target of the flood control rule curve at specific times of the year.

3. Monitoring Data

3.1 Precipitation Data

Three different precipitation sources were evaluated for use in this project: rain gauges located near SCR, Gauge-adjusted Radar Rainfall (GARR) product (15 minutes interval), and the Quantitative Precipitation Estimation (QPE) product (15 minutes interval). Rain gauge data were downloaded from the Valley Water Surface Water Data API (https://alertdata.valleywater.org/). The GARR product and the QPE product were provided by Valley Water. The rain gauge installed at SCR (Valley Water Sensor ID: 6001) has rainfall data available since Water Year 1980 at 15-minute intervals. The GARR data is available from Water Year 2017 to 2021. The GARR precipitation products at 1 km resolution were averaged within the boundaries of subwatersheds to get the area-weighted GARR rainfall time series for the contributing area of SCR. The QPE rainfall data is available from December 1, 2022, to January 17, 2023, for the testing of extreme rainfall events.

Table 2 and Figure 5 show the differences in rainfall from the different rainfall data sources. Compared to the annual GARR time series, the annual rainfall derived from rain gauge data was 1–12.7 inches less (10%–108% of the rain gauge annual rainfall). GARR-derived watershed rainfall was always greater than the rain gauge rainfall at the monthly scale (Figure 5). The largest difference in monthly rainfall between the rain gauge and GARR was 6.6 inches in November of 2017; the average difference is 1.6 inches. The rainfall amount derived from QPE data (provided by Valley Water as area average for Stevens Creek watershed) was also 9.8 inches more than the rain gauge data for the storm events between December 1, 2022, and January 17, 2023. The spatial heterogeneity of rainfall suggests one rainfall gauge cannot capture the spatial variation of rainfall for the drainage area upstream of SCR.

Table 2. Annual rainfall* (inches) from different precipitation sources

Water Year* / Period	**Rain Gauge @ SCR (Sensor ID: 6001)**	**GARR**	**QPE**
2017	41.3	54.0	N/A
2018	6.9	14.4	N/A
2019	35.0	45.0	N/A
2020	12.2	17.3	N/A
2021	9.6	10.6	N/A
12/1/2022-1/17/2023	30.9	N/A	40.7

* Annual rainfall was summarized, excluding the periods with missing data.

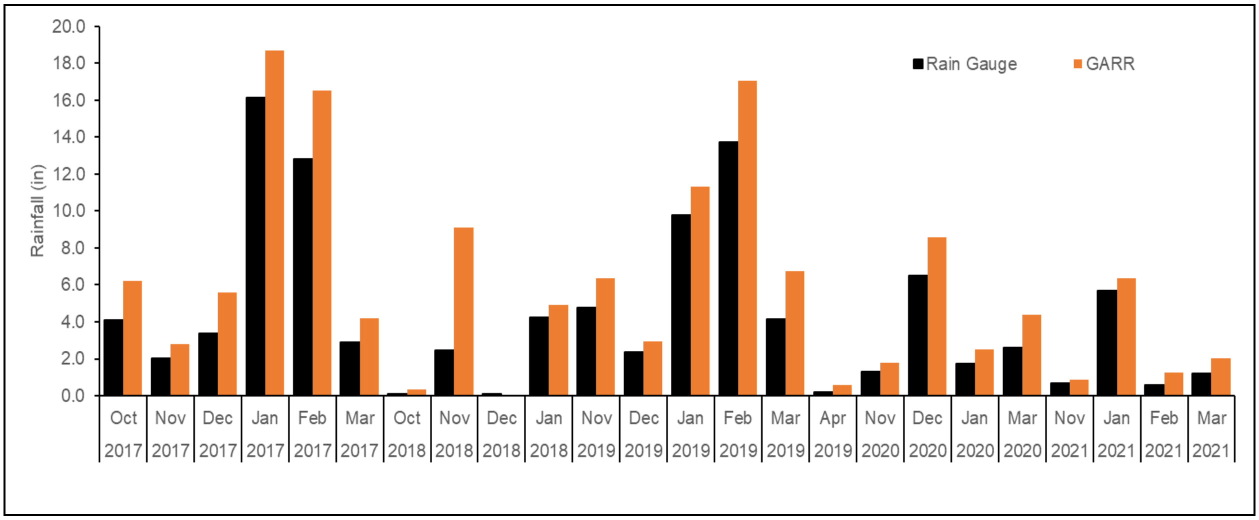

Figure 5. Monthly rainfall comparison between rain gauge and GARR data

For this project, the watershed model was designed to run continuously to provide inflow predictions in a near real-time manner. The GARR precipitation data, while spatially distributed, does not cover the whole period of calibration (the months that the GARR data covers are shown in Figure 5). Conversely, the rain gauge data is a single point measurement, but has relatively complete temporal coverage from water year 1980 to 2021. To have a better soil moisture dynamic simulation and a better estimate of rainfall-runoff processes with antecedent drying periods, the rain gauge data was selected to drive the rainfall-runoff simulation. Knowing the rain gauge derived rainfall is lower compared to other rainfall data sources, we recommend further analysis of the accuracy of the spatially distributed rainfall datasets and possible rainfall forecast products, to select the best rainfall monitoring data and forecast product to most accurately estimate area rainfall for future watershed model calibration and FIRO analysis.

3.2. Flow and Reservoir Storage

3.2.1. Storage and Flow Data Description

Stream gauges located both upstream (Valley Water sensor id: 5045) and downstream (Valley Water sensor id: 5044) of SCR, provide historical and current flow rates to and from the reservoir. A stage sensor at the spillway (Valley Water sensor id: 4009) provides water elevation data and associated storage volume. The stage sensor is sensitive to water level fluctuations of 0.1 ft. All sensors record data at synchronized 15-minute intervals. The upstream gauge, located on the mainstream of Stevens Creek, has been collecting data since 2017. The inflow at this gauge (Figure 6) does not include the contributions from two small tributaries, Swiss Creek and Montebello Creek, and mismatches were found between the upstream inflow and back-calculated inflow from reservoir storage change (details in Appendix A). Thus, the data from the upstream flow gauge were only used to check watershed model performance. The storage sensor and downstream stream gauge have data records starting in 1979 and 1961, respectively. The inflow was derived from the outflow at the downstream gauge and the changes of the reservoir storage volume. These data were then used for the reservoir water budget calculation (see Section 3.2.3) and the watershed model calibration and validation (see Section 4.3).

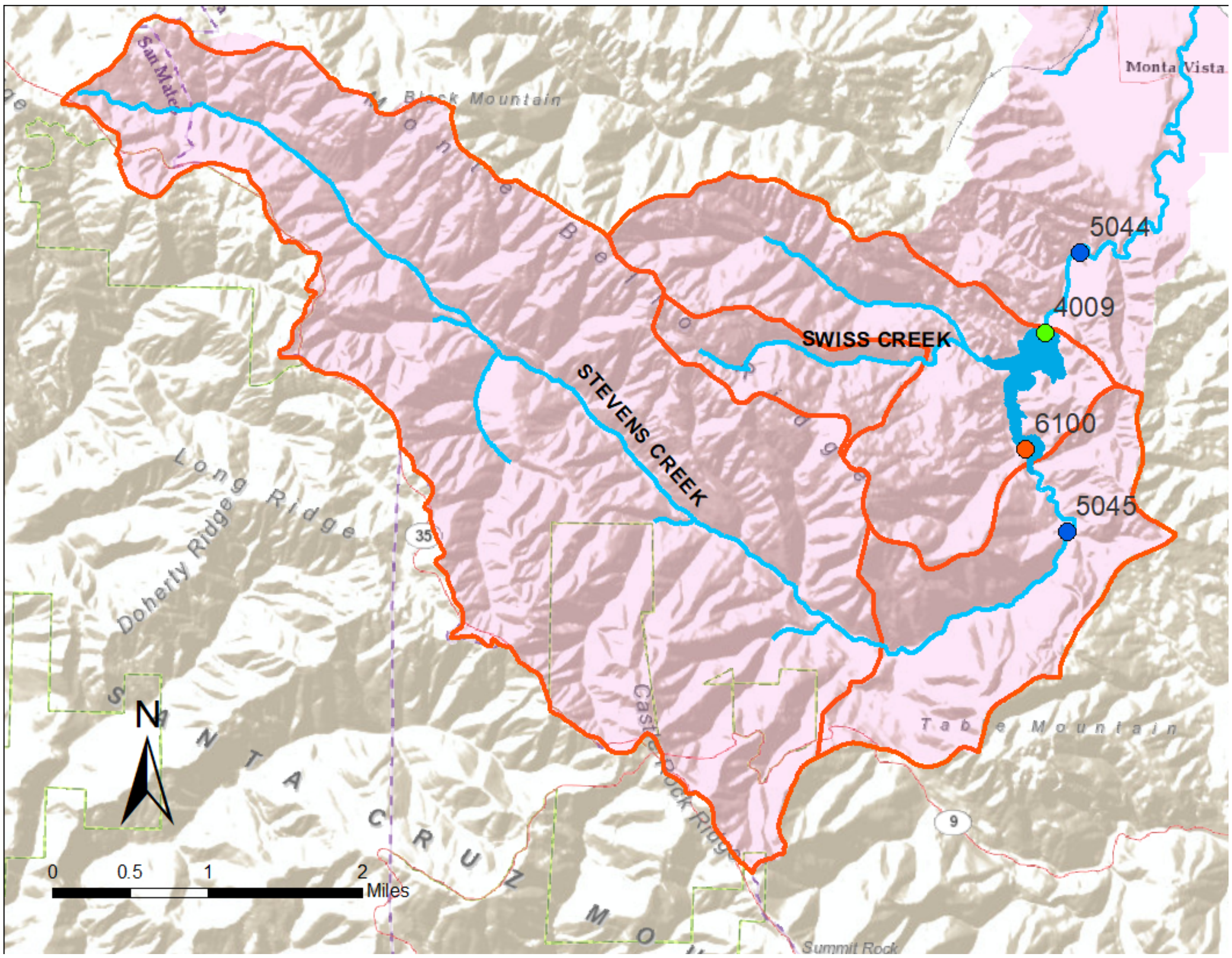

Figure 6. Stevens Creek Reservoir and its contributing watersheds (orange outline) and the monitoring gauges (stream - blue, reservoir stage - green, precipitation - orange) at Stevens Creek Reservoir (Basemap credit: ESRI, USGS, NOAA).

3.2.2. Storage Data Filtering

Equipment data drift is regularly found within the reservoir storage datasets (Figure 7). The elevation sensor is sensitive to the tenth of a foot, and a 0.1 ft elevation change can constitute considerable changes in storage (e.g., 8 acre-feet). The reading values from the elevation sensor sometimes fluctuate ±0.1 ft, which leads to sudden changes of reservoir storage without associated changes of inflow or outflow. When evaluating the change in storage, these errors propagate and cause unrealistic variations in reservoir storage. For example, a 0.1 ft drift from 532.3 ft to 532.2 ft in reservoir stage reading in one time step (15 minutes in this project) would cause a net water release at the rate of 431 cfs from the reservoir for 15 minutes, if the unfiltered storage data were used to derive the water budget of the reservoir.

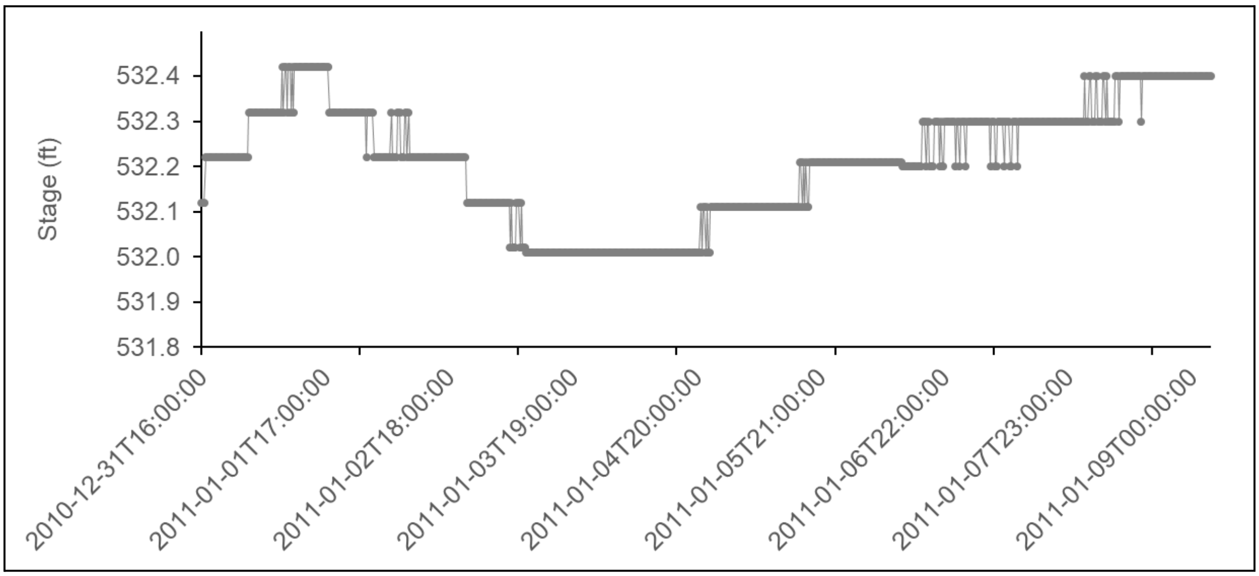

Figure 7. Monitored reservoir stage data

Addressing the equipment drift issue required determining the appropriate data smoothing method. Commonly used methods, such as moving average, are not suitable to filter the reservoir stage data because those filter methods will shift the timing and magnitude of peaks. To smooth the raw reservoir stage data while conserving the timing and magnitude of peaks, we developed a script to automatically and consistently remove the equipment drift issues using a digital signal processing based method. SCRipt and user guide are attached as supplemental material (Appendix B). Data filtering is accomplished with a Chebyshev 2 stopband ripple filter that is intended to remove information related to the highest frequency variations in signal. A number of parameters must be selected to apply the filter to the dataset. During testing, the data filtering caused some issues where extreme reservoir volumes (high and low values) were inaccurate in the filtered data—the differences were more than 10% from the measured value. To overcome this, the difference between a 24 hour moving average window of the measured values and filtered data was added back to the dataset.

The combination of these two data processing techniques (removing the high frequency information via a Chebyshev 2 stopband ripple filter and adding the smoothed difference back to the reservoir storage dataset) produced significantly better results when compared to the original dataset (Figure 8). The comparison between raw and filtered storage time series is shown in Figure 9. The filtered reservoir storage time series was used to derive the inflow time series for SCR.

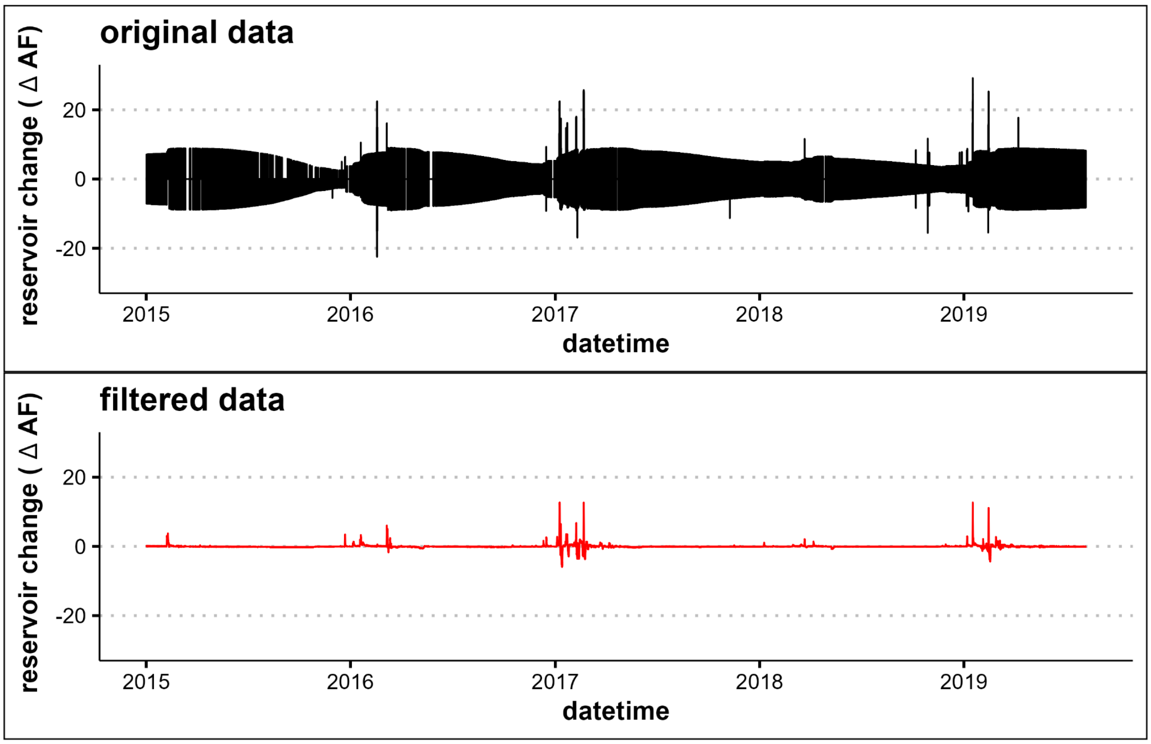

Figure 8. Change in reservoir storage (in acre-feet) of the original dataset (top) and the filtered data (bottom) using the data filtering process. Much of the noise has been removed following the high frequency filter and smoothed difference.

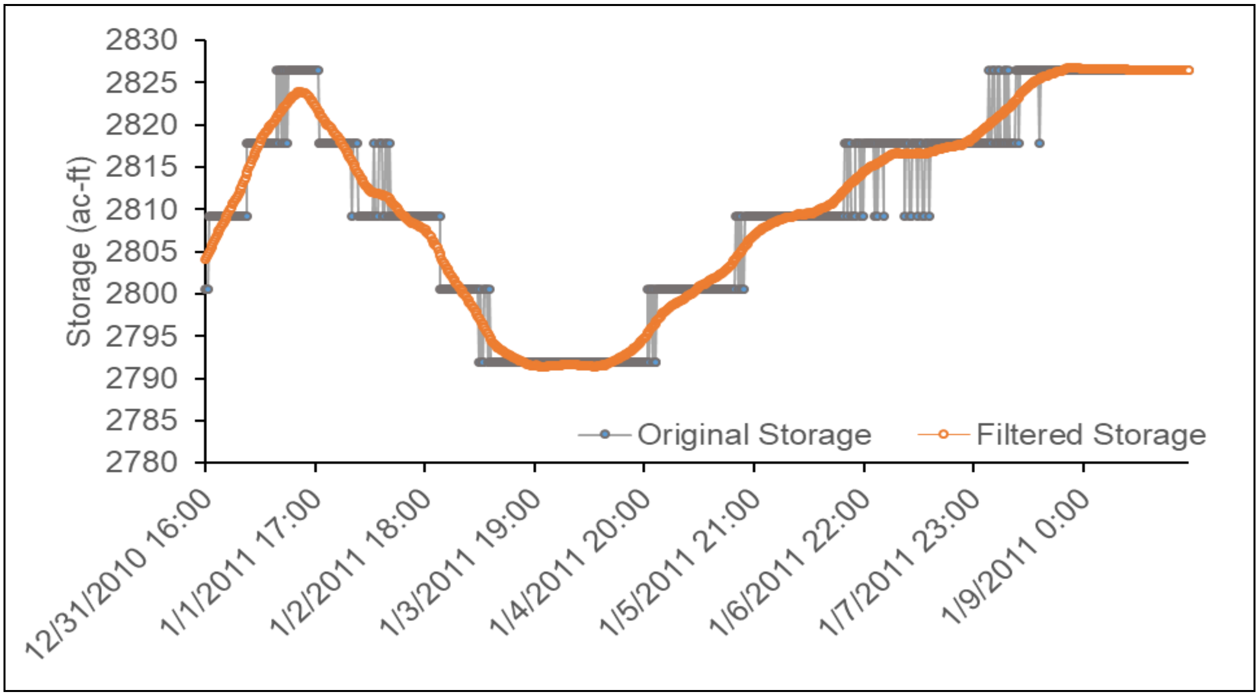

Figure 9. Comparison of the original (gray) and the filtered (orange) reservoir storage (in acre-feet). Many of the abrupt changes in sensor readings were smoothed.

3.2.3. Back-Calculated Inflow

In order to estimate the total inflow to SCR, we developed a water budget model to estimate the inflow of SCR at a given time by utilizing observed storage and outflow data. To do this we back-calculated inflow using the following equation:

$$I = \Delta V + O$$

where I is inflow volume per time step, ΔV is change in storage per time step, and O is outflow volume per time step. The evaporation and groundwater flux were assumed to be insignificant compared to the inflow and outflow fluxes, and were not explicitly represented in the calculations. We processed the change in storage and outflow rates at 15 minute intervals, as described below.

Observed SCR water elevation was filtered using the above mentioned method and then was used to initiate our model. There were occasional gaps in elevation sensor data, so we implemented a basic gap-filling function that duplicates the elevation value from the record immediately preceding it. The inflow was back-calculated with the filtered storage and observed outflow, using the above equation. Negative changes in storage were occasionally greater than observed outflow, thus the resulting negative inflow values were converted to zero. The inflow to SCR was back-calculated from water year 1998 to water year 2021 for the FIRO analysis.

4. Watershed Model

4.1 Model Structure

A watershed model was developed for SCR contributing watersheds to estimate the inflow into SCR. The watershed model developed for the drainage area upstream of SCR is a refined version of an existing regional watershed modeling effort: Watershed Dynamic Model (WDM) (Zi et al., 2021, 2022). The WDM was developed with a process based model (Loading Simulation Program in C++, LSPC). The hydrological process representations of the WDM are shown in Figure 10. The model provides a dynamic, continuous simulation of hydrologic processes. Both upland hydrological processes and channel hydraulics can be simulated using the WDM. This hydrological simulation of the regional watershed model has been calibrated and validated at the regional scale (i.e., local watersheds that drain to the Bay). It serves as a basis for the development of the upstream watershed model for SCR.

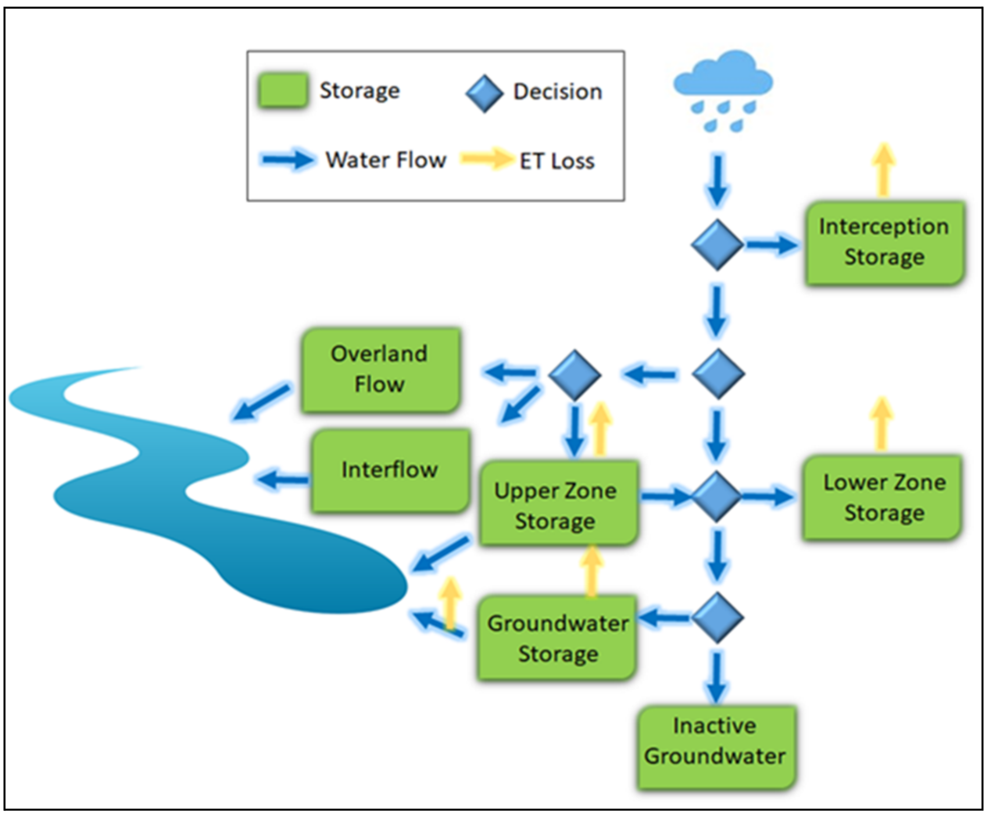

Figure 10. Hydrological processes represented in the Watershed Dynamic Model (WDM).

The WDM was developed with watersheds ranging from 10 to 20 square miles. To capture the hydrological processes at an appropriate temporal and spatial resolution, the contributing area upstream of SCR was refined to four subwatersheds ranging in size from 0.7 to 10.8 square miles (Figure 6). The watershed delineation and stream network geospatial data were provided by Valley Water and align with Valley Water's existing modeling domain. These four subwatersheds were modeled to estimate the inflow to SCR.

The WDM uses a Hydrologic Response Unit (HRU) as the basic modeling unit. A HRU is a unique combination of land surface features (e.g., imperviousness, underlying soil characteristics, slope) that is expected to give a consistent runoff response to rainfall. The HRU approach involves modeling all possible combinations of land surface features present within the modeling domain and then summarizing the HRU results at the watershed scale. The HRU used in this project is based on the WDM and then customized for the Stevens Creek watershed. With the different combinations of land cover, imperviousness, soil types, and slopes, a total of 17 HRUs were developed to represent the hydrological processes occurring at different land surfaces. Forest occupies more than 80% of the area upstream of SCR, and urban area is less than 10%. The details of HRU classification and the data sources used to derive the HRUs for the Stevens Creek watershed can be found in the supplemental material (Appendix A).

Each subwatershed was assigned to one stream segment in the refined Stevens Creek watershed model. Reaches and stream network development relied on the geospatial layer received from Valley Water. Reach length and slope data for natural reaches were estimated using the geospatial layer provided by Valley Water and the USGS National Elevation Dataset DEMs (10 m). The refined WDM model was used to estimate the inflow into SCR. The inflow predictions generated by the refined WDM model were then linked with the reservoir water budget model to update the change in reservoir storage.

4.2 Watershed Model Performance Metrics

One major purpose of the linked Watershed-Reservoir modeling system is to predict if and when the reservoir will reach its storage capacity before big storm events, so that flow releases can be timed e to avoid reservoir spill. This requires high accuracy of inflow and reservoir storage predictions from the model especially during large storm events. Thus, three factors (reservoir inflow volumes, peak inflow rate, and timing of storm events) were selected to evaluate the model results from the watershed model. Percent of bias (PBIAS) was selected to evaluate the water budget simulation. The overall PBIAS, wet season PBIAS, and PBIAS for flow higher than the 90th percentile were used to evaluate the performance of the watershed model. The agreement between observed and modeled flows was assessed using the Nash-Sutcliffe efficiency (NSE), a widely used and reliable statistic for assessing the goodness of fit of hydrology calibration (Nash and Sutcliffe, 1970). NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance and reflects the overall fit of a hydrograph. Values may vary from -∞ to 1.0. A value of NSE = 1.0 indicates a perfect fit between modeled and observed data, whereas values less than 0 indicate that model predictions of temporal variability in observed flows are worse than using the average of observed data. NSE is an indicator of the goodness-of-fit on the timing and magnitude of the flow peaks given it is sensitive to the fit of large events. The higher NSE value the better the watershed model represents the hydrographs of big storm events.

Given the approximate nature of models and inherent uncertainty and errors associated with input and observed data, it is recommended that acceptable ranges, rather than absolute criteria, should be used as general targets or goals for model calibration and validation. Table 8 lists general calibration/validation acceptable ranges that are reported in the literature for two key statistics (Donigian, 2002; Moriasi et al., 2007; Duda et al., 2012). The NSE targets raised by Moriasi et al. (2007) were based on monthly simulation results. For this project, the model performance is evaluated at a 15-minute time step to make sure the model generates an accurate hydrograph at within-event scale.

Table 3. General acceptable targets for watershed hydrology calibration

Statistic	Very Good	Good	Fair	Poor
PBIAS	< 10	10-15	15-25	> 25
NSE	> 0.75	0.65-0.75	0.5-0.65	< 0.5

4.3 Model Calibration and Validation

The watershed model was calibrated against the back-calculated inflow time series to capture changes to reservoir storage. Detailed discussion of model performance and the mismatch between stream gauge readings and reservoir storage changes can be found in Appendix A. The modeled channel flow from the contributing watershed upstream of SCR was compared to the inflow time series. The watershed model simulated the inflow to SCR from water years 1998 to 2019. The model was calibrated with the inflow time series from water years 2010 to 2019, and the data earlier than water year 2010 were used for model validation. Figure 11 shows the comparison between the modeled and back-calculated reservoir inflow time series during the calibration period at a 15-minute time step. Figure 12 is the comparison for the validation period. The watershed model generally has a reasonable response for different water years (e.g., wet year, dry year). At a 15-minute time step, the peak inflow rates were overestimated by the model in several water years, but performed well for two recent wet water years (2017 and 2019).

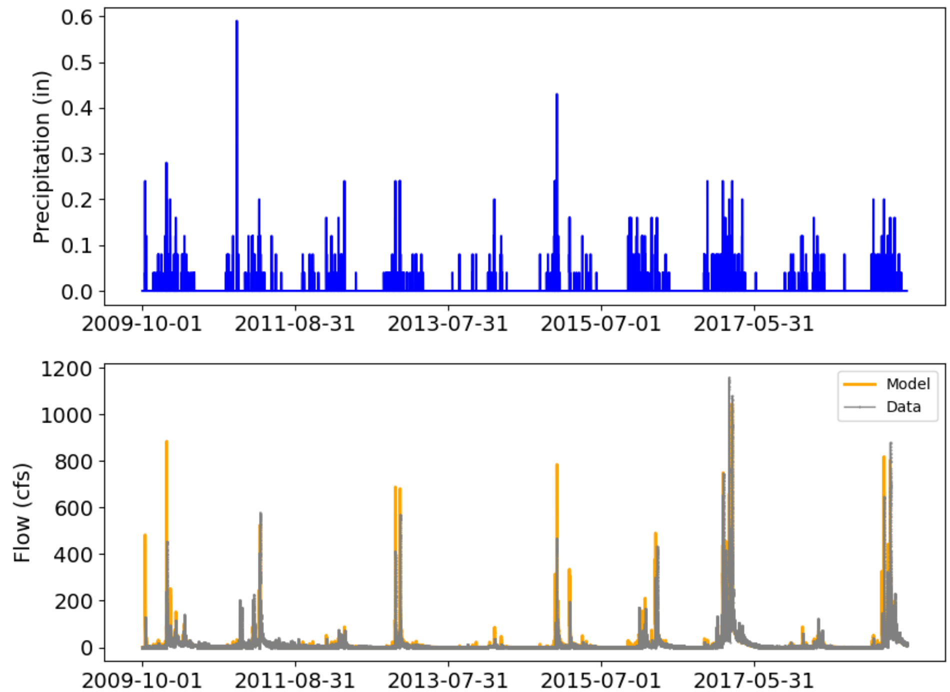

Figure 11. Comparison of modeled and back-calculated inflow time series (15-minute interval) during the calibration period.

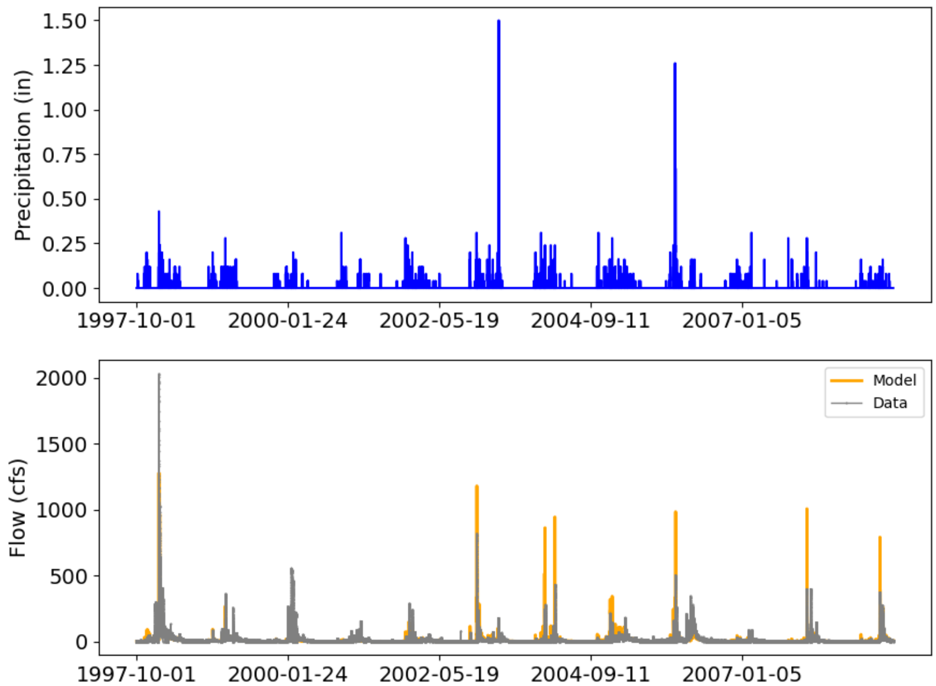

Figure 12. Comparison of modeled and back-calculated inflow time series (15-minute interval) during the validation period.

Table 4 summarizes the performance metrics for the calibration and validation periods. The watershed model does well predicting inflow volume during the entire simulation period (average of less than 4% relative error as indicated by PBAIS score) and the inflow volume of high flow events during the calibration period (High Flow PBIAS). The average relative volume error is less than 10% for high flow periods. The NSE value in the calibration period also indicates a good match between modeled hydrographs and back-calculated hydrographs. The model also performs well in the validation period; the high flow PBIAS is less than 10% for the validation period. Of note is that the directions of the bias at calibration and validation periods are opposite. The model overestimated inflow during the calibration period while underestimating the inflow during the validation period. This indicates dynamic rainfall-runoff responses at the contributing areas along the temporal domain, which is challenging to represent with a fixed set of modeling parameters. Several possible reasons could cause the change of the watershed's rainfall-runoff behavior, for example, changes in land cover, climate (rainfall patterns), groundwater table.

Table 4. Watershed model performance on inflow prediction

	Calibration Period (Water Year 2010 to 2019)	Validation Period (Water Year 1998 to 2009)	Whole Period (Water Year 1998 to 2019)
PBIAS	12.29%	-15.26%	-3.83%
Wet Season PBIAS	16.23%	-8.41%	2.43%
High Flow PBIAS*	7.43%	-7.80%	0.40%
NSE**	0.82	0.53	0.68

* PBIAS of the flow volume at the periods that the flow rates are equal to or larger than 90th percentile flow rate.
**NSE is calculated based on daily time series.

5. FIRO Framework

5.1 Baseline Scenario

The flood control rule curve for SCR has been updated since 2019 and the reservoir operations are manually conducted, which may not follow the operation rules exactly. As a result, the historical reservoir storage time series do not reflect the expected outcome of current reservoir operation rules. In order to assess the benefits of FIRO and compare the benefits with the current reservoir operation rules, we created a baseline scenario in which the reservoir operations exactly follow the current reservoir operation rules. The current SCR operations were mainly guided by two requirements: the flood control rule curve which defines the maximum reservoir storage during the wet season, and the minimum flow release requirements for the wet and dry season. The baseline scenario developed covered water years 1998 to 2019. The flowchart of the current reservoir operations can be found in Figure 13. SCR storage at the beginning of each water year was used as the initial condition, the back-calculated inflow and the outflow rate based on current reservoir operation rules was used to update the reservoir storage.

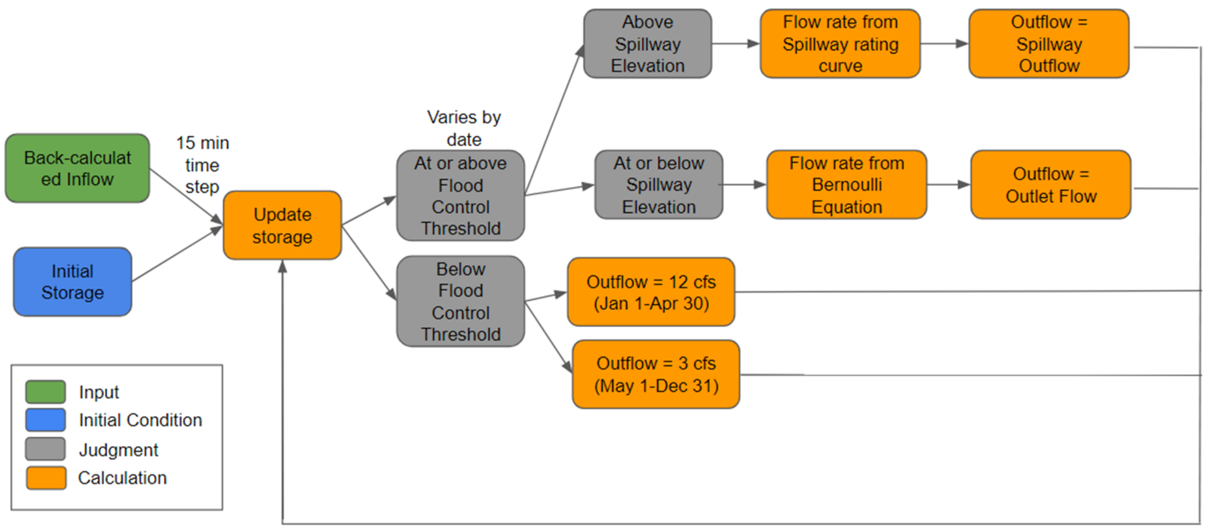

Figure 13. The flowchart showing how the baseline scenario was derived

If the reservoir stage was above spillway elevation, the outflow was derived from the spillway rating curve. If the reservoir stage was above the flood control rule threshold but below the spillway elevation, the outlet was fully opened and the flow rate was derived from Bernoulli equation:

$$Q = a\sqrt{\frac{2gH}{1+K_m+(K_p \times L)}},$$

where Q is the flow rate (cfs), a is the pipe area (ft^2), g is acceleration of gravity (ft/sec^2), H is the elevation head difference (ft), K_m is coefficient of minor losses, K_p is pipe friction coefficient, and L is the length of pipe (ft).

If the reservoir stage was above the flood control rule curve, the outlet fully opened and SCR released water to the downstream area for 6 hours. After 6 hours, a check was conducted to see if the reservoir stage was below the flood control rule curve. If the stage was below the flood control rule curve, the outlet was closed. If not, the outlet remained open for another 6 hours and checked again to decide the status of the outlet.

If the reservoir stage is below the flood control rule curve, the outflow rate follows the minimum release requirement based on the season of the year. Figure 14 shows the observed and baseline reservoir storage. These two time series have a good correlation most of the time. The baseline storage is lower during several dry years (e.g. water year 2002, water year 2007, and water year 2012). The reason for the difference is that the baseline scenario follows the minimum flow release requirement exactly (wet season 12 cfs, dry season 3 cfs); the reservoir release in reality does not always follow the minimum release requirement when reservoir storage is low. The deviances at water year 2002, 2007, 2012, 2015, and 2018 are caused by the required minimum wet season release rate (12 cfs) is larger than the inflow rate. The baseline scenario follows the requirement but the reservoir does not release more water than the inflow in reality. Resulting in decreasing storage under baseline scenario but storage increased based monitoring data.

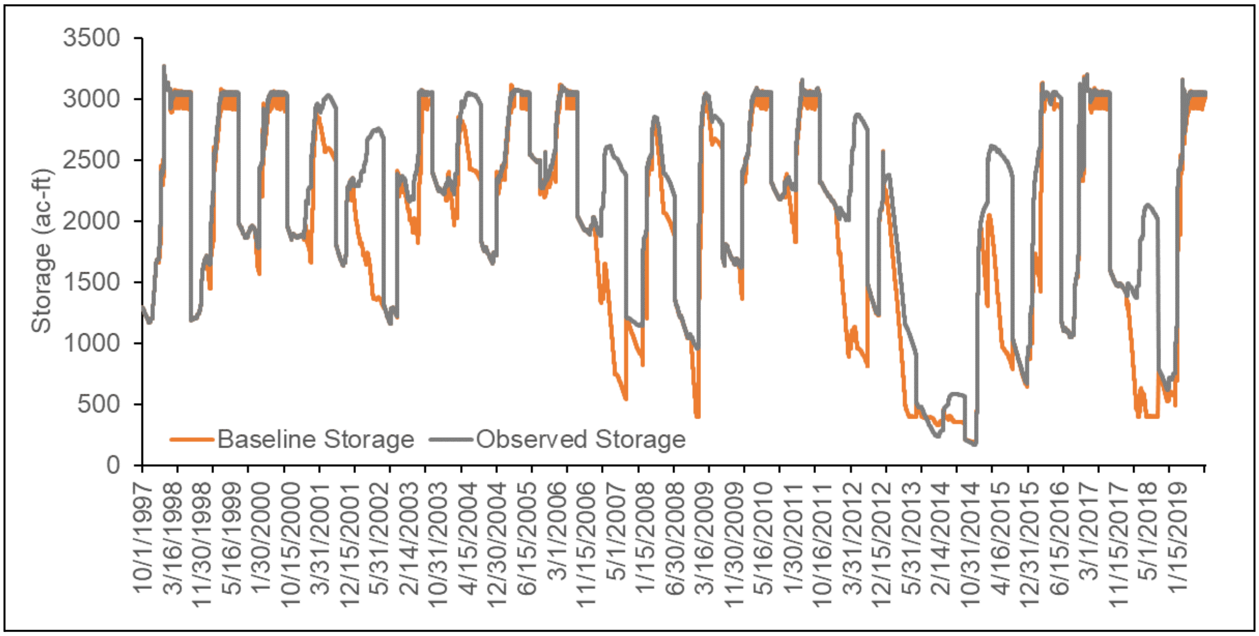

Figure 14. The time series of baseline and observed storage

5.2 FIRO Scenarios

The core objective of the FIRO analysis is to use predicted reservoir inflow and storage change to guide reservoir operations. In this project, we used the inflow forecast with a lead time of 5 days to conduct the FIRO analysis. The choice of 5-day lead time is based on the estimated maximum release capacity of the SCR outlet (86.3% of SCR storage can be released from the fully opened outlet in 5 days) for a 5-day window. The leading day is a key variable for the FIRO analysis. More details will be included in the discussion section.

Similar to the baseline scenario, the storage check was conducted every 6 hours for the FIRO scenarios based on the 5 day lead time prediction. If the reservoir stage was predicted to be above the flood control rule curve/spillway elevation in 5 days, the outlet would fully open and SCR would release water to the downstream area for 6 hours. After 6 hours, a check was conducted to see if the predicted reservoir stage would be below the flood control rule curve/spillway elevation. If the stage was below the flood control rule curve/spillway elevation in 5 days, the outlet was closed. Otherwise, the outlet stayed open for another 6 hours and was checked again to decide the status of the outlet.

The uncertainties of the FIRO analysis are mainly associated with the weather forecast and the inflow prediction. Valley Water was in the process of finalizing rainfall forecast products for FIRO analysis during the implementation of this project. We focused the analysis to gauge the uncertainty of the inflow prediction in this project. To evaluate the feasibility and uncertainty of using model predicted inflow for the FIRO analysis, two different types of scenarios were created. The first is the perfect hindcast scenario, which uses the back-calculated inflow as the inflow prediction to conduct the FIRO analysis by using observed inflow as predicted inflow to create perfect hindcast for 5 days. This scenario represents the best case for FIRO in terms of analysis accuracy and reliability by eliminating errors from weather and inflow forecasts. The second is the modeled inflow scenario. This scenario uses historical weather data to drive the watershed model to provide the inflow forecasts for the FIRO. The real-time reservoir storage is updated based on monitored data. The operation judgment is made based on the model predicted inflow in the next 5 days. This scenario incorporates the errors of inflow prediction from hydrologic modeling into FIRO analysis.

It is expected that the FIRO approach would improve reservoir operations for flood control and water supply purposes. To evaluate that, two operation scenarios were designed in this study. One operation scenario is to follow the current flood control rule curve while conducting the FIRO analysis. If the reservoir stage is predicted to be above the flood control rule curve in 5 days, the reservoir would start to release water 5 days ahead. This operation scenario seeks to reduce flood risk while matching the water supply benefit to current reservoir operations. Another operation scenario is to relax the constraint from the current flood control rule curve, and only start releasing water when there is a risk of spill based on the 5-day prediction. This operation scenario accepts higher flood risk and also has the potential to increase water supply.

Table 5 summarizes the different scenarios of FIRO analysis in this study. Figure 15 is an example of the FIRO scenarios. FS1 (orange line) and FS2 (green line) scenarios both start to release water 5 days ahead of the big storm events centered on 2/21/2017. The FS1 scenario is bounded by the flood control rule curve, in which the maximum storage allowed at the time of this example is less than the reservoir capacity. The FS2 scenario is bounded by the capacity of the reservoir. As a result, the water released under the FS1 scenario is more than the water released under the FS2 scenario to avoid reservoir storage increase beyond the flood control rule curve. The reservoir storage was adjusted to below the flood control rule curve for FS1 and the reservoir storage is kept below the reservoir capacity for FS2 after the event. The two model-based FIRO scenarios (MFS1 and MFS2) follow the same rules but used model-predicted inflow rather than the back-calculated inflow.

Table 5. Scenario summary of FIRO analysis

Scenario Name	FIRO Applied	Hydrological Modeling Uncertainty	Follow Current Flood Control Rules
Baseline	N	N	Y
FS1	Y	N	Y
FS2	Y	N	N
MFS1	Y	Y	Y
MFS2	Y	Y	N

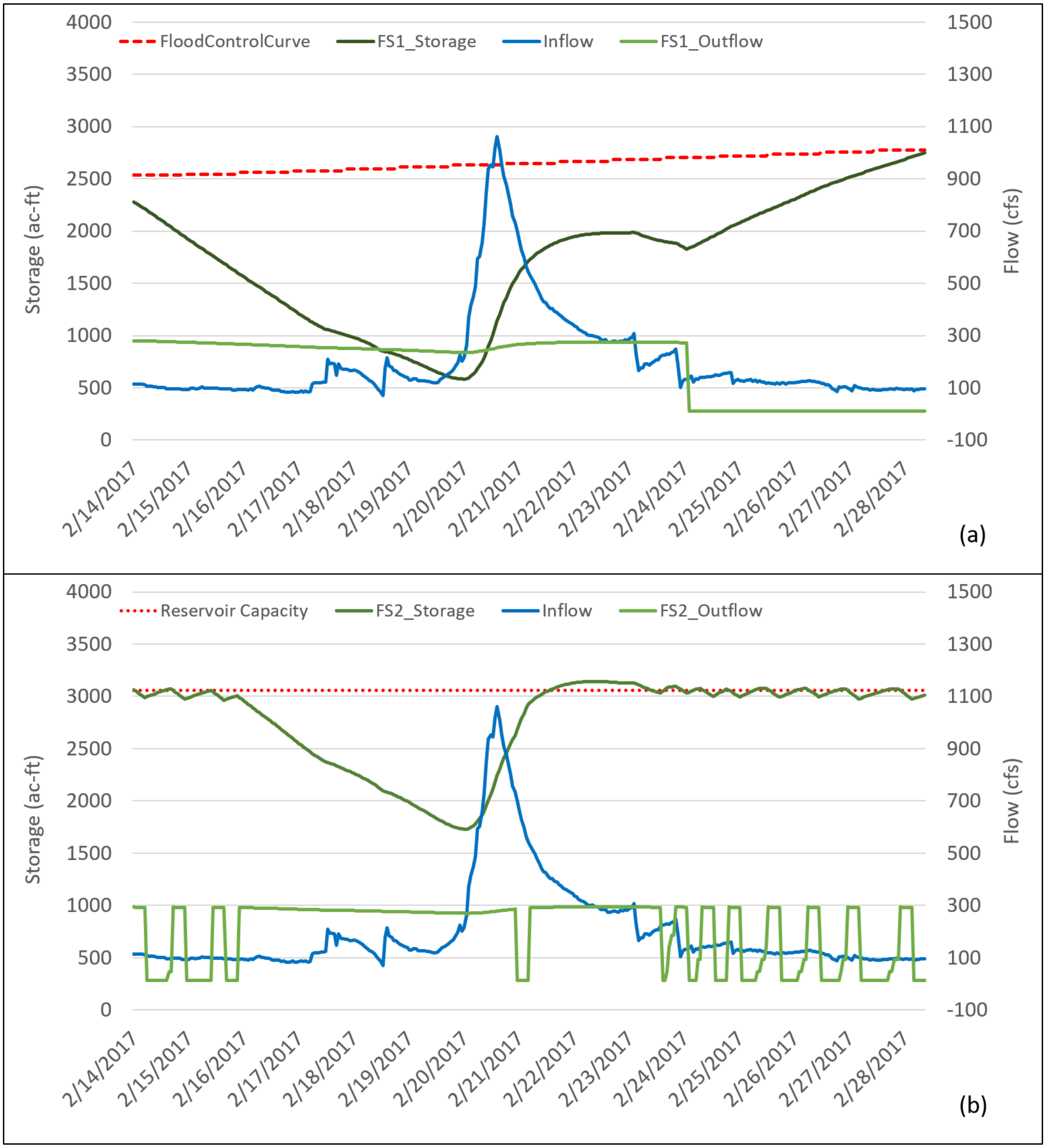

Figure 15. Examples of FIRO scenarios, (a) FS1, (b) FS2.

5.3 Performance Metrics

For this study, we evaluated the benefits of the FIRO scenarios from flood control and water supply perspectives. For flood control, we expected that FIRO would have lower reservoir storage before large inflow events and a lower peak outflow rate during spill events than the baseline scenario. For water supply, we expected that FIRO would have higher reservoir storage at the end of winter than the baseline scenario. We used the same performance metrics (Table 6) that Valley Water used for the Lexington Reservoir FIRO analysis to evaluate the benefits of FIRO at SCR.

Table 6. Performance Metrics for FIRO Analysis.

Criteria Type	Criteria #	Criteria	Desired Value	Measured Using
Flood Risk	1	Average reservoir storage before large inflows	Lower than baseline	Empirical exceedance of storage for selected events
	2	Reservoir peak outflow during spill events	Lower than baseline	Comparison of peak outflows during spill events
Water Supply	3	Reservoir storage at the end of winter	Higher than baseline	Direct comparison and empirical exceedance of storage at the end of April

The peak-finding algorithm method was used to identify the large inflow events for evaluation of Criteria 1. A peak or local maximum is defined as any sample whose two direct neighbors have a smaller amplitude. The maximum flow rate from the outlet is 293 cfs based on the Bernoulli equation. The inflow rate of 300 cfs was used as a threshold for peak identification to eliminate the inflow events that can be fully released by the reservoir outlet. Figure 16 shows the selected large inflow events from the back-calculated inflow time series. A total of 47 events were selected from water years 1998 to 2021. The period including both the rising and falling limbs of the hydrographs centered at the identified peaks were selected for analysis. The average reservoir storage during the inflow events was compared between FIRO scenarios and the baseline scenario.

The peak outflow rates during spill events and the reservoir storage on April 30th were evaluated for both FIRO and baseline scenarios. If the FIRO scenario met the selected criteria, it will have a score of one on that criterion, otherwise if no benefits were achieved from the FIRO scenario, a score of negative one is given to that criterion. The baseline has zeros on all criteria. Only the FIRO scenario with a positive score from the sum of three criteria was considered to have better performance than the baseline scenario.

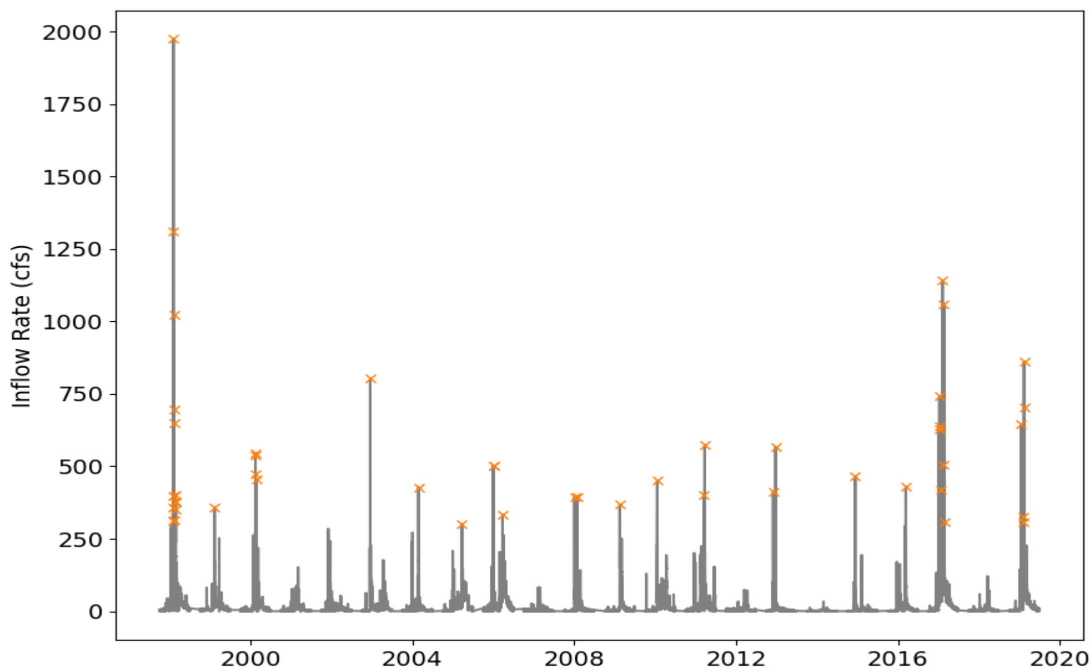

Figure 16. Large inflow events (orange cross) selected for the evaluation of Criteria One.

6. Results

6.1. Results Summary

6.1.1. Perfect Hindcast

Figures 17 to 19 show the performance of the perfect hindcast FIRO scenarios on the three selected criteria compared to the baseline scenario. Figure 17 shows the empirical probability of exceedance of the reservoir storage before large inflow events (47 events) identified by the peak-finding algorithm. Compared to the baseline scenario, both perfect hindcast FIRO scenarios have smaller storages before the large inflow events, indicating that the FIRO operations can reduce spill events by increasing storage capacity before large storm events. For example, for a 75th percentile inflow event (XXX cfs), the reservoir storage for the baseline scenario is 3111 ac-ft, and 1670 ac-ft and 2994 ac-ft for FS1 and FS2 scenarios respectively. The FIRO scenarios have much larger storage capacity before extreme storm events.

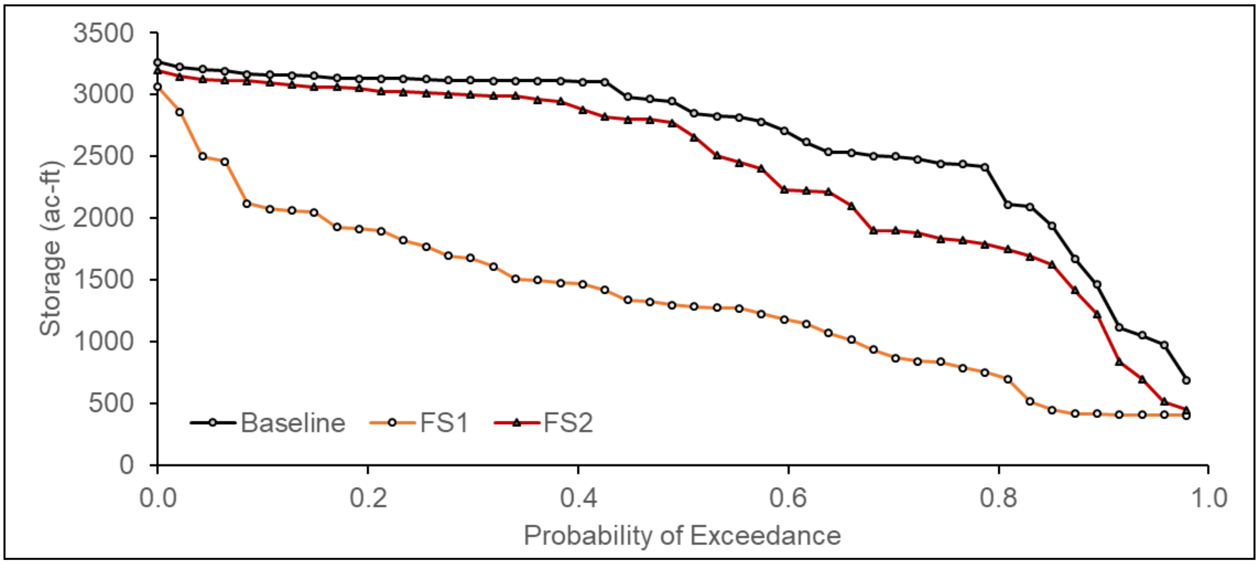

Figure 17. The comparison of empirical probability of exceedance curves of reservoir storage before large inflow events between baseline scenario and perfect hindcast FIRO scenarios.

Figure 18 further illustrates the flood control benefits of the two FIRO scenarios. For the whole simulation period (water years 1998 to 2019), the FS1 scenario did not have any spill event occur by strictly following the 2019 flood control curve and adjusting the reservoir storage 5 days in advance. The FS2 scenario relaxes the storage constraint for water supply purposes and still has fewer spill events than the baseline scenario. The total hours that the reservoir stage is above spillway elevation and outflow rate from the spillway is larger than the maximum outlet flow rate for the baseline scenario is 358 hours for the whole simulation period and 158 hours for the FS2 scenario. The peak spillway flow rates from the FS2 scenario are equal to or smaller than the spillway flow rates from the baseline scenario with the exception of the spill event on February 7, 1998. It is worth noting that the storm events in early February 1998 are multi-day events. SCR started to spill as early as February 3rd in the baseline scenario with a near 2,000 cfs spillway flow rate, and the spill lasted for seven days from February 3-9. In the FS2 scenario, the early February extreme storm events caused a spill starting from February 7th and lasted to February 9th. Both the duration and the peak spillway outflow from the FS2 scenario are less than the baseline scenario for the early February storm events. Both FIRO scenarios showed large reservoir operation improvements for flood control.

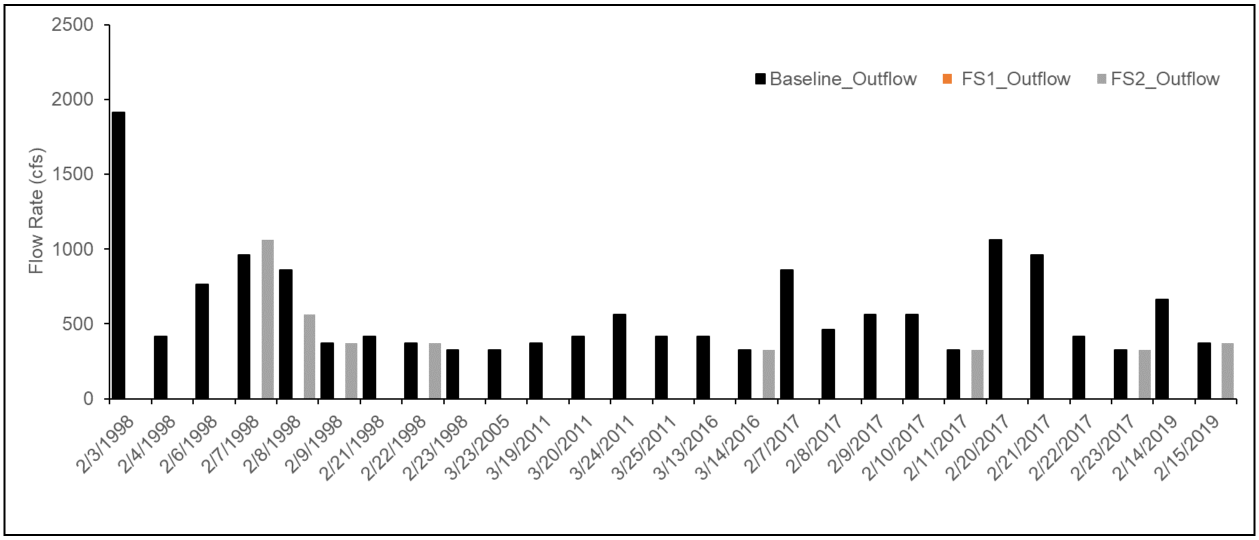

Figure 18. The peak spillway outflow rates comparison during spill events between the baseline scenario and perfect hindcast FIRO scenarios (only showing the spill events with spillway flow rates that are larger than the maximum outlet flow rate. No spills occurred under the FS1 scenario).

Figure 19 shows the reservoir storage at the end of winter for the three scenarios. For 10 out of 22 years the FS1 scenario results in a larger end of winter storage than the baseline scenario. The average reservoir storage on April 30th for the baseline scenario and FS1 scenario are 2175 ac-ft and 2122 ac-ft, respectively. The FS2 shows a larger water supply benefit compared to the baseline scenario. The average April 30th reservoir storage for the FS2 scenario is 2,320 ac-ft. FS2 resulted in considerable increases in reservoir storage at the end of winter in 2002 (801 ac-ft) and 2013 (782 ac-ft). The FS2 scenario results in an average of 145 ac-ft more water storage each year than the baseline scenario.

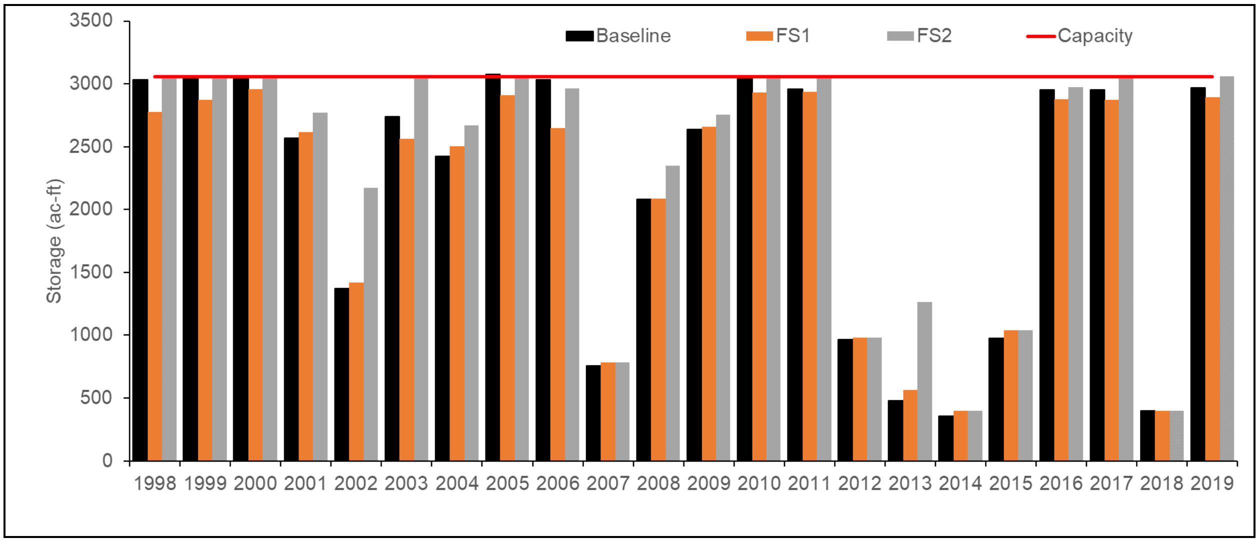

Figure 19. The comparison of reservoir storage at the end of winter (April 30th) between baseline and perfect hindcast FIRO scenarios.

6.1.2. Watershed Model Hindcast

The benefits of FIRO scenarios using model predicted inflow were also evaluated for the same three criteria. The model hindcast FIRO scenarios incorporate the uncertainties from watershed model simulation into the operations. Figures 20 to 22 show the performance of the FIRO scenarios with the modeled hindcast. Figure 20 shows the empirical probability of exceedance of the reservoir storage before large inflow events (baseline: 47 events, modeled: 43 events) identified by the peak-finding algorithm. The modeled inflow events with a peak flow rate larger than 300 cfs had 4 fewer events than the back-calculated inflow time series, indicating the deviation of the model simulated inflow from the back-calculated inflow. The model hindcast FIRO scenario that follows the current flood control rule curve (MFS1) has lower storage capacity before the large inflow events, indicating that FIRO operations can reduce spill events by increasing storage capacity before big storm events using modeled predictions. The FIRO scenario with relaxed flood control constraint (MFS2) has reservoir storages before the large inflow events similar to or larger than the baseline scenario except a few events. For high percentile inflow events (> 60th percentile), the reservoir storages of MFS2 are lower than baseline storage. For example, storage capacity for baseline and model hindcast FIRO scenarios before the 75th percentile inflow events are 3,111 ac-ft, 1,879 ac-ft (MFS1), and 3,085 ac-ft (MFS2) respectively.

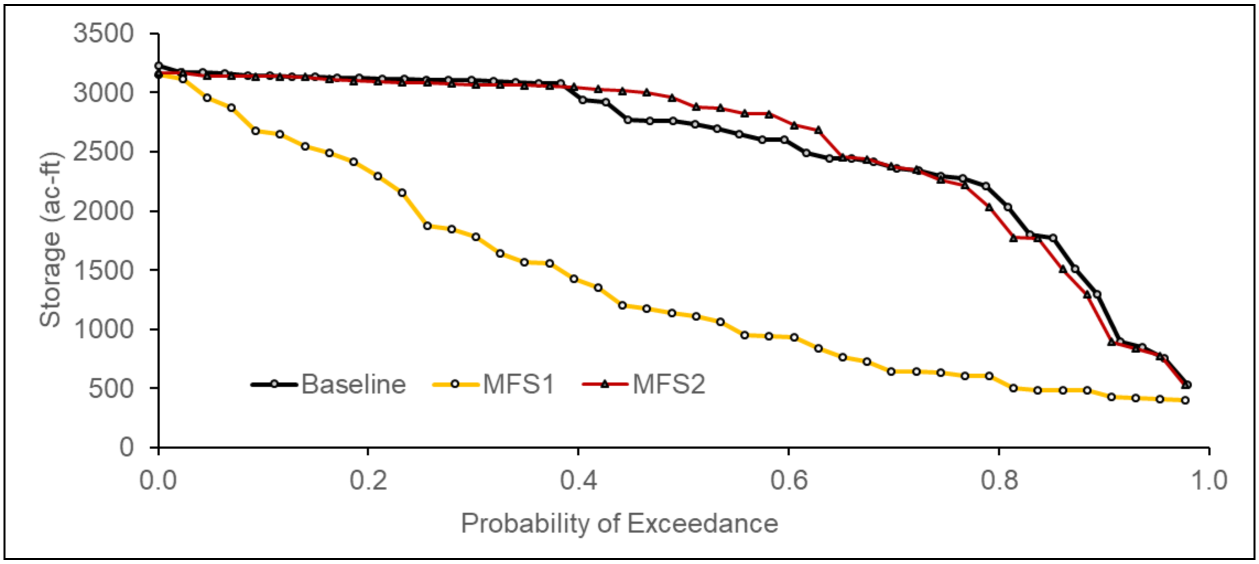

Figure 20. The comparison of empirical probability of exceedance curves of reservoir storage between the baseline scenario and modeled inflow FIRO scenarios.

Figure 21 shows the comparison of peak outflow rates during the spill events. For the whole simulation period (water years 1998 to 2019), the MFS1 scenario only has two spill days compared to 27 days from the baseline scenario, and both spill days have lower spillway outflow rates than the baseline scenario. The MFS1 scenario achieved a larger flood control benefit than the baseline scenario. The MFS2 scenario has the same 27 spill days as the baseline scenario. The total hours, that the reservoir stage is above spillway elevation and outflow rate from the spillway is larger than the maximum outlet flow rate, is 358 hours for the baseline scenario and 411 hours for the MFS2 scenario. Even though the MFS2 scenario avoids a few spill events (for example, February 20 and 21, 2017) compared to the baseline scenario, it also has some spill events that did not occur in the baseline scenario (for example February 14, 2000). The MFS2 has a comparable number of spills that occurred during the simulation period and a slightly longer hours of water levels above the spillway. Overall the MFS2 scenario did not show a larger flood control benefit than the baseline scenario due to the higher flooding risk brought by the relaxed storage constraint and the level of uncertainties caused by the watershed model inflow prediction. The scenario is using the observed rainfall as the ‘perfect weather forecast’ data to drive the model. If the real weather forecast data is used for inflow prediction, another level of uncertainty (the uncertainty of weather forecast accuracy) would be added into the results.

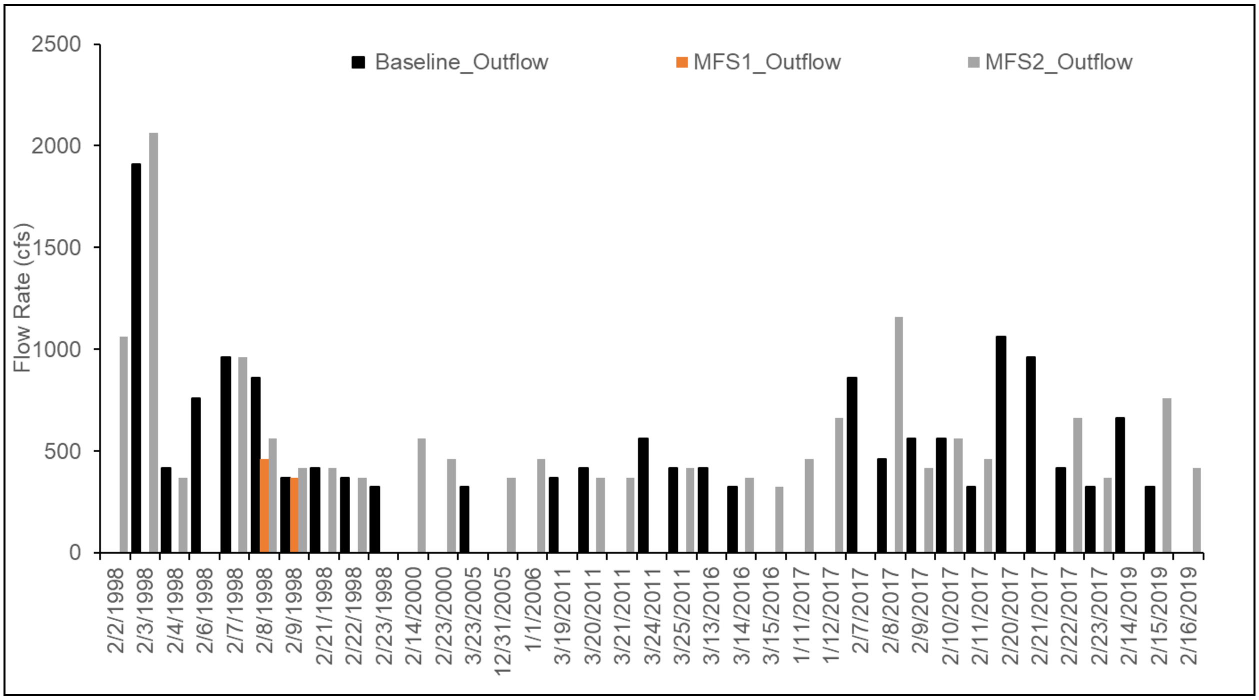

Figure 21. The peak spillway outflow rates comparison during spill events between the baseline scenarios and modeled inflow FIRO scenarios (only showing the spill events with spillway flow rates that are larger than the maximum outlet flow rate).

Figure 22 shows the reservoir storage at the end of winter for the three scenarios. The MFS1 scenario does not show a larger water supply benefit than the baseline scenario. For 14 out of 22 years the MFS1 scenario results in a lower end-of-winter storage than the baseline scenario. The average reservoir storage on April 30th for the baseline scenario and MFS1 scenario are 2,175 ac-ft and 2,054 ac-ft, respectively. The MFS2 shows a larger water supply benefit than the baseline scenario. The average April 30th reservoir storage for the MFS2 scenario is 2,322 ac-ft. The reservoir storage at the end of winter increased considerably by applying the MFS2 operations in 2002 (801 ac-ft) and 2013 (782 ac-ft). The MFS2 scenario results in an average of 147 ac-ft more water storage each year than the baseline scenario.

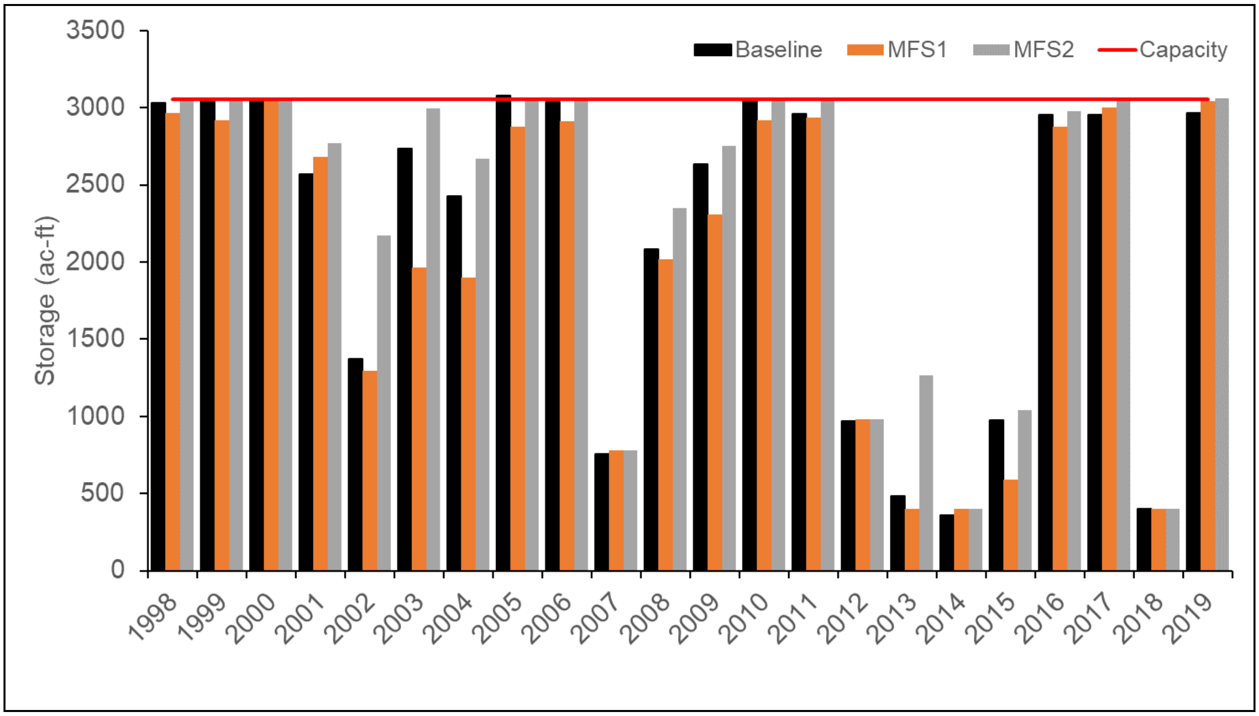

Figure 22. The comparison of reservoir storage at the end of winter (April 30th) between baseline and modeled inflow FIRO scenarios.

6.1.3. Results Summary

Table 7 summarizes the performances of the four FIRO scenarios. In an ideal prediction situation (FS1 and FS2), both FIRO scenarios show larger benefits than the current operation. The FS1 scenario resulted in a similar water supply benefit versus the baseline scenario (2,122 ac-ft vs 2,175 ac-ft), and totally avoided the spill events. The FS2 scenario gained larger benefits than the baseline scenario from both water supply (2,320 ac-ft vs 2,175 ac-ft) and flood control (8 spill days vs 27 spill days). The FIRO scenarios with modeled inflow show either larger flood control benefits or water supply benefits than the baseline scenario. MFS1 sacrificed some water supply benefit (2,054 ac-ft vs 2,175 ac-ft) to achieve a larger flood control benefit (2 spill days vs 27 spill days) than the baseline scenario. MFS2 resulted in a similar flood risk (27 spill days vs 27 spill days) but a larger water supply benefit (2,322 ac-ft vs 2,175 ac-ft).

The results for the perfect prediction FIRO scenarios imply that FIRO could achieve both flood control and water supply benefits. The current reservoir operation rules could be improved by applying FIRO and adjusting reservoir storage with a lead time given perfect information. The current flood control rule curve sacrifices the water supply benefit to avoid flooding, and the FS2 results show that flood risk can be reduced even with a relaxed storage constraint.

The two modeled inflow based FIRO scenarios did not achieve larger benefits on both flood control and water supply, compared to the baseline scenario. The errors in inflow prediction reduced the effectiveness of FIRO. However, there is still potential to improve reservoir operations. Both scenarios score as least as good as the baseline, indicating the potential benefits could be achieved even with errors brought by model prediction. The MFS1 scenario basically eliminates the spill events by applying the current flood control rule curve to modeled forecast data and 120 ac-ft lower water supply than the baseline. The MFS2 scenario applies a ‘fill and spill’ rule, which has the highest risk of flooding and achieved comparable performance on criteria one and criteria two to the baseline scenario, and an average of 147 ac-ft more storage than the baseline scenario. The results from the two model based scenarios implies the possibility of achieving benefits on both ends if the current operation rules can be relaxed but not as greedy as the ‘fill and spill’ scenario. Reservoir operations that result in lower flood risk than the ‘fill and spill’ rule while storing more water than the current flood control rule curve are worth exploring for the model hindcast FIRO scenarios.

Table 7. Summary of the performances of FIRO scenarios

Scenario	Reservoir storage before large inflows	Reservoir peak outflow during spill events	Reservoir storage at the end of winter	Total
Baseline	0*	0	0	0
FS1	1	1	-1	1
FS2	1	1	1	3
MFS1	1	1	-1	1
MFS2	0	-1	1	0

* meaning of scores: ‘0’: similar to baseline; ‘1’: better than baseline; ‘-1’: worse than baseline.

6.2. Discussion and Recommendations

6.2.1. Precipitation Data and Forecast

The difficulties of using FIRO center on prediction uncertainties. We explored the uncertainties from the watershed model for the inflow prediction by comparing the perfect hindcast scenarios and the modeled hindcast scenarios. Another big uncertainty of FIRO comes from the precipitation input. The rainfall monitoring data have variable accuracy and are unlikely to be representative of the entire Stevens Creek watershed. The rain gauge data used in this project has the longest and continuous record available but underestimates rainfall compared to other precipitation sources (QAPP, QPE) as discussed on Section 3.1. Better rainfall estimate data, if available, is recommended for future FIRO analysis. The accuracy of the precipitation data can impact the watershed model calibration and the inflow precision from the model.

The FIRO is based on the inflow prediction, and the uncertainty from precipitation forecast data is a key variable to consider when implementing FIRO in reality. This project did not test the impact of accuracy level of precipitation forecast on the FIRO effectiveness. It is strongly recommended to conduct FIRO analysis for SCR with the precipitation forecast data once the forecast data source is selected by Valley Water. Precipitation data affects both the accuracy of the inflow forecast and the forecast update frequency. Depending on the source, the update of precipitation forecasts can come once or twice a day. The forecast update frequency is lower than the 6 hour FIRO check we used in this project. The FIRO model can update more frequently to incorporate current condition information. Depending on the sources, forecasts can have different lead times and different accuracy levels with different lead times. The balance between the accuracy of precipitation forecast and lead time for reservoir operations is another key decision to be made for FIRO. Atmospheric River (AR) plays an important role in precipitation patterns in the Bay area. Climate scenarios suggest that ARs will become more frequent in the future (Weihs et al., 2020). Better prediction and monitoring of rainfall are crucial for using forecast data to guide reservoir operation.

6.2.2. Watershed Model

In this project, we used a watershed model with rainfall hindcast data to show it is possible to gain benefits with model predicted inflow to SCR. The FIRO scenarios with modeled inflow show the benefit of FIRO for flood control and water supply, and potentially both at the same time. The viability of FIRO can be improved by improving watershed model performance. As discussed in Section 4.3, the watershed model performance drifted from underestimation to overestimation over the 22 years with the same set of modeling parameters. The fixed parameter set cannot account for the changes that occurred over the simulation period, especially for long time simulation. In practice, the watershed model does not need to run for such a long time to get a solid reservoir inflow prediction and the model parameters are not necessarily fixed. Periodical model re-calibration is recommended to keep the inflow prediction uncertainty low. Data assimilation techniques can be used to improve watershed model performance with the continuously gathered monitoring data.

The forcing data selection and the calibration events for the watershed model can also result in very different model performances. A few recent storm events were used to illustrate the impact of extreme events and data sources on the model prediction. Figure 23 shows the rainfall events that occurred between November 1, 2022, to January 19, 2023, recorded by the rain gauge located at SCR (sensor ID: 6100). A total of 30.9 inches of rainfall were recorded by the rain gauge. A QPE rainfall product provided by Valley Water for the same period has a rainfall estimate of 40.7 inches. These rainfall events represent recording breaking extreme events. Using the historical record from the rain gauge as a comparison, the maximum 14-day, 20-day, and 30-day rainfall totals from 1979 to 2022 were 15.55 inches, 18.63 inches, and 20.23 inches, respectively. The maximum 14-day, 20-day, and 30-day rainfall totals for the rainfall events occurred during the November 2022 to January 2023 were 15.76 inches, 20.92 inches, and 21.92 inches, the wettest period since 1979.

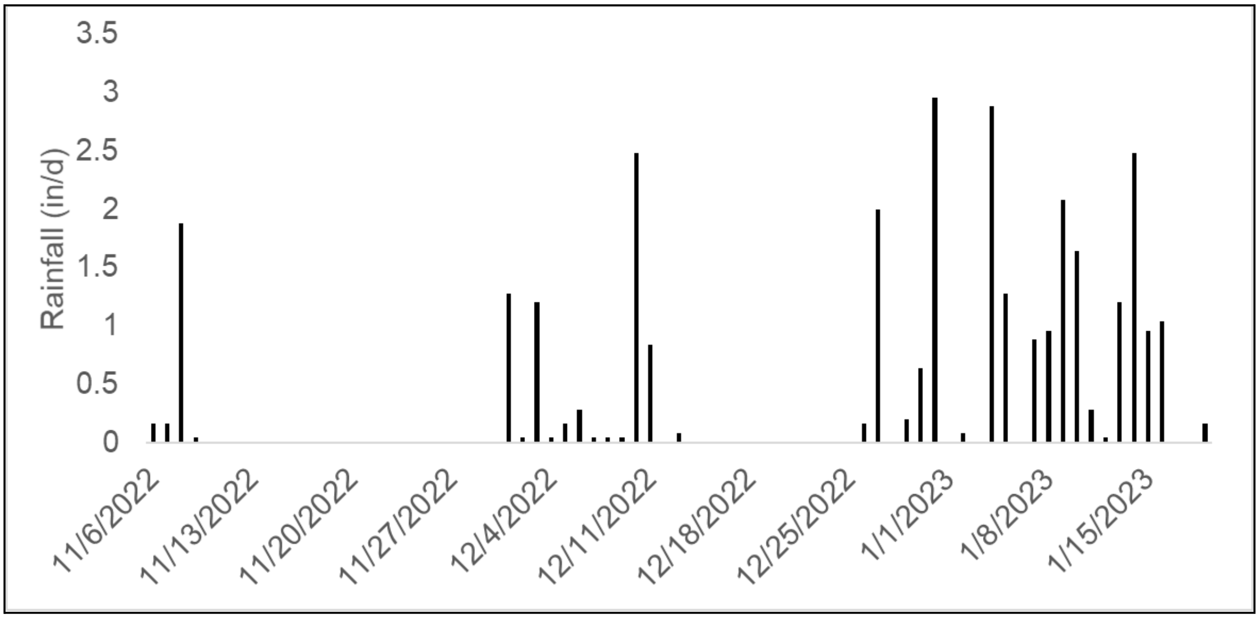

Figure 23. The daily rainfall record from the rain gauge at SCR

Figure 24 shows the model simulated inflow time series with different rainfall forcing data. The watershed model was calibrated with the rain gauge rainfall as the forcing data, thus the rain gauge rainfall data resulted in a better inflow prediction than the model driven with QPE rainfall. However, the QPE rainfall data was considered to have a better rainfall representation at the Stevens Creek watershed than the rain gauge data. The watershed model would need a re-calibration if the forcing data is switched to the QPE data in the future. Another thing to note is the modeled inflow volumes are higher than back-calculated inflow volume, either driven by rain gauge data or QPE data. The model driven by rain gauge data overestimated the inflow volume by 20% and the model driven by QPE data overestimated the inflow volume by 59%. Both relative errors are higher than the average model performance. This is because the extreme events are outside of the hydrological conditions used to calibrate the watershed model. In reality, it is unlikely the watershed model could be calibrated for every extreme condition limited by the available data. One possible solution to address the model uncertainties is to use ensemble predictions from multiple model settings rather than a deterministic model prediction.

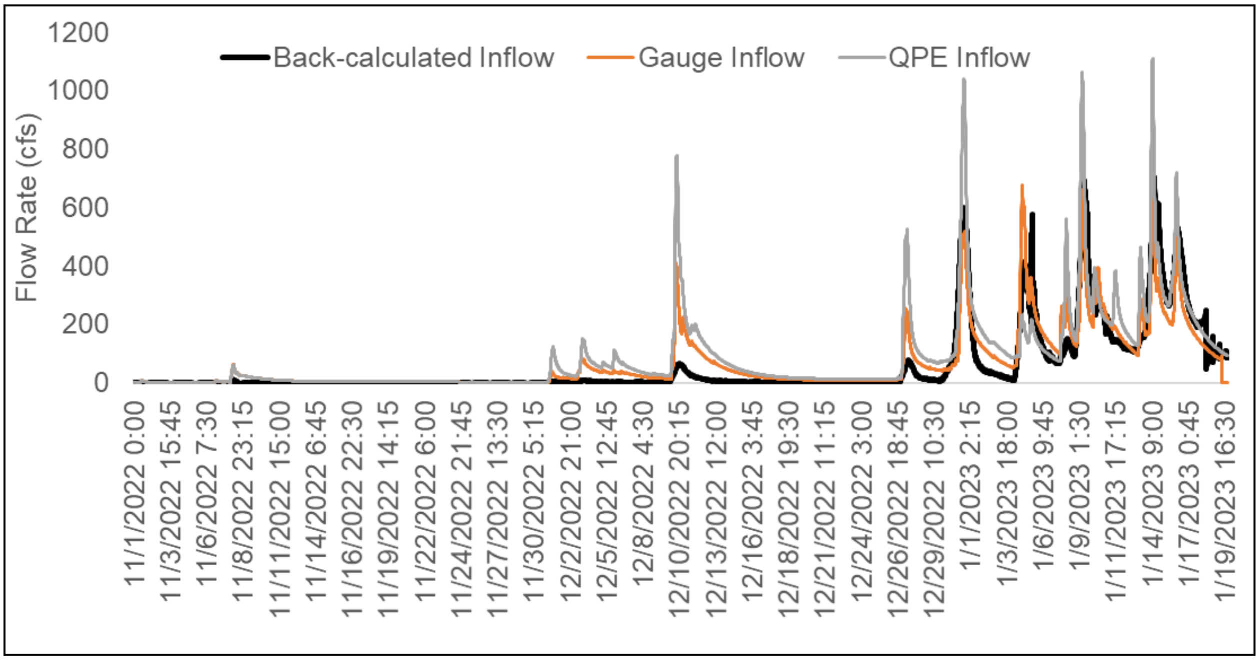

Figure 24. The comparison of back-calculated inflow and model simulated inflows

6.2.3. Other Operations Details

Additional operation details should be considered for FIRO in practice. For example, the outlet takes 10-15 minutes to open fully from a closed position with electric power. For the purposes of modeling, ramp up time is ignored. The maximum outlet flow rate is based on an estimation from the Bernoulli equation. Direct monitoring at the outlet would provide a more accurate estimate. This FIRO study assumes all reservoir operations can be done remotely and do not take a lot of time, and that all the reservoir relevant data can be accessed remotely in a timely manner. The assumption is also made that Valley Water employees can check the FIRO results every 6 hours. All those operational details need to be put into consideration while applying the FIRO in reality.

6.2.4. Incorporating Ecosystem Needs

This study focused on the flood control and water supply benefits of FIRO. The reservoir operations can also play an important role in ecosystem management for downstream channels and watersheds. Stevens Creek is a FACHE creek, which has flow requirements to support steelhead and the health of the ecosystem more broadly. As proposed in Phase Two of this project, for ecosystem management, consideration of flow recommendations will focus on the potential role of "functional flows" (Yarnell et al., 2015, Yarnell et al., 2020) that retain specific process-based components of the hydrograph as opposed to more static minimum flows or attempting to mimic the full natural flow regime. This approach to flow management can support key hydrogeomorphic and ecological processes and functions downstream of the reservoir while also supporting flood management and water supply objectives. Furthermore, this work will explore how flow recommendations, coupled with channel-floodplain modifications, can be evaluated for a range of metrics indicating physical and ecological benefits.

Phase One of the FIRO analysis for SCR showed the possibility to improve reservoir operations to achieve a larger flood control and water supply benefit. A further test with a rainfall forecast product is recommended as the next step. Further exploration of the accuracy of different precipitation products and recalibration of the watershed model with selected sources of precipitation data for FIRO analysis are recommended to improve watershed model estimation. Once the downstream watershed model is completed by Valley Water, the integrated upstream-reservoir-downstream modeling system can be used to develop an initial framework for multi-benefit reservoir flow management (e.g., flood control, water supply, ecosystem support), as well as explore the opportunities to couple this with downstream channel-floodplain modifications, that addresses the needs of people while supporting healthy ecosystems through physical and ecological processes and functions.

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Appendix A Tech Memo One: Stevens Creek Reservoir Modeling System: Calibration and Validation (Delivered on 3/31/2022)

Appendix B Tech Memo Two: Reservoir Storage Data Filtering Tool User Guide (Delivered on 12/28/2022)

Appendix C Other Deliverables (in zip file)

- Stevens Creek Watershed Model for the subwatersheds upstream of SCR
- Stevens Creek Reservoir Water Budget Model
- FIRO analysis scripts