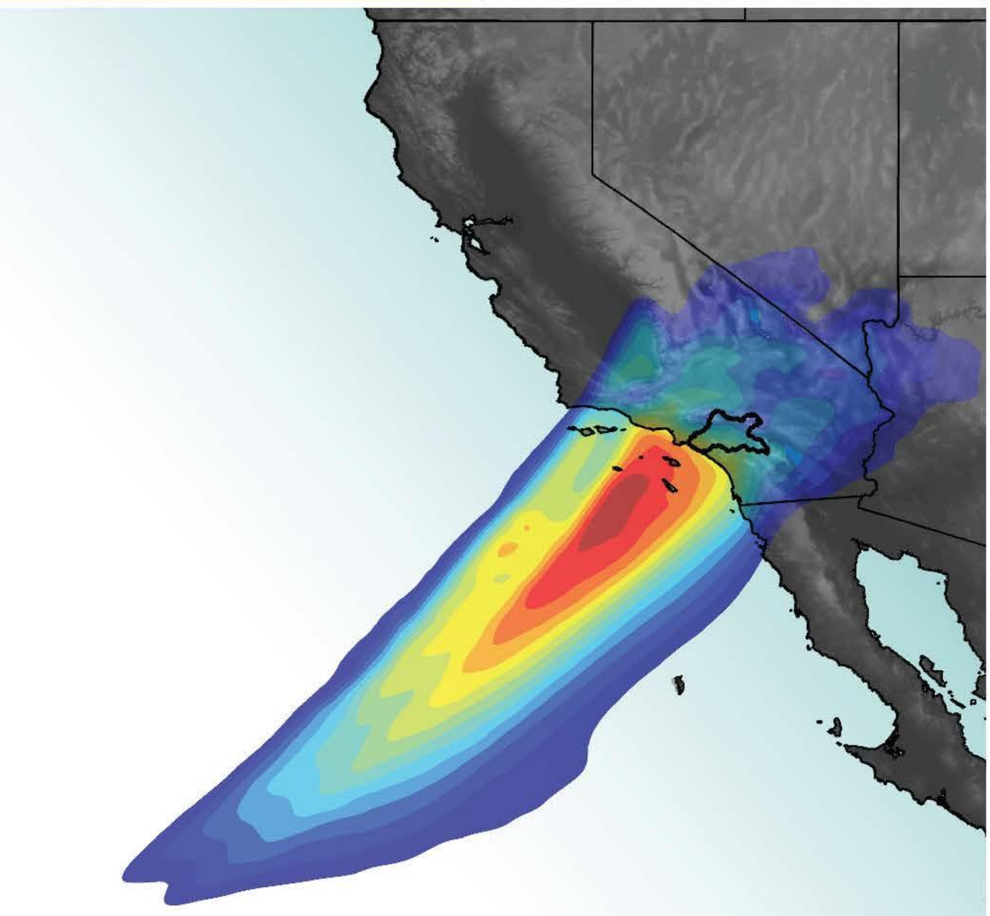
Prado Dam
FORECAST INFORMED RESERVOIR OPERATIONS

Final Viability Assessment

November 2023



Prado Dam FIRO Steering Committee

- **F. Martin Ralph:** CW3E (Co-chair)
- **Adam Hutchinson:** Orange County Water District (Co-chair)
- **Greg Woodside (2017-2023):** Orange County Water District (Co-chair)
- **Michael Anderson:** California Department of Water Resources
- **Cary Talbot:** USACE Engineer Research and Development Center
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- **Alan Haynes:** California Nevada River Forecast Center
- **Tim Fairbank:** USACE Los Angeles District
- **Jon Sweeten:** USACE Los Angeles District
- **James Tyler:** Orange County Public Works
- **Rollie White:** U.S. Fish and Wildlife Service, Palm Springs
- **Jay Jasperse:** Chief Engineer, Sonoma Water

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- **Adam Hutchinson** (2023–present): Recharge Planning Manager, OCWD
- **F. Martin Ralph**: Director, Center for Western Weather and Water Extremes (CW3E), Scripps Institution of Oceanography, UC San Diego

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- **Joseph Forbis**, USACE Water Management Integration Lead, ERDC
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- Cuong Ly for his steady words of wisdom, which helped guide us along the way.

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Abbreviations

For brevity, this document uses the following acronyms and other abbreviations:

Abbreviation	Definition
ac-ft	acre-feet
AEP	annual exceedance probability
AR	atmospheric river
AR Recon	Atmospheric River Reconnaissance
AWB	Anaheim, Warner, and Burris
cfs	cubic feet per second
CHPS	Community Hydrologic Prediction System
CNRFC	California Nevada River Forecast Center
CSI	critical success index
CW3E	Center for Western Weather and Water Extremes
CWMS	Corps Water Management System
DWR	California Department of Water Resources
ECMWF	European Centre for Medium-Range Weather Forecasts
EFO	Ensemble Forecast Operations
ERDC	Engineer Research and Development Center
FEWS	Flood Early Warning System
FIRO	Forecast Informed Reservoir Operations
FVA	Final Viability Assessment
GEFS	Global Ensemble Forecast System
GFS	NCEP Global Forecast System
GPS	Global Positioning System
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HAS	Hydrometeorological Analysis and Support
HEC	Hydrologic Engineering Center
HEC-HMS	HEC Hydrologic Modeling System
HEC-RAS	HEC River Analysis System

Abbreviation	Definition
HEC-ResSim	HEC Reservoir System Simulation
HEFS	Hydrologic Ensemble Forecast System
HEMP	hydrologic engineering management plan
HRRR	High-Resolution Rapid Refresh
IFS	Integrated Forecast System
IOP	Intense Observations Period
IVT	integrated water vapor transport
IWCM	Interim Water Control Manual
IWCP	Interim Water Control Plan
LAD	Los Angeles District
MAP	mean areal precipitation
MEFP	Meteorological Ensemble Forecast Processor
MWD	Metropolitan Water District
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEXRAD	Next-Generation Weather Radar
NGVD 1929	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
OCPW	Orange County Public Works
OCWD	Orange County Water District
PFO	EFO model with perfect forecasts
PVA	Preliminary Viability Assessment
QPE	quantitative precipitation estimation
QPF	qualitative precipitation forecast
RAOP	research and operations partnership

Abbreviation	Definition
RFM	Recharge Facilities Model
RMSE	root mean square error
ROC	Reservoir Operation Center
SARM	Santa Ana River Mainstem
SCE	Shuffle Complex Evolution
SFO	Simpler Ensemble-Forecast Operations
SPFO	SFO model with perfect forecasts
SIO	Scripps Institution of Oceanography
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WCM	Water Control Manual
WCP	Water Control Plan
West-WRF	Western Weather Research and Forecasting
WRE	Water Resources Engineering
WRF	Weather Research and Forecasting
WY	water year

Section 1. Executive Summary

1.1 Background

Orange County Water District (OCWD) has been capturing and recharging stormwater from the Santa Ana River since 1936. Prado Dam, located about 10 miles upstream of OCWD's groundwater recharge sites, was constructed by the U.S. Army Corps of Engineers (USACE) in 1941 for the primary purpose of flood risk management. USACE, which also operates the dam, has been collaborating with OCWD to temporarily impound water and release it from the dam to facilitate recharge of the Orange County groundwater basin, which provides water for over 2.5 million people. To ensure reliability of Orange County's water supply in light of climate change and the increasing cost and unpredictability of imported water, OCWD initiated a partnership with USACE and the Center for Western Weather and Water Extremes (CW3E) at UC San Diego's Scripps Institution of Oceanography to test Forecast Informed Reservoir Operations (FIRO) as a method to improve water supply reliability, while not impairing and possibly enhancing habitat and flood risk management.

This Final Viability Assessment (FVA) presents results and recommendations for future FIRO operations. It builds on the 2021 Preliminary Viability Assessment (PVA), which demonstrated that FIRO is viable at Prado Dam. The ultimate goal of this project is to inform the update of USACE's Water Control Manual (WCM) for Prado Dam to allow flexible FIRO operations, as demonstrated by rigorous analyses and documented in this FVA.

The current buffer pool, which stores a maximum of 20,000 acre-feet at an elevation of 505 feet, temporarily stores water and can be used for recharge (Figure 1-1). In April 2021, the Prado Dam interim WCM was modified to increase the buffer pool elevation from 498 feet to 505 feet throughout the year. This FIRO viability assessment tests whether higher buffer pool elevations could be safely managed to provide further water supply reliability benefits for Orange County. Infrastructure improvements that are underway—including increasing the downstream channel capacity from 10,000 cubic feet per second (cfs) to 30,000 cfs (WCM update #1) and raising the elevation of the spillway from 543 feet to 563 feet (WCM update #2)—provide a unique opportunity to integrate FIRO into future dam operations to maximize co-benefits.

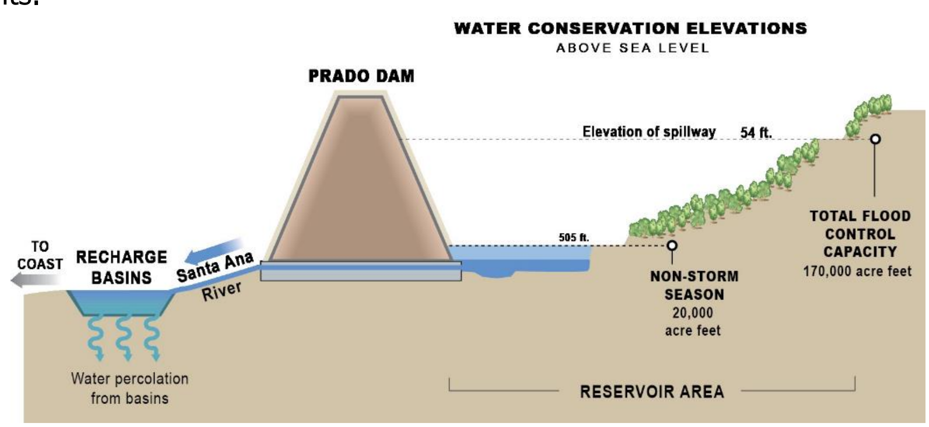

Figure 1-1. *Schematic of Prado Dam water conservation elevation for stormwater storage and capture (credit: OCWD).*

1.2 Atmospheric Rivers and FIRO

Atmospheric Rivers (ARs) are responsible for more than half of all beneficial precipitation and over 90 percent of flood damages in California. Long, narrow bands of concentrated moisture, ARs stretch thousands of miles across the Pacific Ocean When ARs make landfall, they can release a staggering amount of rain and snow, as was demonstrated during a particularly active AR season from October 2022 to April 2023, when 16 ARs produced a maximum of nearly 74 inches and an average of 29 inches of precipitation in the Santa Ana River watershed. (Figure 1-2 shows a landfalling AR that impacted the watershed in mid-March.)

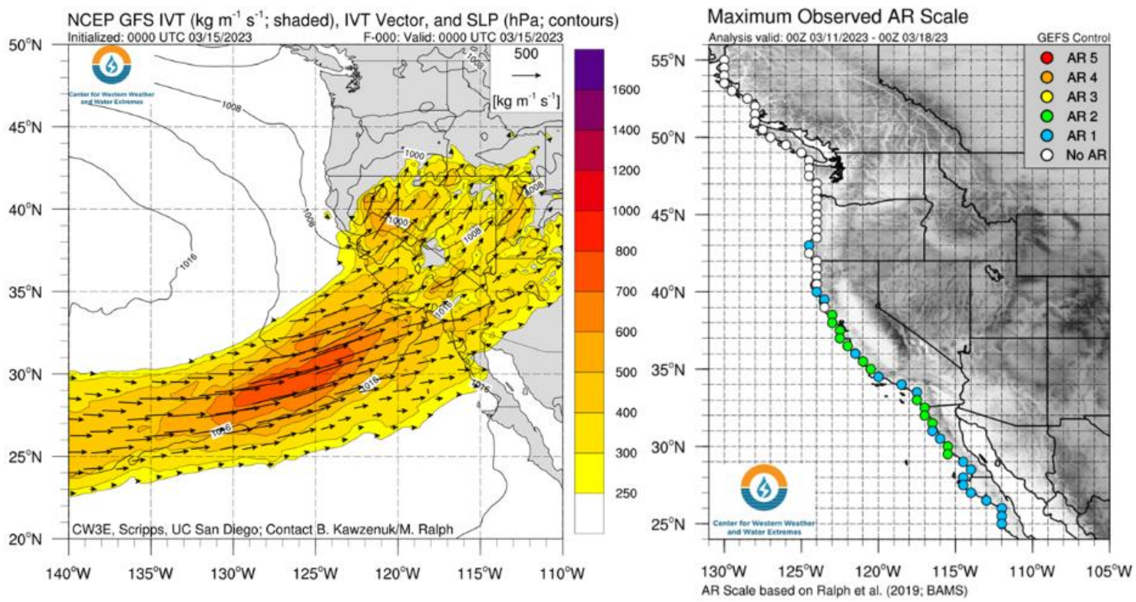

Figure 1-2. *A landfalling AR on 15 March 2023, one of several that contributed to >140% of normal precipitation for the Los Angeles basin as of this date. Right: Estimated impact of the AR as measured on the AR scale, on 11 March 2023. The AR scale is determined based on the duration of AR conditions (with integrated water-vapor transport (IVT) >250 kg m-1 s-1) and maximum IVT during the AR).*

A Steering Committee was formed to guide the FIRO effort at Prado Dam. Members include USACE, U.S. Fish and Wildlife Service, the California Nevada River Forecast Center, The California Department of Water Resources, and Orange County Public Works. OCWD and CW3E provided leadership, oversight, and additional resources as Steering Committee Co-Chairs. Using the collaborative Steering Committee process, FIRO has proven viable on Lake Mendocino in Northern California and is currently being assessed at Lake Sonoma (Russian River Watershed), New Bullards Bar Reservoir and Lake Oroville in the Yuba and Feather River watersheds, Seven Oaks

What is FIRO?

FIRO is a flexible water management strategy that uses data from watershed monitoring and modern weather and hydrologic forecasting to help water managers selectively retain or release water from reservoirs in a manner that reflects current and forecasted conditions. FIRO uses emerging science and technology to optimize limited resources and adapt to changing climate conditions. Scientific research on the intensity, duration, and location of ARs is central to FIRO.

Dam in the upper Santa Ana River Watershed, and at Howard Hanson Dam on the Green River in Washington.

1.3 Results and Recommendations

To evaluate FIRO, the Steering Committee established operational constraints and boundary conditions, and tested variables such as spillway elevations (with and without a planned spillway raise) and maximum release schedules for buffer pool elevations up to 520 feet. Five water management alternatives with five buffer pool elevations combined for a total of 26 scenarios (including baseline), which were modeled using a 1990–2019 hindcast and extreme events scaled to 100-, 200-, and 500-year three-day Prado Dam inflow volumes. Results were compared against 12 decisional metrics. Key findings and recommendations are summarized below.

1.4 Key Findings

- FIRO strategies can successfully enhance recharge for OCWD.
- On average, FIRO strategies from elevation 508 feet to 512 feet are estimated to yield 4,000 to 6,000 acre-feet per year of additional groundwater recharge over existing operations. Increasing the maximum buffer pool elevation to 520 feet yields an average of 12,000 acre-feet of recharge annually.
- Over the range of the hindcast period (1990–2019) and for scaled events (100-, 200-, and 500-year three-day volume), FIRO strategies (Ensemble-Forecast Operations and Simpler Ensemble Forecast Operations) have a slight positive impact on flood risk management outcomes associated with reservoir spill and releases in excess of channel capacity for all buffer pools tested up to 520 feet.
- The type of buffer pool can impact the frequency of inundation at elevations of 514 feet and 520 feet, but all FIRO strategies at all buffer pools perform better than the baseline WCM when considering the frequency of exceeding 520 feet. The change in the inundation frequency of Corona Municipal Airport (514 feet) for Ensemble Forecast Operations and Simpler Ensemble Forecast Operations with buffer pools up to 512 feet is insignificant when compared to baseline WCM operations.
- Data suggests that wetter conditions improve vireo habitat. Except for the understory, data does not indicate irreparable forest damage from prolonged inundation. Additional monitoring and operational triggers are needed to further study impacts and adjust water levels as needed for habitat and nesting season protection during FIRO operations.

*For a detailed list of findings and recommendations, refer to Section 7 and Section 8.

1.5 Recommendations

Based on the work conducted for the FVA, the Prado Steering Committee recommends that a buffer pool of 510 ft to 512 ft be explored during the interim operations period before WCM update #2.

Steering Committee involvement should continue throughout the interim operations period, through to finalization of the updated WCM #2.

A decision support system (DSS) is critical for FIRO implementation and must be adaptive to future improvements in forecast skill and infrastructure. Elements of the DSS should be developed and tested to support the planned minor deviation to the Water Control Manual. Once the preferred alternative is selected, the DSS should be modified accordingly and integrated into the existing USACE Los Angeles District's DSS framework.

AR tools, observations, and precipitation forecast products should be tailored and dedicated to the Santa Ana River watershed to support real-time operations at Prado Dam and, in the future, coordinated FIRO operations with Seven Oaks Dam for watershed-based FIRO operations.

Work to evaluate potential improvements and advances in meteorological and hydrologic forecasting models should continue for additional FIRO benefit.

USACE will consider The FVA recommendations as it updates the Prado Dam Water Control Plan, a key component of the WCM, which governs operation of Prado Dam. Figure 1-3 below shows the timeline from the PVA to interim operations and completion of the two planned WCM updates (see Figure 1-3 for the overall FIRO process).

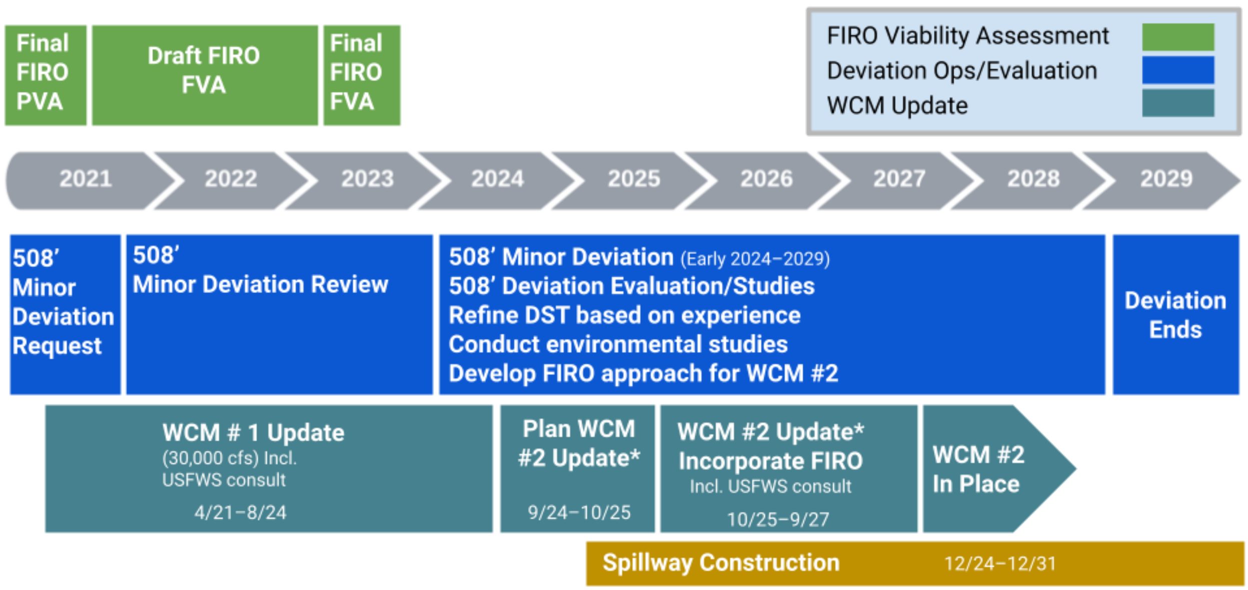

Figure 1-3. *Prado Dam FIRO Viability Assessment and WCM update timeline.*

Note that two WCM updates are planned for Prado Dam. WCM update #1 addresses the increased maximum discharge capacity of the Prado Dam outlet and the downstream channel (30,000 cfs). WCM update #2 will include a formal consideration of FIRO. During the Interim Operations period (prior to WCM update #2), work will continue to further develop the FIRO approach and evaluate a planned Minor Deviation at an elevation of 508 feet.

Section 2. Introduction

2.1 Prado Dam FIRO Project Overview

2.1.1 Atmospheric Rivers and FIRO

Atmospheric rivers (ARs) are responsible for half of all beneficial precipitation and over 90 percent of flood damages in California. In addition, 90 percent ($26.3 million out of $29.3 million total) of insured losses in Orange County, California, from 1978 to 2018 were associated with ARs (Corringham et al. 2019). ARs are Long, narrow bands of concentrated moisture that stretch thousands of miles across the Pacific Ocean, carrying over 20 times more water than the Mississippi River. When ARs make landfall, they can release a staggering amount of rain and snow. For this reason, studies of AR behavior and improved AR forecasts are essential to inform and implement Forecast Informed Reservoir Operations (FIRO); in many ways, AR forecasting represents the "F" in FIRO.

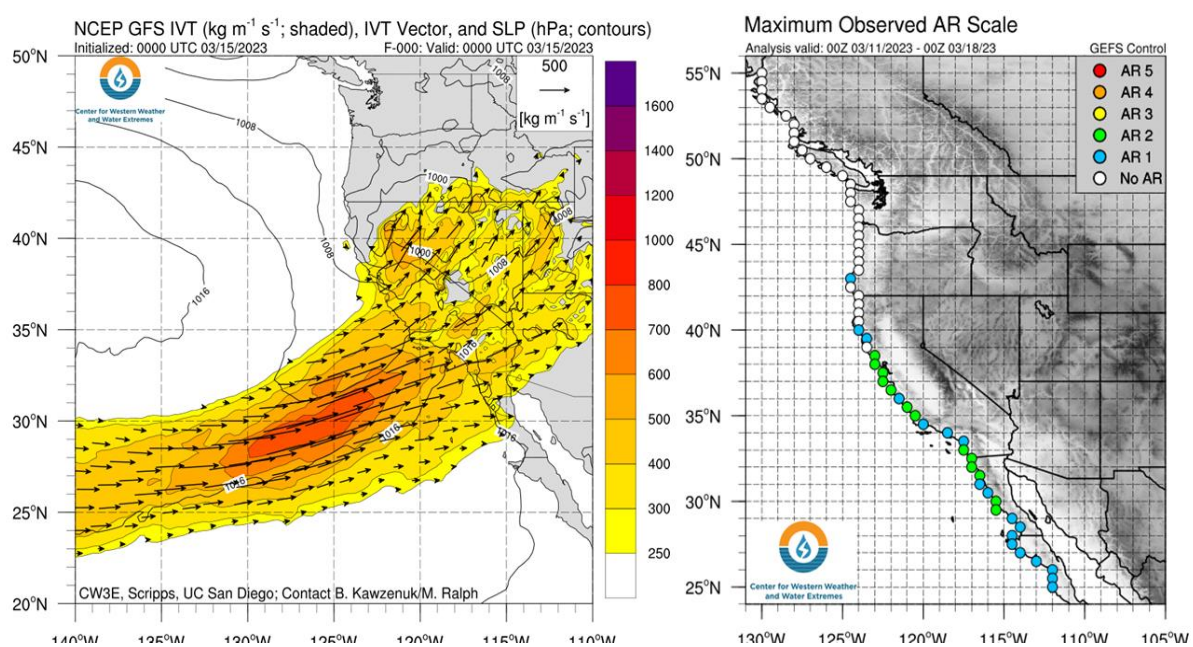

Figure 2-1. *Left: A landfalling AR on March 15, 2023, one of several that contributed to >140 percent of normal precipitation for the Los Angeles basin. Right: Estimated impact of the AR as measured on the AR scale on March 11, 2023.*[1]

FIRO is an innovative research and operations partnership that uses modern weather forecasting, runoff modeling, and watershed monitoring to help water managers selectively retain or release water from reservoirs based on current and forecasted conditions. FIRO's application of modern science and technology can optimize the use of limited water resources and represents a cost-effective option to adapt to extreme weather events unique to the U.S. West Coast.

[1] The AR scale is determined based on the duration of AR conditions (with integrated water-vapor transport (IVT) >250 kg m^{-1} s^{-1}) and maximum IVT during the AR).

2.1.2 Overview of the FIRO Collaborative Process

The Prado Dam Steering Committee was formed in late 2017 and first met in March 2018. Committee members bring together innovative leaders that collaborate and contribute expertise and resources to accomplish common goals. While the Steering Committee guides overall project directions, work teams support each section of the viability assessment, and report their progress quarterly to the Steering Committee. The work teams bring high-level technical or policy issues to the Steering Committee for their deliberation and decision.

Steering Committee Co-chairs

- **Greg Woodside** (2017–2023): Executive Director of Planning and Natural Resources, Orange County Water District (OCWD)
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Steering Committee vision, mission, goal, and strategies

- **Vision.** Develop robust forecast data and tools that support increased flexibility in reservoir operations, improving water conservation, flood control, and habitat management outcomes.
- **Mission.** Guide a highly collaborative engagement process to ensure deliverables reflect interdisciplinary perspectives and interagency input.
- **Goal.** Develop clear pathways to assess the viability of FIRO at Prado Dam.

- **Strategies.** Draft a Preliminary Viability Assessment (PVA) outlining tasks, roles, schedule, and requirements for assessing FIRO viability; conduct preliminary technical studies; and develop a PVA based on current forecast skill, as well as a Final Viability Assessment (FVA) based on potential improvements in forecast skill.

Figure 2-2. *left: Rob Hartman, Jon Sweeten, Mike Anderson, Jay Jasperse, John Spencer, Forest Cannon, Marty Ralph, Greg Woodside, Cary Talbot, Cuong Ly, Rene Vermeeren, Van Crisostomo, James Tyler, and Arleen O'Donnell.*

Process for Achieving Mission

- Hold an annual workshop with other FIRO project partners to learn from each other.
- Pursue communication and outreach opportunities.
  - Develop a strategy for launching the viability assessment, including staffing, funding, and implementation commitments.

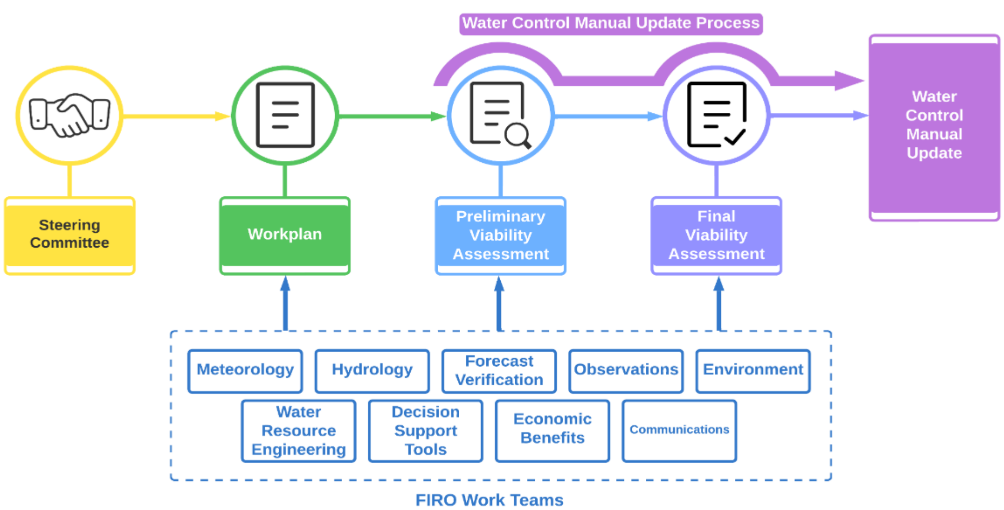

Figure 2-3. *Overview of the FIRO process showing the four steps (top row) and the work teams that support the work plan, PVA, and FVA.*

2.1.3 Prado Dam Authorization, Current Operations, and Improvements

Authorization for the Prado Dam and Reservoir project is contained in the Flood Control Act of June 22, 1936 (PL 74-738).

On March 12, 1937, the Chief of Engineers approved a report titled *Definite Project for the Construction of Reservoirs and Related Flood Control Works in Orange County, California*, which included Prado Dam. The report gives the following description of the project:

"The Prado Retarding Basin is located on the Santa Ana River in Riverside County, California, about two miles north of the Orange County line. Its primary purpose is flood protection for those residents of Orange County whose lands have previously been subject to the destructive action of uncontrolled floodwaters. There is also a water conservation feature to be utilized in connection with the automatic release of floodwaters. Due to the high absorptive qualities of the material underlying the riverbed below the dam, and the large natural underground storage characteristics of the valley, it will be possible through automatic regulation to conserve a large portion of the flood flows heretofore wasted to the ocean.

The storage capacity of the retarding basin below spillway crest elevation is 180,000 acre-feet. The Orange County Flood Control District has estimated that the practical capacity of the Santa Ana River below the Prado Retarding Basin is approximately 6,000 cfs. In order to limit the outflow to this quantity, it is necessary to provide the storage capacity of 180,000 acre-feet with the retarding basin operated for flood control and conservation as described below. The Orange County Flood Control District has assumed that the channel downstream from the proposed Prado Dam site will be absorbed by percolation flows from 1,000 to 2,000 cfs. It is further assumed that the retarding basin could safely be operated for conservation to elevation 507.5 (capacity of 54,000 acre-feet). The remaining net storage capacity of 126,000 acre-feet is to be reserved for flood control."

With the authorization found in the Flood Control Act of 1936 and in accordance with the report approved by the Office of the Chief of Engineers on March 12, 1937, the original Prado Dam and Reservoir project was constructed in accordance with the May 1938 report titled *Analysis of Design—Prado Dam*, and construction was completed in April 1941 at a cost of approximately $9,450,000.

Further modifications to the original project authorization are contained in the Water Resources Development Act of 1986 (PL 99-662) to provide additional capacity for the storage of floodwaters and sediment by enlarging the existing Prado Dam and Prado Reservoir to take advantage of increased downstream channel capacity by increasing the release capacity of the outlet works. Congress authorized the modification, which was based on a plan recommended by USACE LAD, as described in *Design Memorandum No. 1: Phase II GDM on the Santa Ana River Mainstem Including Santiago Creek, Volume 2: Prado Dam*, dated August 1988. The environmental justification for this modification is provided in a report titled *Supplemental EIS and Project Environmental Impact Report for Prado Basin, Including Stabilization of the Bluff Toe at Norco Bluffs*, dated December 2001. The details of the modifications, also called the Santa Ana River Mainstem (SARM) Project, are summarized below.

2.1.4 SARM Project and Opportunities for Increased Stormwater Capture

The SARM Project includes the following elements:

- Constructing a 550-foot earth and rockfill dam (Seven Oaks Dam).
- Raising the embankment of Prado Dam by 28 feet.
- Widening and deepening the 23-mile river channel between Prado Dam and the Pacific Ocean outlet in Orange County to accommodate releases of 30,000 cubic feet per second (cfs) from the dam.
- Increasing the flood risk management capacity of Santiago Creek.
- Widening and deepening three major flood channels (Oak Street Drain in Riverside County and San Timoteo Creek and Mill Creek Levees in San Bernardino County).

The spillway modification will occur when Orange County Public Works has acquired all lands within the new taking line (566 feet) in fee or easement. As of March 2023, 103 of 113 parcels have been acquired. The 563-foot spillway elevation and 566-foot taking line are based on the engineering analysis developed for the SARM project and are not subject to reconsideration because of the analysis performed as a part of this FVA.

The spillway modification work is currently in the design phase. While the spillway structure remains at 543 feet in elevation, a major flood runoff event that exceeds the current reservoir capacity could cause damage in an area downstream inhabited by about 2 million people. An event of this nature would inundate over 110,000 acres of highly urbanized land and directly involve hundreds of thousands of homes, businesses, and factories, as well as hundreds of schools. The direct damages from a flood of this magnitude are estimated at about $15 billion.

Since the Prado dam was originally constructed in 1941, OCWD and USACE have collaborated to utilize the Dam to increase capture and recharge of stormwater to the OCWD groundwater recharge basin. Over the years, the volume of stormwater that could be temporarily impounded behind Prado Dam has increased to the current elevation (at any time of year) of 505 feet, which equates to approximately 20,000 acre-feet of storage. Captured stormwater is released slowly at a rate that can be handled by OCWD recharge facilities located downstream of Prado Dam. This FIRO assessment considered higher surface water elevations that could provide opportunities to yield greater volumes of water for groundwater recharge (Table 2-1).

Table 2-1. *Water storage volume at select elevations based on the 2021 topographic survey.*

Reservoir Elevation (ft)	Storage (ac-ft)	Storage Above 505 ft (ac-ft)	Potential Additional Ave. Annual Recharge (ac-ft)
505	19,987	0	0
508	25,919	5,932	2,500
510	30,376	10,389	4,200
512	35,211	15,224	5,800

Reservoir Elevation (ft)	Storage (ac-ft)	Storage Above 505 ft (ac-ft)	Potential Additional Ave. Annual Recharge (ac-ft)
514	40,493	20,506	7,500
520	59,391	39,404	13,000

Note: Feet in elevation are measured based on the National Geodetic Vertical Datum of 1929.

OCWD uses two inflatable dams on the Santa Ana River, the Santa Ana River channel, and various off-channel recharge facilities to divert, capture, and recharge stormwater downstream of Prado Dam. At the beginning of the storm season, when most of the recharge system storage is available and the recharge basins are clean, OCWD can divert up to 800 cfs from the Santa Ana River. When recharge facilities are filled, the diversion rate declines to about 500 cfs. The rate of diversion from the river declines to approximately 350–400 cfs as the recharge basins become clogged with sediment.

OCWD is always looking for ways to increase its ability to capture and recharge stormwater, and over the past 25 years, it has been convening an internal, multidisciplinary group called the Recharge Enhancement Working Group. The goal of this group is to develop concepts and projects designed to improve OCWD's groundwater recharge system. Notable projects include:

- **Recharge Facilities Model.** This model, based on GoldSim software, simulates the operation of OCWD's groundwater recharge system. It can be used to conduct scenario planning to assess how various modifications could affect the capture and recharge of stormwater or other water supplies. This model was leveraged in evaluating FIRO alternatives as described in Section 4 and Section 5.
- **Riverbed Filtration System.** One of the key constraints to stormwater recharge is clogging due to sediment accumulation in recharge facilities. Stormwater typically contains high suspended sediment loads that can quickly clog recharge basins. Over the past few years, OCWD has been testing a system that collects recharge water through a subsurface collection gallery placed about 3 feet below the surface. The collected water is then conveyed in a pipeline to a small recharge basin. Testing conducted thus far shows that the filtration system removes more than 90 percent of the suspended solids, which has increased the recharge capacity of the receiving basin by a factor of two.

2.2 Prado Dam and Santa Ana Watershed Geophysical Characteristics

The Santa Ana River, more than 90 miles long, is the longest river entirely within Southern California. The effective contributing drainage of the entire river is approximately 2,450 square miles, 92 percent of which is controlled by Prado Dam. Figure 2-4, below, shows the extent of the watershed. Santa Ana River tributaries originate in the San Bernardino Mountains and flow southwest through San Bernardino, Riverside, and Orange Counties before emptying into the Pacific Ocean. The watershed is ringed by the San Gabriel, San Bernardino, and San Jacinto Mountains, each with at least one peak greater than 10,000 feet high. These mountains and their foothills represent about one-third of the total drainage area.

Principal tributaries to the Santa Ana River above Prado Dam include San Antonio Creek, Chino Creek, Cucamonga Creek, Lytle Creek, Mill Creek, San Timoteo Creek, and the San Jacinto River, which flows into Temescal Creek. The Lytle, Mill, and San Timoteo Creeks converge with the Santa Ana River just above the city of Riverside. The others discharge directly into Prado Reservoir. Santiago Creek is the largest tributary to the lower Santa Ana River downstream of Prado Dam.

The Santa Ana River has an average gradient of 240 feet/mile in the mountains and about 20 feet/mile closer to Prado Reservoir. The average gradient of the principal tributaries is 700 feet/mile in the mountains and 30 feet/mile in the valleys.

Prado Dam is the principal flood risk management dam in the watershed. Two other flood risk management dams capture runoff from relatively small areas of the mountainous upper watershed: San Antonio Dam on San Antonio Creek (drainage area 27 square miles) and Seven Oaks Dam, located on the Santa Ana River (drainage area 177 square miles).

The Seven Oaks Dam project, about 30 miles northeast of the Prado Basin, is jointly owned by local sponsors (Orange, Riverside, and San Bernardino Counties). Releases from Seven Oaks Dam, in addition to local runoff downstream of Seven Oaks Dam, are captured and temporarily stored behind Prado Dam. As discharge from Seven Oaks Dam could affect decisions at Prado Dam, flood risk management operations are also closely coordinated. A FIRO Viability Assessment is underway for Seven Oaks Dam, which will advance watershed-wide FIRO management.

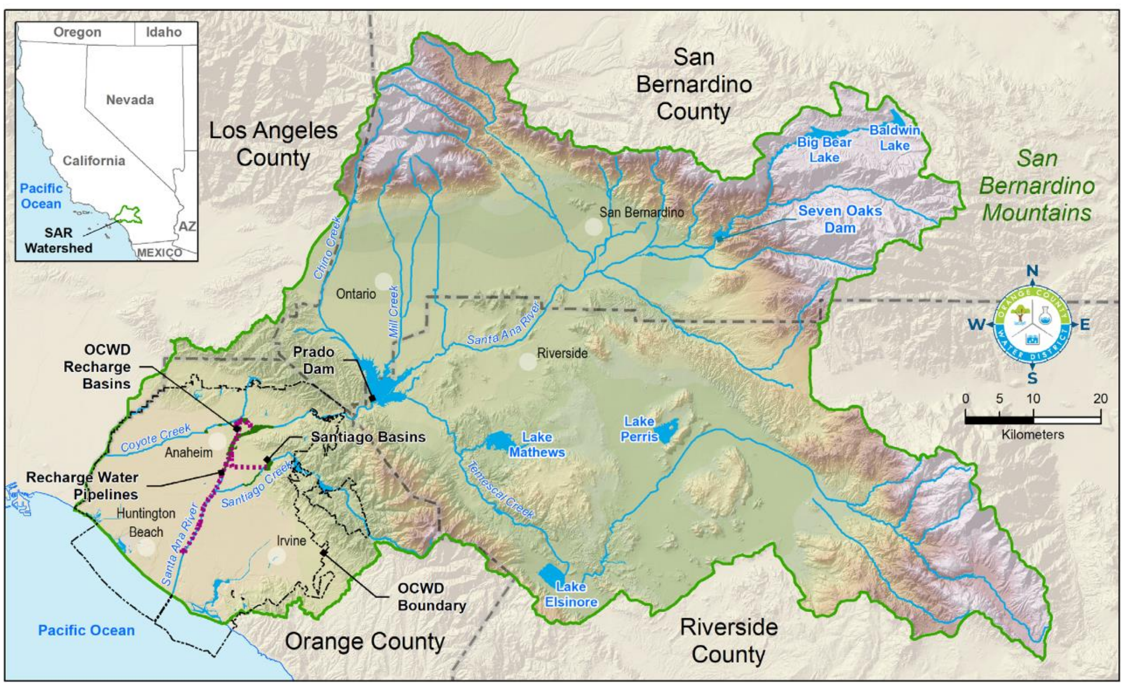

Figure 2-4. *Santa Ana River Watershed with Prado Dam and OCWD Groundwater Recharge Basins.*

2.2.1 Endangered Species: Least Bell's Vireo

The Prado Basin, comprising 12,000 acres, is located at the confluence of four of the watershed's largest tributaries where flood control, water management, and wildlife habitat requirements are balanced. More than a third of the basin (about 4,500 acres) consists of riparian habitat dominated by willow woodlands, freshwater marshes, and ponds. The Prado Basin houses the single largest forested wetland in coastal Southern California, supporting an abundance and diversity of wildlife, including many listed and sensitive species.

There are many sensitive bird species, such as the southwestern Willow Flycatcher, Yellow-billed Cuckoos, Yellow-breasted Chat, and the least Bell's vireo that reside in the Prado Basin and depend on the riparian critical habitat. However, the least Bell's vireo (*Vireo belli pusillus*) is the only federally threatened or endangered species known to be affected by Prado Dam reservoir operations (Figure 2-5). Therefore, the vireo and the riparian habitat they depend on are a key environmental concern for FIRO.

Figure 2-5. *Photo of least Bell's vireo adult on nest (courtesy of OCWD)*

Vireos spend the winter in southern Baja California, Mexico, and migrate to Southern California, typically arriving in the Prado Basin in mid-March. Nesting usually occurs in early April. Vireos nest and forage in dense riparian understory dominated by mule fat and willows in the spring and early summer. Since 1987, over 80 percent of observed vireo nests have been built in willows and mule fat (Pike 2022). Nesting success depends, in part, on how water levels behind the dam are managed. If water levels rise after the arrival of the vireo, nests could be flooded. If the water is held for long periods of time in the wet years, the vegetation required for nesting and foraging could be negatively impacted; however, it appears that the vegetation rebounds during the drier periods. Much success has been made to recover vireo populations since monitoring began in the Prado Basin (the area below 566 feet in elevation) in 1986, when 19 vireo territories (defined as the location of a singing male vireo) were observed (Figure 2-6). Additional information on vireo, including a summary of observations and monitoring in the Prado Basin during 2022, can be found in Appendix E.

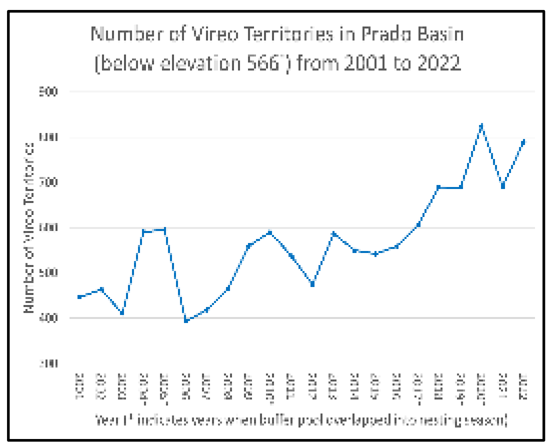

Figure 2-6. *Total Vireo Territories 2001-2022 in Prado Basin*

2.3 Meteorology and Climatology of the Santa Ana River Watershed

The Santa Ana River Watershed's climate is Mediterranean and consists of warm, dry summers and cool, wet winters. The San Gabriel, San Bernardino, and San Jacinto Mountains, which ring the upper boundary of the Santa Ana River Watershed, form a barrier to moisture transport during winter storms, including ARs. During these extreme events, moisture transported from the Pacific Ocean is forced upward into high elevation watershed topography to generate clouds and precipitation. Rainfall accumulation during a handful of extreme events each winter season accounts for 40 to 50 percent of annual precipitation, with large interannual variability in total precipitation primarily due to differences in AR activity.

The climatology of landfalling ARs in southern California for water years 1960–2023 (through February 2023) contains an average annual frequency of 3.7 ARs and a standard deviation of 2.8 ARs (Figure 2-7). A majority (86 percent) of landfalling ARs in Southern California have an AR scale rank of AR1 or AR2 according to the Ralph et al. (2019) scale; very few achieve a rank of AR3 or higher.

Landfalling ARs are most common during December, January, and February, with an average monthly frequency of less than 0.8 per month per year, but 2.2 per year during the December–February period (see Figure 2-8 below).

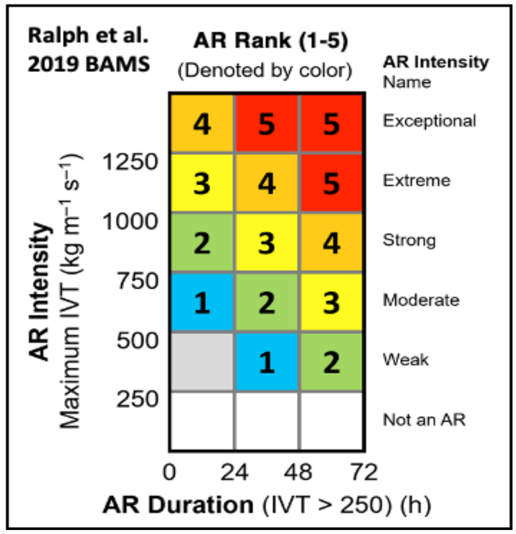

Figure 2-7. *The AR Scale is based on AR intensity (measured as the maximum concentration of water vapor and the duration (in hours) of the AR; to be considered an AR, it must have a minimum water vapor concentration of 250 kg m^{-1} s^{-1})*

These relatively infrequent extreme events contribute significantly to flood hazards and water supply within the Santa Ana River Watershed. USACE operations at Prado Dam have historically accounted for such storms, but recent advances in understanding and predicting ARs and the physical mechanisms that generate precipitation in the watershed yield the potential to enhance water supply reliability and flood risk management at the dam. This project builds on over a decade of science to understand AR formation and evolution and their impact on the U.S. West Coast.

See Section 6.3 for more information on climatology and runoff characteristics of the Santa Ana River Watershed, including the range in annual precipitation rates across the watershed, maximum observed historical rainfall events, and runoff statistics such as the 25-year and 50-year event peak inflow rates into the Prado Basin.

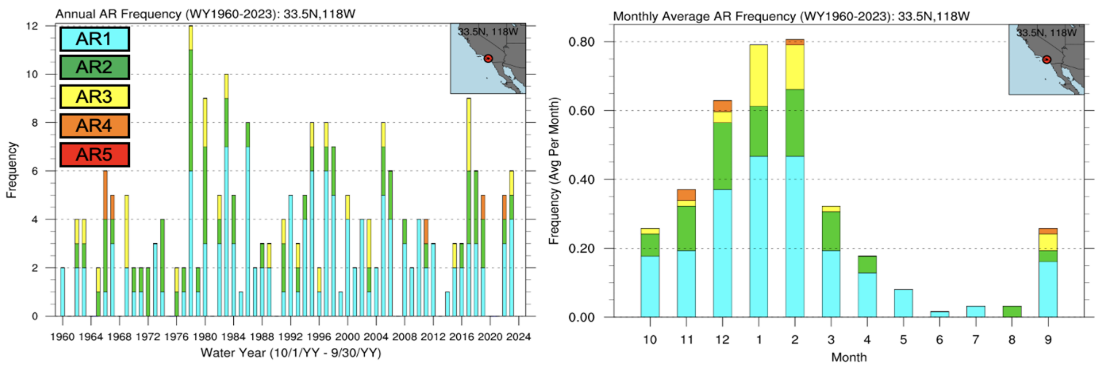

Figure 2-8. *Climatology of landfalling ARs at Prado based on Ralph et al. (2019) AR scale using integrated vapor transport (IVT) magnitude by year and month at 33.5N, 118W. Climatology is based on ECMWF ERA5 dataset for water years 1959 through 2023.*

2.3.1 Observational Network

2.3.1.1 Gage Network

The CNRFC, which is part of NOAA's NWS, provides hydrologic guidance, including reservoir inflow forecasts, that are used extensively by reservoir managers. The CNRFC gathers precipitation and air temperature data from about 80 observation stations in the Santa Ana River Watershed. The stations are owned and operated by local, state, and federal agencies. About 25 of these stations are quality controlled and used for hydrologic modeling (Section 6.2). The CNRFC quality controls these station data and produces six-hour mean areal precipitation and temperature for each of the sub-basins used in its hydrologic modeling.

The CNRFC considers this network of precipitation and temperature gages adequate for the current hydrologic forecasting services it provides. Temperature tends to be relatively smooth when analyzed spatially, primarily varying due to elevation, and is exclusively used in the snow model portion of the CNRFC suite of hydrologic forecasting tools.

2.3.1.2 AR Observatory

The California Department of Water Resources and NOAA AR observing systems contribute to the land-based monitoring effort of ARs. An AR observatory at Santa Barbara Airport provides measurements of the onshore flux of water vapor associated with ARs making landfall in the region. A profiling radar in Devil's Canyon provides the snowline elevation. A number of Global Positioning System meteorology stations in the region quantify water vapor concentration in ARs.

2.3.1.3 NWS Next-Generation Weather Radar

Four regional NWS Next-Generation Weather Radar (NEXRAD) installations cover coastal Southern California and adjacent mountains: San Diego (KNKX), Santa Ana (KSOX), Los Angeles (KVTX), and Vandenberg (KVBX). The NWS NEXRAD stations range in elevation from about 1,000 to 3,300 feet and have a base scan elevation angle of around 0.5°. NWS radars in Southern California are well-placed to detect approaching storms, and they help the regional forecast offices monitor, predict, and warn of flash floods and other events related to heavy precipitation (National Research Council 2005).

Topographic blocking and range effects are major impediments for operational monitoring of intense precipitation. Figure 2-9 below illustrates the minimum elevation of a 0.5° scan angle with a 1° beam width from each radar to approximate the minimum coverage height over the Southern California Bight. At 100 kilometers range, the majority of the radar beam is above a 2-kilometer altitude, which is above the elevation of most intense precipitation in most cases. De Orla-Barile et al. (2022) demonstrated challenges in the regional radar network's ability to observe key precipitation events, and previous work (e.g., Martner et al. 2008) demonstrated challenges in converting radar reflectivity to precipitation due to gaps in measuring microphysical processes. Both these challenges were targeted by the FIRO field campaign (Section 6.2.2), including using radiosondes to observe the vertical structure of precipitating systems, and profiling radars and disdrometers to observe hydrometeor characteristics aloft and at the surface, respectively.

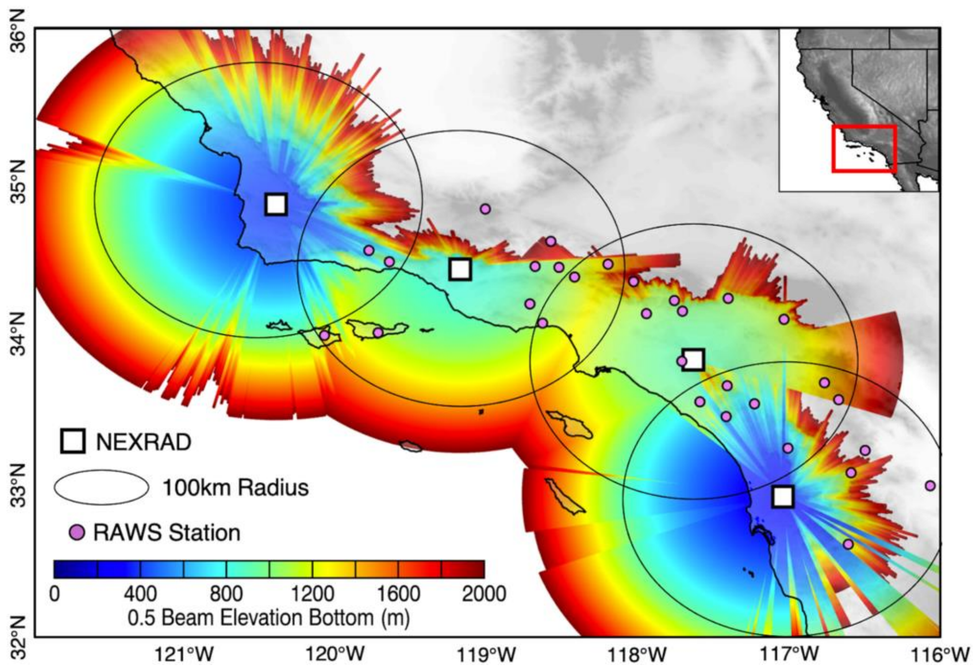

Figure 2-9. *Approximate minimum radar coverage height over the Southern California Bight (colorfill). A 100-kilometer radius (black circles) is plotted around each NEXRAD site (squares).*

2.4 References

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Section 3. Assessment of Current Forecast Skill

3.1 Overview and Purpose

The Prado Forecast Informed Reservoir Operations (FIRO) project is grounded in the concept that using high-quality forecast information can lead to better decisions about water storage, capture, and releases at Prado Dam. It is an important step to establish benchmarks of the quality of the meteorological and hydrologic forecast information over time, as it provides statistical measures of confidence and situational awareness for water managers wanting to use forecast information.

This section describes the evaluation of forecast skill associated with the prediction of atmospheric river (AR) type storms–related atmospheric and hydrologic characteristics relevant for FIRO in the Santa Ana River watershed. For this effort, the study team evaluated forecasts over available periods of record for each model and observation source, using a verification framework that considered the datasets, time scales, metrics, and tool appropriate for describing baseline forecast skill under AR conditions. ("baseline forecast skill" describes the long-term predictability of AR and hydrologic characteristics aggregated over relevant time scales.)

This section discusses precipitation and inflow forecasts, then the underlying primary mechanism—ARs—and measures of their skill.

3.2 Precipitation Forecast Skill

3.2.1 Motivation

Precipitation is the primary source of hydrologic forcing for runoff generation in the Santa Ana River watershed. Its intensity, timing/duration, and spatial distribution play an important role for hydrologic prediction and water management strategies. The study team evaluated The prediction of precipitation and its multi-dimensional characteristics to provide better context for FIRO applications and confidence in current state-of-the-art atmospheric numerical weather prediction (NWP) forecast skill during extreme events.

3.2.2 Methods and Analysis

The team evaluated Forecasts from several NWP and operational models for their skill in predicting 24-hour mean areal precipitation (MAP). The Center for Western Weather and Water Extremes (CW3E) has produced a 34-year reforecast between 1986 and 2019 using its West-WRF (Weather Research and Forecasting) model (Martin et al. 2018; Cobb et al. 2023); the team used 3-kilometer data from this reforecast in its analysis. The team also compared the West-WRF model's performance to that of the Global Ensemble Forecast System version 12 (GEFSv12) control member in order to evaluate the performance of a high-resolution regional model (with regionally tailored physics) and a global ensemble model. The observed precipitation was derived from an archived California Nevada River Forecast Center (CNRFC) quantitative precipitation estimate, or QPE (https://www.cnrfc.noaa.gov/arc_search.php) and the Stage-IV precipitation product produced by the National Oceanic and Atmospheric

Administration (NOAA). The precipitation observations and forecasts were individually averaged over the Santa Ana River watershed to generate MAP values. MAP was calculated first on the native resolution of each source to reflect its own model/observation capabilities. Then the skill of MAP was computed and compared across forecast models. Skill was expressed using:

- **critical success index (CSI)**—the categorical performance of correct forecasts (hits) divided by the total number of storms and misses.
- **relative forecast error**—a percentage indicating the ratio of the forecast error to the magnitude of the precipitation total. The forecast error is the absolute value of the forecast minus the observed precipitation total.
- **QPF error**—the difference, in millimeters, between the forecasted value and the observed value.

Other weather-related characteristics were cross-referenced with the errors of precipitation skill and collated into a catalog to identify potential correlated patterns in atmospheric processes (e.g., integrated water vapor transport [IVT] intensity) and precipitation predictability. More information on the generation of the catalog can be found in Section 6.3.2.1. This analysis compares the performance of the precipitation errors against conditions within the watershed and/or characteristics of the mechanisms responsible for generating precipitation (e.g., ARs).

3.2.3 Key Findings

Figure 3-1 below shows the CSI of 24-hour MAP at one- through five-day lead times using data from the winters of 2005 through 2018. The study team used CSI above 50 percent for events with precipitation above 0.5 millimeters as a threshold for defining forecast skill. This analysis shows that West-WRF and GEFSv12 forecasts have skill in predicting 24-hour MAP above 0.1 millimeter through at least five days and above 10 millimeters out to four days ahead of the event. The skill of the 90th percentile MAP in the Santa Ana River watershed is well represented by the over-10-millimeter threshold, indicating that even larger events are well predicted out to four days ahead. There were 47 total days, in the period analyzed, on which 24-hour MAP was above 25.4 millimeters (1 inch). For these events, the forecast skill of the West-WRF reforecast extends out to three days' lead time; GEFSv12's skill extends only to one day's lead time. The GEFSv12 data are not adjusted from their native resolution, so they represent a coarse estimate of precipitation in the Santa Ana River watershed. Appendix A3.1 shows the distribution of relative forecast errors of MAP compared to a climatological reference.

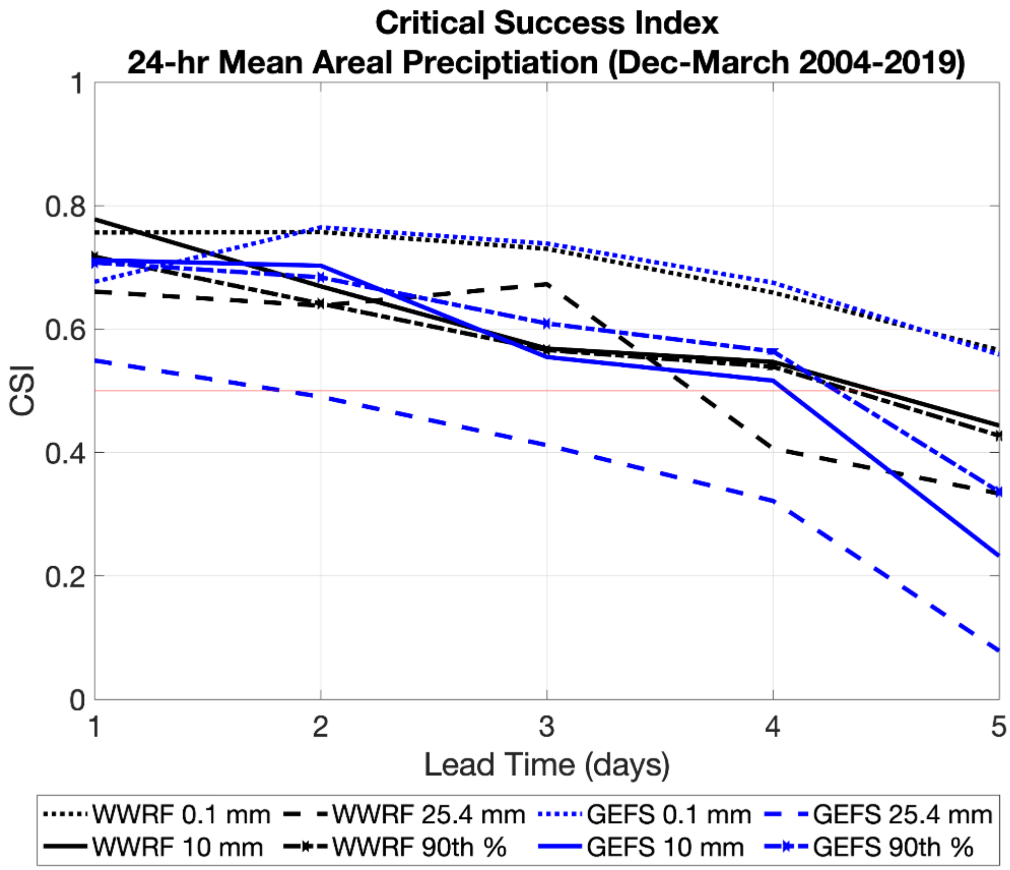

Figure 3-1. *CSI of 24-hour MAP using data from the West-WRF Reforecast (black) and GEFSv12 (blue) between December and March of water years 2005–2019. The different line styles indicate different thresholds used to calculate the skill of different magnitudes of precipitation: dotted for MAP above 0.1 millimeter, solid for MAP above 10 millimeters, dashed lines without a symbol for MAP above 25.4 millimeters, and dashed lines with an x for MAP above the 90th percentile of the forecast distribution. The horizontal red line represents a CSI of 0.5.*

Results show that, at a four-day lead time, precipitation errors are equal to or less than 50 percent of the observed value. Evaluating both CSI and relative error lends additional confidence that GEFSv12 retains skill in predicting extreme events up to a four-day lead time in the Santa Ana River watershed.

The relationship between precipitation errors and presence and/or characteristics of ARs was also examined. Figure 3-2 below shows the relationship between observed and forecasted IVT from the West-WRF reforecast at the point 33.5°N, -122.5°E (nearest Prado) and the resulting MAP forecast errors as a function of lead times. The black diagonal line represents the best -fit line where the forecasts equal the observations. The scatter of dots around this line represents the magnitude of the errors between the forecasted and observed IVT. As lead time increases, the dots become more scattered, indicating an increased forecast error. When forecasts of IVT above 250 kg /m/s are underestimated at a five-day lead time, there is a higher likelihood of underestimating MAP. This further confirms the importance of predicting AR activity as a prerequisite for producing skillful precipitation forecasts.

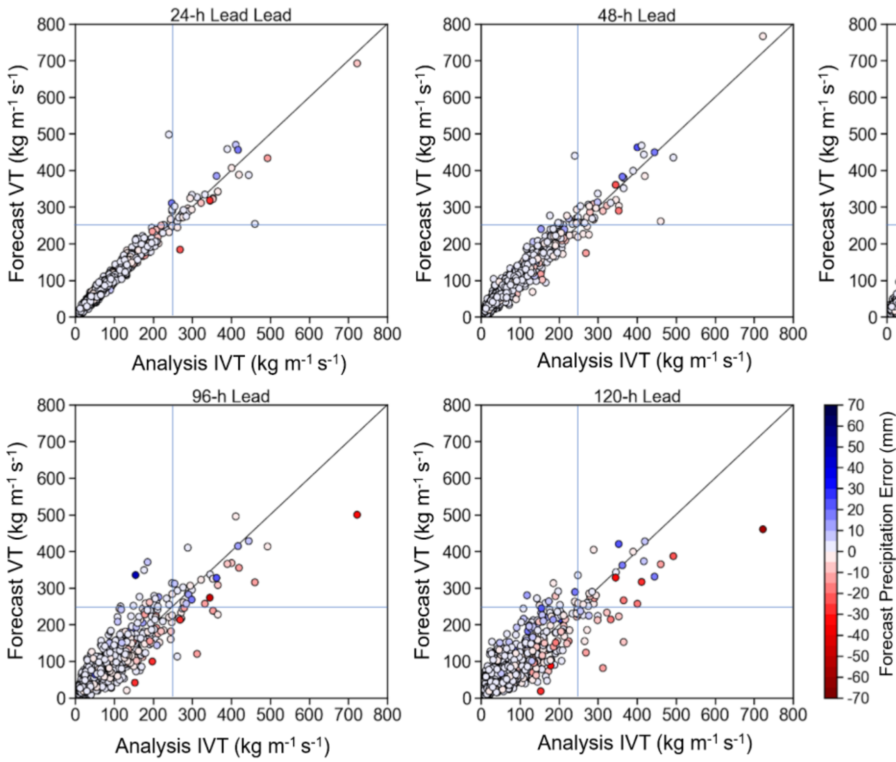

Figure 3-2. *Analyzed daily mean IVT magnitude from the ERA-5 Reanalysis vs. West-WRF reforecast daily mean IVT magnitude at 33.5°N at lead times of 24, 48, 72, 96, and 120 hours. Shading represents the associated West-WRF reforecast 24-hour QPF errors. Blue vertical bars indicate when IVT was above 250 kg /m/s to signify AR conditions. Data are based on forecasts valid on 937 days during water years 2012–2019.*

3.3 Inflow forecast skill

3.3.1 Motivation

CNRFC currently provides inflow forecasts that the U.S. Army Corps of Engineers (USACE) uses for decision making and further reservoir modeling. Therefore, we assessed the inflow forecast skill and potential for future improvement. The study team examined three-day (72-hour) total inflow forecasts for Prado Reservoir in order to (1) provide baseline meteorological/hydrological forecast skill to assess future model improvements, (2) understand the priority forecast skills for FIRO needs, and (3) determine relationships between AR events and model skill.

The Community Hydrologic Prediction System (CHPS) is a baseline NOAA National Weather Service hydrologic model used by CNRFC for creating deterministic and probabilistic/ensemble forecasts. The Hydrologic Ensemble Forecast System (HEFS) is the CHPS operation used by CNRFC to create forecast and hindcast ensembles.

3.3.2 Methods and Analysis

Both ensemble hindcasts and the CHPS period of record were available hourly from October 1989 to December 2019 and assume full natural flow, so no upstream regulations were accounted for in their simulations. The verification focused on the period of record (1989–2019) as a benchmark evaluation. Observed inflow to Prado Reservoir was not available, so a synthetic inflow dataset composed of synthetic baseflow and historical stormflow was used as the observation. This synthetic observation was available daily from October 1989 to September 2019 and has been used for model calibration by the CNRFC.

The ensemble hindcasts (hereby forecasts) were generated using HEFS. By design, HEFS translates an ensemble of meteorological inputs through hydrologic models—in this case is a coupled snow (SNOW-17)–soil (SAC-SMA) model—to produce an ensemble of streamflow outputs. HEFS uses ensemble meteorological inputs to address weather uncertainty using a statistical model called the Meteorological Ensemble Forecast Processor. Reforecast datasets from GEFSv12 are available from 1989 to 2019; the Meteorological Ensemble Forecast Processor uses the resulting ensemble means for precipitation and temperature to generate an ensemble of weather forcings for HEFS. The ensemble three-day total inflow is derived from aggregating the hourly data at rolling lead times of one to three days (one to 72 hours), four to six days (73–144 hours), and seven to nine days (145–216 hours). The study team evaluated three scenarios:

- All time, including both clear-sky/baseflow and precipitation periods
- All AR events
- Top 5 percent AR-related flows during the wet season (November–April)

AR periods are identified using Rutz's AR catalog (Rutz et al. 2014) at the nearest point to Prado Dam, which is available from 1980 onward.

The study team evaluated ensemble forecast three-day inflow verification metrics—including 10, 25, and 50 percent (median) non-exceedances; spread-skill plot; reliability diagram; and Brier score (Brier 1950)—for every lead-time aggregate and scenario. ("Non-exceedances" refers to values within the ensemble indicating the probability of flows that are not top 10th, 25th, or 50th percentile events.) The all -time (November–April of 1989–2019) forecast 80 percent exceedance value was used to evaluate the reliability diagram and Brier score at all lead time aggregates and in all scenarios. A threshold based on the observation instead of forecast was considered, but it yielded similar results and conclusions. The same all-time threshold is used to maintain a consistent benchmark across different data subsets. The CHPS period of record simulation error (as root mean square error, or RMSE) and Nash-Sutcliffe Efficiency, or NSE (Nash & Sutcliffe 1970), were also computed. However, due to the relatively limited independent sample size, the statistics associated with the CHPS period of record were computed at a daily scale.

3.3.3 Key Findings

Figure 3-3 below illustrates the ensemble in the three-day 10 percent, 25 percent, and 50 percent non-exceedance forecasts compared to the observation at different lead time aggregates and scenarios. Errors are generally larger at longer lead times, with higher non-exceedance forecasts and all ARs under-forecasted (negative error). Larger events, typically those resulting in three-day inflows over 40,000 acre-feet (ac-ft) and most notably those associated with the top 5 percent AR-related flows, exhibit larger errors (diverging from the 1:1 line) against the observation. These results show that forecast errors increase with longer lead times as well as when flows associated with AR events are exceptionally high.

Table 3-1 shows that the ensemble has a reasonable three-day inflow forecast skill with Brier scores under 0.55. However, the forecast accuracy tends to deteriorate with longer lead times. Brier scores are generally better in the all -time subset than the all -ARs subset, indicating the lower forecast accuracy under AR conditions. The Brier skill scores exhibit the same pattern with all values above 0 (Table A-1 in Appendix A), which confirms that the ensemble forecasts are still more skillful than the reference forecast based on climatology.

Table 3-1. *Brier scores of the ensemble forecast's three-day total inflow to Prado Reservoir at lead-time aggregates of one to three days, four to six days, and seven to nine days, for all -time, all -non-AR, and all -AR events spanning November–April of 1989–2019. The threshold is 80 percent exceedance based on the observations.*

Lead time Aggregate	Brier Score (lower numbers indicate better skill)	
	All Time	All ARs
1-3 days	0.394	0.502
4-6 days	0.398	0.514
7-9 days	0.404	0.513

Ensemble characteristics, including reliability, were also examined and are summarized in Appendix A3.2. In general, the prediction is considered reliable when the spread is approximately equal to the error. Overall, the ensemble spread is representative of the forecast error when the spread is relatively small (under 5,000 ac-ft). When the spread is larger, the ensemble appears under-dispersive during AR events. During the top 5 percent AR-related flows, the ensemble shows notably large error ranges when flows are above 20,000 ac-ft in most cases. We also found that at seven to nine days' lead time, there is an under-forecast tendency during AR conditions. Further research is needed to understand implications of the forecast dispersiveness and underestimation of the top 5 percent AR-related flows.

Note that the hydrologic forecast evaluation reflects a culmination of forecast errors from the meteorological forcings/model, downscaling and ensemble processing, and the hydrologic model. While precipitation forecasts in the West (particularly the CNRFC's forecast area) have better predictive skill than in other locations across the country (see Sukovich et al. 2014), more work needs to be done to understand how the skill of precipitation translates and evolves through the processing chain into streamflow forecasts and the uncertainties that are introduced through that processing chain.

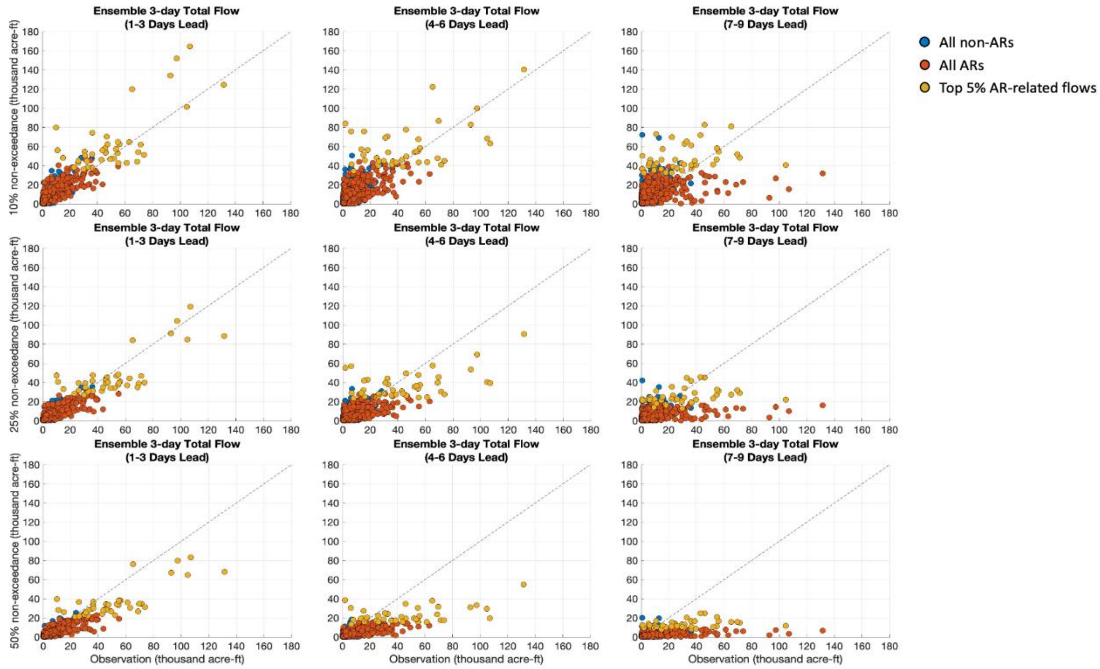

Figure 3-3. *Ten percent (top), 25 percent (middle), and 50 percent (bottom) non-exceedance scatter plots of the ensemble forecast's three-day inflow to Prado Reservoir against observation at lead-time aggregates for one to three days (left), four to six days (center), and seven to nine days (right) for all non-ARs (blue), all ARs (red), and top 5 percent flows during AR periods (yellow) periods spanning November–April of 1989–2019.*

The CHPS period of record simulation daily inflow mean errors, RMSEs, and NSEs are shown in Table 3-2. For reference, the ensemble forecast bias and RMSE distributions are shown in Appendix A.2 (Figure A3.2.1). Both the mean errors and the RMSEs show that the simulation errors are larger in the all -ARs subset than in the all -non-ARs subset, particularly in the top 5 percent scenario. This difference is related to the fact that ARs are responsible for larger precipitation events in California (Dettinger et al. 2011). However, the mean errors are negative in the all -ARs subset and positive in the other subsets, indicating under-forecasting tendency in the former and over-forecasting tendency in the latter. The NSEs indicate reasonably skillful simulation with values above 0.5 in all subsets. The NSE is highest in the all -ARs subset (0.86) and lowest in the top 5 percent AR-related flows subset (0.53). Aside from the simulation error, NSEs also account for the correlation between the simulation and the observation. The latter suggests a particularly strong correlation in the all -ARs subset.

Table 3-2. *CHPS* period *of record daily-total inflow simulation errors (ac-ft), RMSEs (ac-ft), and NSEs at Prado Reservoir, for all non-AR events, all AR events, and top 5 percent flow during AR periods spanning November–April of 1989–2019.*

Metric	All non-ARs	All ARs	Top 5% AR flows
Error (acre-ft)	168	-194	4486
RMSE (acre-ft)	1151	2818	7555
NSE	0.72	0.86	0.53

In conclusion, CNRFC ensemble forecasts largely capture the forecast uncertainty with a 90 percent confidence level, especially with shorter lead times where the forecasts tend to be less biased. However, they become more underdispersive when the spread grows larger, typically during larger AR events. Overall, the ensemble has skill at forecasting the three-day inflow volume, but it is also shown to potentially benefit most from improvement during AR events. The result from CHPS period of record simulation supports the fact that the three-day inflow prediction, though reasonably skillful, exhibits larger errors during AR events.

3.4 AR landfall skill

3.4.1 Motivation

As shown in Section 2.1.1, ARs are a major source of precipitation in the Santa Ana River watershed during the winter months (October–March) and their predictability can significantly affect operations during potential urban flooding and/or times of encroachment in Prado Reservoir. The location and timing of AR-related water vapor flux has direct implications for precipitation and runoff generation, so understanding the predictability of these measures can provide confidence for water managers and guidance on uncertainties when accounting for forecast error. This section focuses on landfall error as the "first line" influence of predictability, as error in the placement of the large-scale storms responsible for precipitation will often dominate the predictability of precipitation on local scales.

3.4.2 Methods and Analysis

AR landfall is calculated using fields of IVT to define AR boundaries. Landfall is the location at which the maximum IVT within the AR crosses the coastline. The intensity of the AR is defined as the 90th percentile IVT value within the AR. The study team used the ERA-5 reanalysis to represent the observed AR distribution and computed the forecast skill using two models: the control member of the GEFSv10 forecasts and CW3E's West-WRF 34-year Reforecast (Cobb et al. 2023) from the data prepared by DeHaan et al. (2021). Note that GEFSv10 is coarser in resolution than GEFSv12; however, v10 was used as forcing for the 34-reforecast and therefore provides an apples-to-apples comparison when determining the added value of the dynamical downscaling in the Reforecast.

Several scores are used to define skill in AR landfall: the Probability of Detection (POD) represents the ratio of total correct forecasts to the total number of events observed, the False Alarm Ratio (FAR) describes the ratio of the number of false alarms to the total number of forecasted events, and the CSI (otherwise known as the threat score) represents the ratio of the number of correct forecasts to the total of observed and forecasted events. These are computed based on contingency table statistics (see https://www.swpc.noaa.gov/sites/default/files/images/u30/Forecast%20Verification%20Glossary.pdf for glossary definitions of contingency table formation and skill score definitions).

3.4.3 Key Findings

The left panel in Figure 3-4 below shows the frequency of ARs making landfall in Southern California (33°N–35°N) using an IVT threshold of 250 kg /m/s. Comparatively, landfall is less frequent along the Southern California coast than anywhere else along the U.S. West Coast (note that the smallest landfall bin represents all ARs making landfall south of 30.5°N, not just within the 0.5° gridbox). At a one-day forecast lead time, there are a total of 148 matched (correct hit) forecast/analysis landfalling ARs in the GEFS reforecast over the 31-year period using a 250 kg /m/s threshold (Figure 3-5 below). At the same lead time, there were only 13 ARs using a 500 kg /m/s threshold during the whole period of record. This means that there is a larger distribution of weaker ARs that affect Southern California than of stronger ARs with a more broadly defined area of IVT above 500 kg /m/s. The landfall error between West-WRF and GEFS is generally similar for ARs for each threshold; errors are under 100 kilometers at a one-day lead time and increase to above 400 kilometers at a seven-day lead time, using a 250 kg /m/s threshold. For the smaller sample of ARs defined by a 500 kg /m/s threshold, the landfall error is smaller at all lead times in both models. Because of the significant reduction in sample size of stronger ARs, more data are needed to examine statistical significance. The West-WRF and GEFS reforecasts show similar errors across both thresholds; West-WRF has a larger error on average at the one- and two-day lead times and smaller error at the six- and seven-day lead times using the 250 kg/m/s threshold. The positive error suggests that both forecast models place the landfall of the AR too far to the north of the watershed.

With the 250 kg /m/s threshold in use, AR landfall over Southern California has a very low FAR compared to the POD (Figure 3-6 below). In fact, the FAR never exceeds the POD through a seven-day lead time. CSI also exceeds 0.5 out through a seven-day lead time, suggesting that there are more correct landfall predictions at a seven-day lead time than not. This is also true for landfalling ARs in a narrower latitude band between 32°N and 34°N, closer to the Santa Ana basin (not shown).

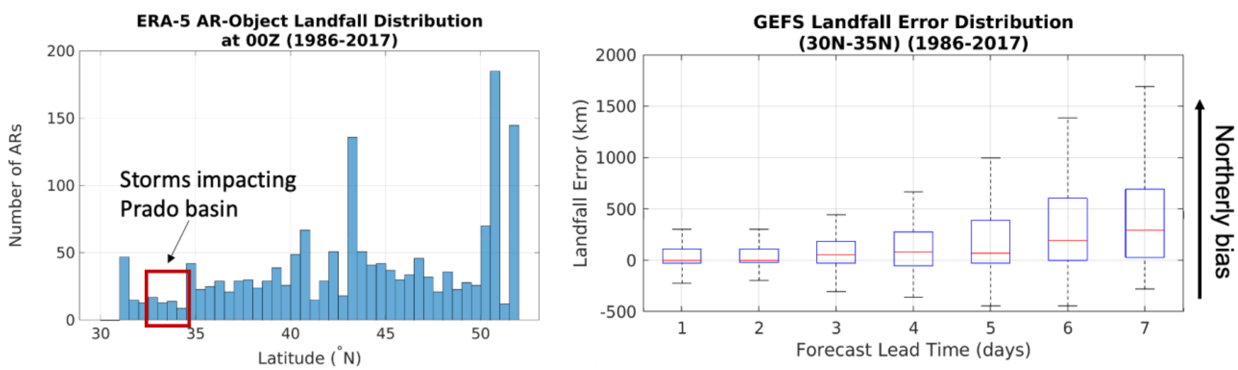

Figure 3-4. *Left: Histogram of ARs making landfall along the U.S. West Coast. ARs are defined as objects using a threshold of 250 kg /m/s from the ERA-5 Reanalysis. The red inset represents a band of latitudes in which an AR making landfall affects the Santa Ana watershed. Right: Boxplot of landfall error (in kilometers) of ARs making landfall in Southern California (30°N–35°N) using the control member of the GEFS ensemble as a function of lead time. Positive values indicate a northerly bias. The red bar represents the median value, the bounds of the blue box represent the 25th and 75th percentiles of the errors at each lead time, and the whiskers represent the minimum and maximum error values across the entire period of record (December 1–March 31 of each year between 1986 and 2017).*

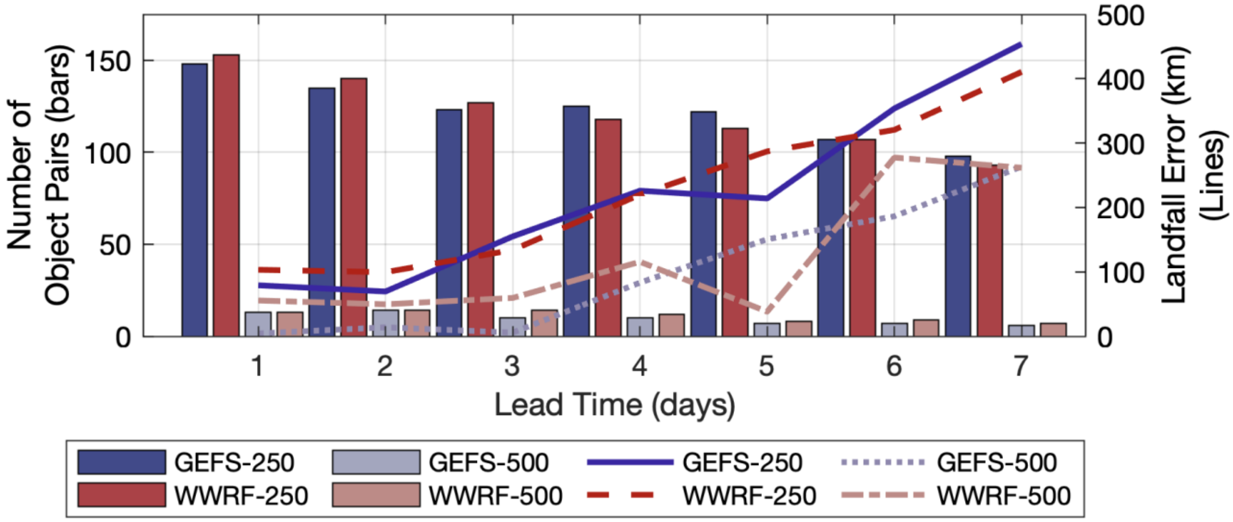

Figure 3-5. *Forecasted landfall error (kilometers, lines) and number of matched forecast/analysis AR objects (bars) as a function of lead time (days) using the GEFSv10 (blue) and West-WRF (WWRF, red) Reforecasts. Data using objects defined using a 250 kg /m/s threshold are plotted in the darker shades of color, and those using a 500 kg /m/s threshold are given in the lighter shades.*

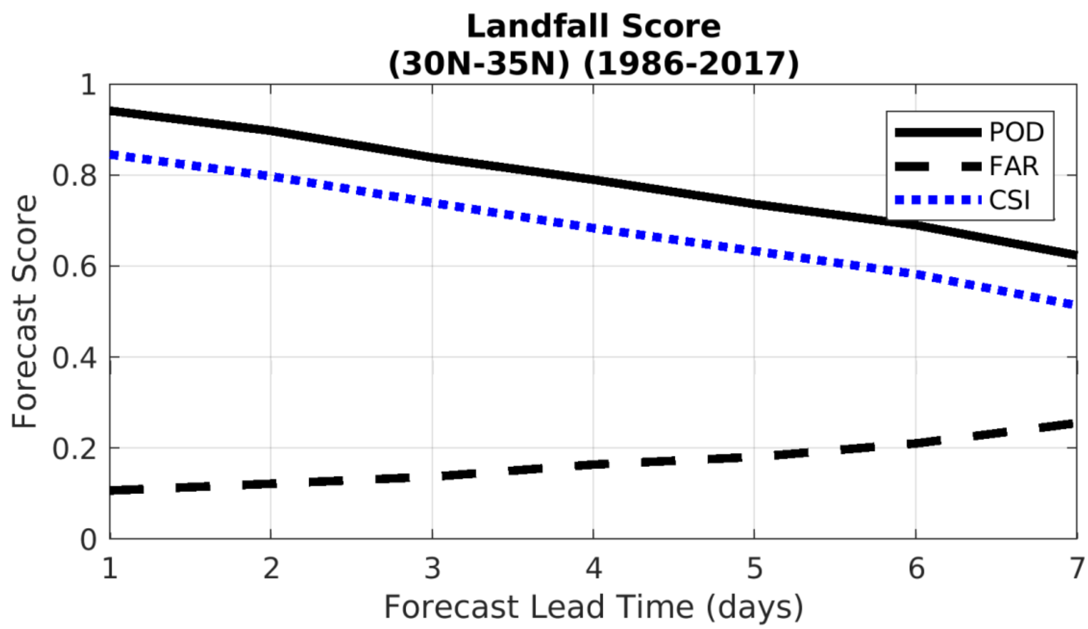

Figure 3-6. *POD (solid black line), FAR (dashed black line), and CSI (dotted blue line) of AR landfall over Southern California (30°N–35°N) using the West-WRF Reanalysis between 1986 and 2017. ARs are defined as objects using the 250 kg /m/s threshold.*

3.5 Prado December 2021 Case Study

3.5.1 Motivation

In late December 2021, a unique sequence of precipitation events led to major forecast changes and subsequent operational decisions that provided a good opportunity to learn about the role of weather and water forecasts and their applications in reservoir operations decisions for Prado Dam. The analysis of this event and the associated reservoir release decisions provided valuable insight into the sensitivity of weather and water forecast errors (uncertainty). It also helped clarify the release decision process used by USACE's Los Angeles District (LAD).

3.5.2 Methods and Analysis

Several sources of weather forecasts were analyzed to study how they predict precipitation and the responsible meteorological mechanisms, and thus to understand the implications of resolution and uncertainty of the forecasts, including CW3E's West-WRF near real-time system and the Global Forecast System (GFS). To verify the precipitation forecasts within and surrounding the Santa Ana basin, the forecasts were compared to the 4-kilometer gridded QPE from the CNRFC. Both time series data at 117.63°W, 33.89°N and the full gridded fields over Southern California were extracted between December 24, 2021, and January 1, 2022. To contextualize the presence or lack thereof of AR activity, the IVT series was extracted from the ERA-5 reanalysis. Periods of time in which IVT exceeded 250 kg/m/s at 117.75°W, 34°N indicate AR conditions at Prado. Hourly reservoir elevations at Prado Dam were obtained from the California Data Exchange, from which they were available at an hourly time step through the period of study. Finally, LAD provided a timeline of its release decisions and the available forecasts it had consulted.

3.5.3 Key Findings

Several pulses of precipitation occurred over the Santa Ana Basin between December 23, 2021, and January 1, 2022. These resulted in the activation of LAD to make water management decisions at Prado Dam. Following a series of precipitation events between December 24 and December 28, the reservoir elevation was 503.42 feet. Any subsequent forecasted rainfall would likely require release decisions at Prado as to avoid further encroachment.

Beginning on December 27, the 00Z GFS forecasts signaled another potential weather system approaching Southern California around 00Z December 30 and additional precipitation over the Santa Ana Basin. The observed weather pattern, a hybrid cutoff low centered at 123°W, 35°N and onshore southwesterly flow in the vicinity of the Santa Ana basin, was predicted to generate precipitation across much of Orange, Los Angeles, and Ventura counties. The IVT in this case is weak during the period of maximum precipitation accumulation, indicating that there is additional dynamical forcing to generate precipitation in association with the cutoff low.

A more comprehensive report of the event, forecast skill, and alignment of forecasts and decision making is provided in Appendix A.3. Below is a summary of key points made within the study:

- The Southern California event was predicted to generate high rainfall totals over the Santa Ana watershed on December 30, 2021.

- Precipitation stalled and primarily fell to the west of the watershed, leading to overpredictions in the Prado drainage basin.
- CW3E's West-WRF 3-kilometer model run reduced the forecast bias by 1.5 inches compared to GFS and better resolved areas of maximum precipitation accumulations at two days' lead time.
- The West-WRF ensemble indicated a great deal of forecast uncertainty two days before the rainfall event, while it correctly predicted the heaviest rainfall in the northern mountains.
- MAP valid on December 31, 2021, varied between about 50 millimeters and about 25 millimeters between a two-day and one-day lead time (Figure 3-7, top) using West-WRF's 3-kilometer model.
- Release decisions require additional lead time for, e.g., agency notifications.
- Forecast alignment and action timelines from LAD indicated that large variability occurred within the precipitation forecasts during critical times in which release and notification decisions needed to be made (Figure 3-7, bottom).

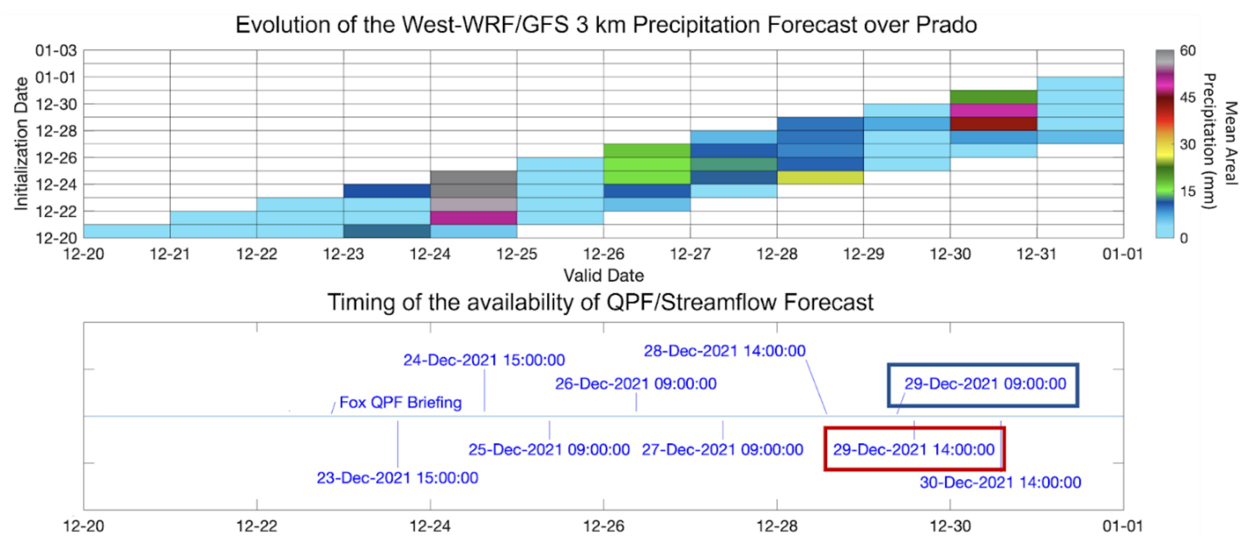

Figure 3-7. *Top: 24-hour MAP over Prado as a function of valid time and forecast lead time. Bottom: timing of the availability of the QPF/streamflow forecasts between December 20, 2021, and January 1, 2022. The red and blue boxes highlight the times for which CNRFC streamflow forecasts were available but the precipitation forecasts within Prado decreased by half.*

This exercise helped reveal the aspects of a rapidly changing forecast evolution for a potentially important precipitation event affecting Prado. It helped the team understand how forecasts are leveraged during a FIRO-like scenario, understand the limitations of operational flexibility with critical decision-making markers (e.g., notifying local agencies), and investigate sources of forecast uncertainty and meteorological predictability of the cutoff low.

3.5.4 Key Findings

<u>24-hr Precipitation Errors</u>:

- Forecasts of 90th percentile events are skillful out to 4 days ahead of time using GEFSv12 using 2 different metrics (CSI vs relative forecast error and climatology)
- West-WRF has additional skill in predicting >1 inch mean areal precipitation out to 3 days in advance over the GEFSv12 control member
- Underforecasts of IVT at Prado often coincide with underestimations of MAP in West-WRF

<u>72-hr Inflow Volume Forecast Errors</u>:

- Forecast accuracy tends to deteriorate with longer lead times, except in the all non-ARs subset
- Brier scores are generally best in the all time subset and worst in the all ARs subset, indicating the lower forecast accuracy under AR conditions
- Ensemble forecasts are still more skillful than the reference forecast based on climatology.
- CHPS model (used by CNRFC) has skill in simulating non-AR, all AR, and top 5% AR flows (NSE>0.53)

<u>AR landfall</u>:

- Generally a northerly bias in AR landfall using GEFS and objects > 250 kg m^{-1} s^{-1} IVT
- Errors at 1-day lead time are ~100 km and ~400 km at 7-day lead time using West-WRF
- West-WRF can skillfully predict AR landfall out to at least 7-days (CSI>0.5, POD>FAR)

<u>Prado Dec 2021 Case Study</u>:

- GFS/NWS forecasts of precipitation event were very volatile through 2-5 day lead times
- NWS local point precipitation forecast for Prado was reduced by half from 2-day to 1-day lead time
- Alignment of forecast errors and decision making timelines proved to be an extremely valuable exercise
- Improved understanding of how forecasts are leveraged
- Understanding limitations of operational flexibility with critical decision making markers (e.g. notifying local agencies)
- Investigating sources of forecast uncertainty and meteorological predictability of cutoff low

3.5.5 Recommendations

- Continue to evaluate forecast skill, particularly for epochs of marked improvements to model development
- Expand the inflow verification to include metrics that describe starting times of increased hydrographs during precipitation events as they represent important triggers for operational decisions
- Continue research into localized impacts/behavior of ARs and extreme precipitation and feedback of key mechanisms to forecast predictability
- Continue to work with stakeholders and operational decision makers to understand key aspects of forecasts used or leveraged in decision making process

- Conduct case studies of QPF->inflow error analysis to understand role of atmospheric forecast uncertainty to hydrologic sensitivity
- Continue to evaluate potential improvements and advances in meteorological and hydrologic forecasting models for additional FIRO benefit

3.6 References

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Section 4. How FIRO Viability Was Assessed

This section describes the framework used to objectively assess a selection of Water Control Plans (WCPs) that leverage streamflow forecasts in their decision logic. Unlike traditional U.S. Army Corps of Engineers (USACE) WCPs, Forecast Informed Reservoir Operations (FIRO) strategies leverage streamflow forecasts. The process used to generate the streamflow forecasts and a description of the forecasts used to evaluate the WCP alternatives are provided in the Simulation Plan (Section 4.3). Additionally, models were needed to (1) simulate reservoir release decisions for varying levels of storage and forecast streamflows and (2) efficiently simulate the operation of Orange County Water District's (OCWD's) groundwater recharge facilities. This work is described in the Modeling Plan (Section 4.2).

The Preliminary Viability Assessment (PVA) summarized work to evaluate the potential for FIRO to provide groundwater recharge benefits without negative impacts to flood risk management or environmental objectives. That work demonstrated potential benefits but also provided keen insight on how the evaluation process could be improved. The PVA recommendations (Table 4-1) were integrated into the Final Viability Assessment (FVA) evaluation described here.

Table 4-1. *Engineering recommendations from the PVA.*

ID	PVA Recommendations
1	Adjust baseflow during the simulation period to reflect current/expected conditions
2	Use GEFS-based scaled hindcasts (not available for PVA)
3	Use hindcasts (POR and scaled) based on updated GEFSv12 model
4	Include scaled events in the calibration of the EFO risk tolerance curves
5	Estimate the maximum buffer pool that can be safely operated without FIRO

4.1 Evaluation Framework: the HEMP

The study team used an established USACE framework called a hydrologic engineering management plan (HEMP) to evaluate the effectiveness of WCP alternatives. As applied and described here, the plan provides a systematic, defendable, and repeatable way to compare alternatives with the existing baseline and with each other. The HEMP can be found in Appendix B; this section provides a summary and describes adjustments made during the evaluation process.

The HEMP includes the following:

- Statement of the objective and overview of the technical study process.
- Specification of requirements for the FIRO alternatives that will be considered.
- Identification of tasks for the technical analysis.

- Identification of analysis tools and methods to be used for the study.
- Identification of the project development team members and their roles and responsibilities in conducting, reviewing, and approving the hydrologic engineering study.

The hydrologic engineering study follows a "nominate-simulate-evaluate-iterate" process, consistent with USACE's typical process for water resources planning studies.

4.1.1 Boundary Conditions

Both hard constraints and operational considerations were defined for the analysis. Table 4-2 provides the hard constraints that must be explicitly followed by each of the alternative WCPs.

Table 4-2. *Operational constraints that all FIRO strategies must satisfy.*

ID	Limiting Condition	Description
1	Must satisfy limits on release rate of change	Release rate of change is governed by the potential impacts on downstream evacuation of the channel and bank erosion and stability. Limits were provided by USACE Los Angeles District (LAD) staff for flows up to 30,000 cfs. (Table 4-8)
2	Must minimize exceeding downstream channel capacity	For this study, it is assumed that the water control plan has been updated to allow a maximum release of 30,000 cfs.
3	Must accommodate maximum release schedule	The maximum release schedule is defined in the Interim Water Control Manual (APR 2021). Chart provided by LAD staff for spillway at 543 feet. Schedule associated with the future 563-foot spillway also provided by LAD staff. (Table 4-7)
4	Must meet instream minimum flow requirements	Minimum release set at 50 cfs. (Environmental requirement).
5	Other	A minimum of 24-hour lead time for notifications are required to coordinate for downstream channel safety.

Tasks in this process include:

- Develop a set of feasibility criteria and performance metrics for assessing and comparing FIRO alternatives.
- Identify a set of alternative FIRO strategies. The strategies are screened to ensure they meet specified requirements.
- Simulate performance of the river-reservoir system with each FIRO strategy using a common set of meteorological and hydrological conditions.
- Use simulation results to evaluate the viability and performance of each strategy. The evaluation uses metrics to compare each alternative to the performance of the baseline condition (505 ft maximum buffer pool).

- Use the technical analysis results to (1) describe the general viability of FIRO for the Steering Committee and (2) identify candidate/recommended FIRO strategies for consideration in the WCM update.

Operational considerations are provided in Table 4-3. These considerations establish the basis for the metrics described below. Note that although impacts to Corona Municipal Airport, Euclid Avenue, and Vireo nests and habitat may be considered, Prado Dam is not operated to avoid inundation of these facilities during flood risk management operations.

Table 4-3. *Operational considerations evaluated in the hydrologic engineering study.*

ID	Operational Consideration	Description
1	Corona Airport	Flooding/closure of Corona Airport at 514 ft.
2	Euclid Avenue, Within Flood Pool Impacts	Euclid Avenue closed at 515 ft (normally closed earlier due to Chino Creek floodwaters).
3	Vireo nests	Increases in the pool elevation of 1 meter or more between March 21 (vireo arrival) and May 1 could flood vireo nests.
4	Potential harm to riparian habitat above 505 feet	Prolonged inundation of riparian vegetation can harm the critical vireo habitat during the growing season (spring and summer).
5	Spillway flow	Spillway flow that results in total releases greater than the downstream channel capacity (30,000 cfs) has serious flood impacts. Any spillway flow has negative implications for the USACE.

With the planned spillway raise, the evaluation also considered both the unraised (543 feet) and raised (563 feet) spillway elevations as shown in Table 4-4 and Figure 4-1 below. Both configurations used the same maximum release schedule as provided by LAD.

Table 4-4. *Spillway elevation and maximum scheduled release conditions associated with phased completion of the Santa Ana River Mainstem project.*

Condition	Spillway Elevation	Maximum Scheduled Release (cfs)
1	543 ft	30,000
2	563 ft	30,000

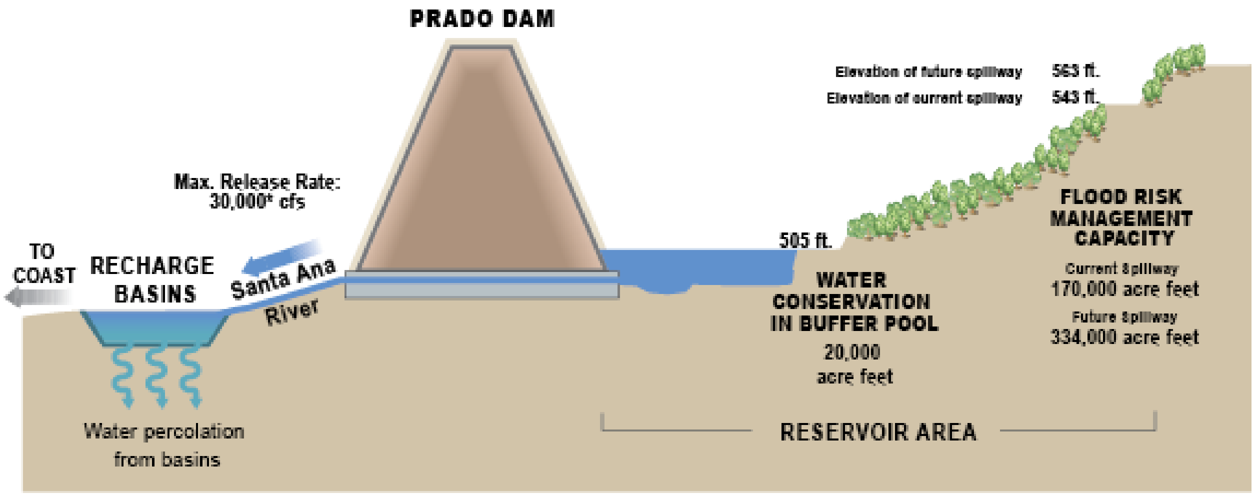


Figure 4-1. *Schematic of Prado Dam depicting final maximum release rate (30,000 cfs) and the current (543 feet) and future spillway (563 feet) elevations.*

4.1.2 Metrics

The metrics to be evaluated for each WCP alternative are shown in Table 4-5. The metrics cover flood risk management, environmental, groundwater recharge, and approved activities within the maximum flood pool.

Table 4-5. *Metrics for the evaluation of FIRO alternatives (listed in Table 4-6).*

ID	Metric Description	Category	Likely Method of Computation
M1	Annual maximum discharge frequency from Prado Dam	Flood risk management	Simulate 30-year hindcast and extend with scaled events of 100-, 200-, and 500-year frequency.
M2	Annual maximum pool elevation frequency function of Prado Dam	Flood risk management and environmental	Simulate 30-year hindcast and extend with scaled events of 100-, 200-, and 500-year frequency.
M3	Vireo nest inundation between 3/21 and 5/1	Environmental	Simulate 30-year hindcast period. Frequency of 1m pool rises between March 21 and May 1.
M4	Average annual number of days of pool above 505 feet	Environmental	Simulate 30-year hindcast.
M5	Average annual number of days of pool above 508 feet	Environmental	Simulate 30-year hindcast.
M6	Average annual number of days of pool above 510 feet	Environmental	Simulate 30-year hindcast.
M7	Average annual number of days of pool above 512 feet	Environmental	Simulate 30-year hindcast.

ID	Metric Description	Category	Likely Method of Computation
M8	Average annual number of days of pool above 514 feet	Environmental, Corona Airport	Simulate 30-year hindcast.
M9	Average annual number of days of pool above 520 feet	Environmental, additional land use impacts	Simulate 30-year hindcast.
M10	Average annual total recharge below Prado Dam	Water supply	Simulate 30-year hindcast.
M11	Average annual release above recharge capacity (volume)	Water supply	Simulate 30-year hindcast.
M12	Potential impacts on San Antonio and Seven Oaks operations	Flood risk management and water supply	TBD in consultation with LAD. Assess post-FVA with Seven Oaks viability assessment.

4.1.3 FIRO WCP Alternatives

The WCP alternatives evaluated for the FVA are briefly described in Table 4-6. In addition to the 505-foot baseline, there are fundamentally five WCP alternatives configured for five buffer pool elevations (508 to 520 feet). The alternatives are the Simpler Ensemble Forecast Operation (SFO), the SFO with perfect forecasts (SPFO), Ensemble Forecast Operations (EFO), the EFO with perfect forecasts (PFO), and no forecast used (NF). Section 4.2 briefly describes The SFO and EFO models, and Section 5 describes the process for the FIRO evaluation. Perfect forecast operations are simulated by using observations to mimic a perfect forecast.

Please note that PFO, SPFO, and NF are not considered viable alternatives for potential implementation but were simulated and evaluated to provide "bookends" on the potential benefits and risks of higher buffer pool elevations.

Table 4-6. *Candidate WCP alternative strategies from the Prado Dam FIRO HEMP.*

ID	Alternative Strategy	Description
1	WCM Unrestricted: 505 ft (baseline)	Buffer pool allowed to extend up to 505 ft without a seasonal restriction. Releases when the pool is ≤ 505 ft at maximum recharge rate. Releases above 505 ft are at the maximum scheduled rate. No forecasts are used, consistent with current (baseline) operations.
2 3 4 5 6	SFO-508 SFO-510 SFO-512 SFO-514 SFO-520	Volume-based method. Uses forecast ensemble mean inflow volumes (1-day, 2-, 3-, 4- and 5-day) to identify release volume needed to stay at or below 5xx ft. Uses forecast ensemble 10th percentile inflow volumes to identify a release volume needed to stay at or below spillway, potentially exceeding the maximum release schedule. Maximum recharge rate release when simulated elevation is below 5xx ft.

ID	Alternative Strategy	Description
		Uses derivatives of the ensemble inflow forecast (mean and range of non-exceedance percentiles of inflow volumes).
7 8 9 10 11	SPFO-508 SPFO-510 SPFO-512 SPFO-514 SPFO-520	Same as Alternatives 2-6 except observations are substituted for the forecast (Perfect Forecasts).
12 13 14 15 16	EFO-508 EFO-510 EFO-512 EFO-514 EFO-520	Buffer pool allowed to extend up to 5xx ft provided risk of exceeding 5xx ft is acceptable. Maximum recharge rate when risk is acceptable. Determines release required to mitigate risk of exceeding 5xx ft, airport (514 ft), and spillway (543 ft or 563 ft). Airport ignored in 520 ft case. Uses ensemble inflow forecast.
17 18 19 20 21	PFO-508 PFO-510 PFO-512 PFO-514 PFO-520	Same as Alternatives 12-16 except observations are substituted for the forecast (Perfect Forecasts). The risk curve is not needed because there is no tolerance for exceeding identified thresholds.
22 23 24 25 26	NF-508 NF-510 NF-512 NF-514 NF-520	Same as baseline but Buffer pool allowed to extend up to 5xx ft. No forecasts are used.

Note that the baseline operation (WCM 505 feet) is not a fair representation of current practice used by USACE LAD. In actual implementation of this plan, the USACE LAD does consider weather and water forecasts in their release decision making process. Informal and nonexplicit use of forecast information by USACE Districts is common where forecasts are available and of adequate skill. Capturing this somewhat subjective process is not, however, practical in a simulation environment.

Each of these alternatives was simulated with 543-foot and 563-foot spillway crests. The 26 alternatives combined with two spillway elevations results in 52 scenarios.

4.2 Reservoir Modeling Plan

Model development was required to simulate both reservoir operations and the potentially controlling influence of the OCWD recharge facilities. Ideally, reservoir releases are made at rates that can be fully recharged to the groundwater basin. Practically, there are times when flood control releases are needed that exceed the recharge capacity. This section describes the reservoir models developed for Prado Dam and the additional integrated modeling that guides releases associated with groundwater recharge.

4.2.1 Hydrologic Engineering Center Model for Prado Dam (SFO)

Hydrologic Engineering Center (HEC) staff developed a straightforward process for integrating available forecasts into release strategies that could be configured within the existing Reservoir System Simulation (ResSim) modeling framework. There are two alternatives depicting SFO scenarios, one using the GEFSv12 hindcasts (SFO) and one using perfect forecast information that is known to be perfect (SPFO).

4.2.1.1 Forecast Input

The SFO alternatives make use of the ensemble forecasts in a different way than the EFO. There are two strategies, one that is used when the starting storage is below the top of the Buffer Pool and one for when it is above the buffer pool. Release recommendations from the SFO are made with each forecast update. For the FVA, hindcasts were available on a daily basis.

The ensembles are first processed to compute volumes for increments of one day for each ensemble member (see Figure 4-2). Then, the mean across ensemble members, or a given percentile of the ensemble sample, is used to compute a release rule. Next, one-, two-, three-, four-, and five-day volumes are computed for each ensemble member, and the 10th percentile, the mean, and the 90th percentile of those volumes are used in decision making. Figure 4-2 shows the cumulative volumes for each ensemble member, as well as the mean, 10th percentile, and 90th percentile of each volume.

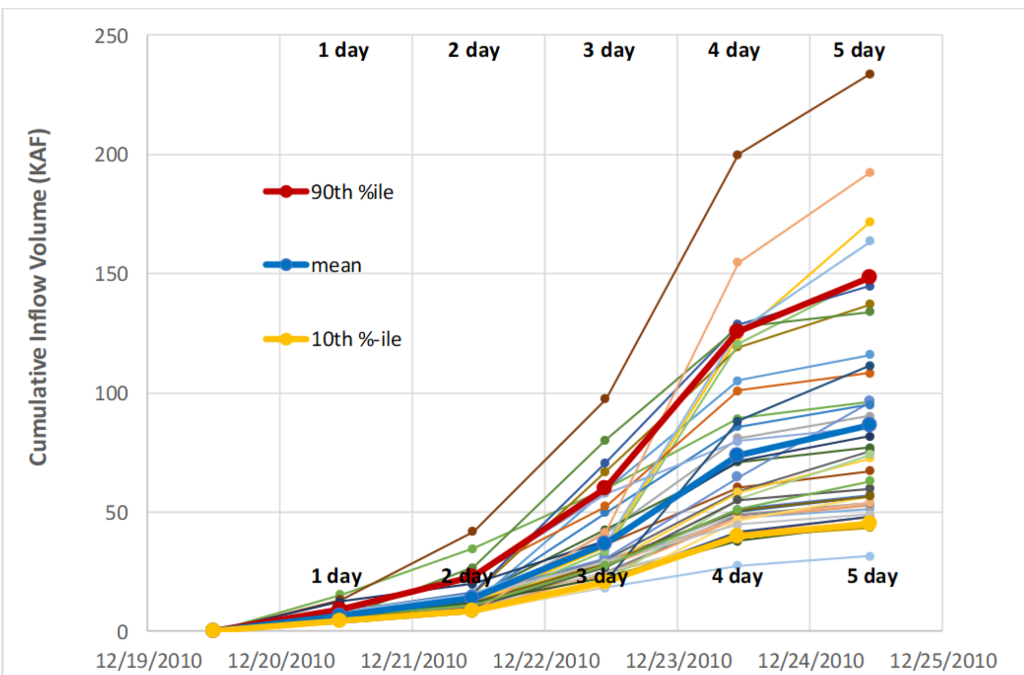


Figure 4-2. *Ensemble forecast cumulative volumes, one day through five days, from a scaling of the December 2010 event as used by the SFO model.*

4.2.1.2 Strategy

Simple volume computations create the forecast metrics upon which the release decisions are made.

Within the buffer pool, any expected volume that will not fit within current buffer pool space is released, at a rate that spans the volume's duration. The ensemble mean volume is used. For example, if the available space in the buffer pool is 10,000 ac-ft, and the mean two-day volume forecast is 15,000 ac-ft, then 15 - 10 = 5,000 ac-ft across two days = 1,262 cfs as the suggested release given that two-day duration.

The same computation is made for the one-, two-, three-, four-, and five-day volume durations, and the largest resulting release is chosen to release from the buffer pool. Figure 4-3 shows a graphic of this decision for the two-day duration.

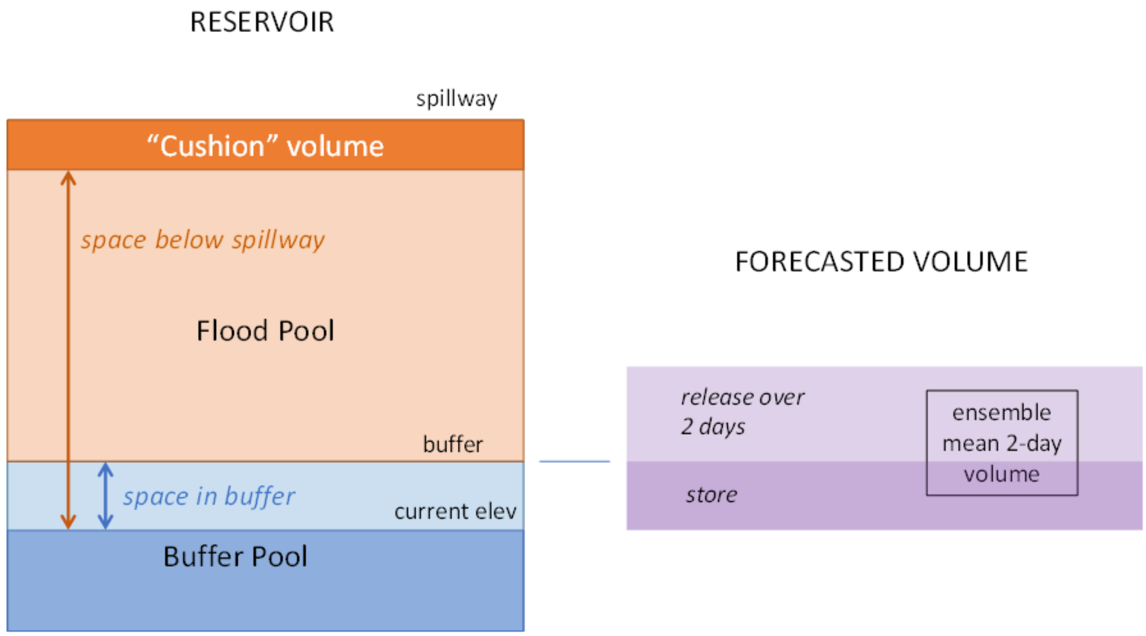


Figure 4-3. *Computed release while reservoir is in the buffer pool for two-day volume. Release also computed for one-, three-, four-, and five-day forecast volume.*

4.2.1.3 Buffer Pool Computation

Plan to store inflow volume that will fit below the top of the buffer (e.g., 505 feet), and release any volume that will not fit. Consider one-, two-, three-, four-, and five-day duration forecasted volumes (from start of forecast) using the ensemble mean:

volume to release = forecasted inflow volume − volume below top of buffer (space)
release rate = volume to release ÷ duration

Then, Compute the volume to release, and the release rate, for one-, two-, three-, four-, and five-day duration volumes. Choose the largest release of those five releases as the release to implement.

Within the flood pool, a similar computation is made, but with a different ensemble forecast metric. A release that may exceed the maximum flood release schedule (see Table 4-7 below) is defined as a "minimum" when a forecasted volume that has a high confidence of being exceeded does not fit below the spillway.

A minimum release (to achieve goal or avoid a problem) for each duration (one, two, three, four, and five days) is defined using percentile volumes that accommodate greater uncertainty with longer lead times. In Figure 4-3 above and Figure 4-4 below, the two-day percentile volume is 90 percent (having a 10 percent chance of being exceeded). Any portion of the volume that will not fit within a "cushion volume" from the spillway is released, at a rate that would span the volume's duration. The available storage space is compared to the percentile of the ensemble volumes for each of one-day to five-day durations, and the largest of the resulting needed releases is chosen. Therefore, the forecast uncertainty is parsed to ensure that a release exceeding the maximum flood release schedule (Table 4-7 below) is only made when there is an acceptable chance it is needed. Figure 4-4 depicts this release computation for the two-day volume. These values were chosen as reasonable starting points, objectively, and with good performance given the hindcasts for the period of hindcast record and scaled events. Additional sensitivity testing and refinement is warranted should this strategy be chosen for operational use.

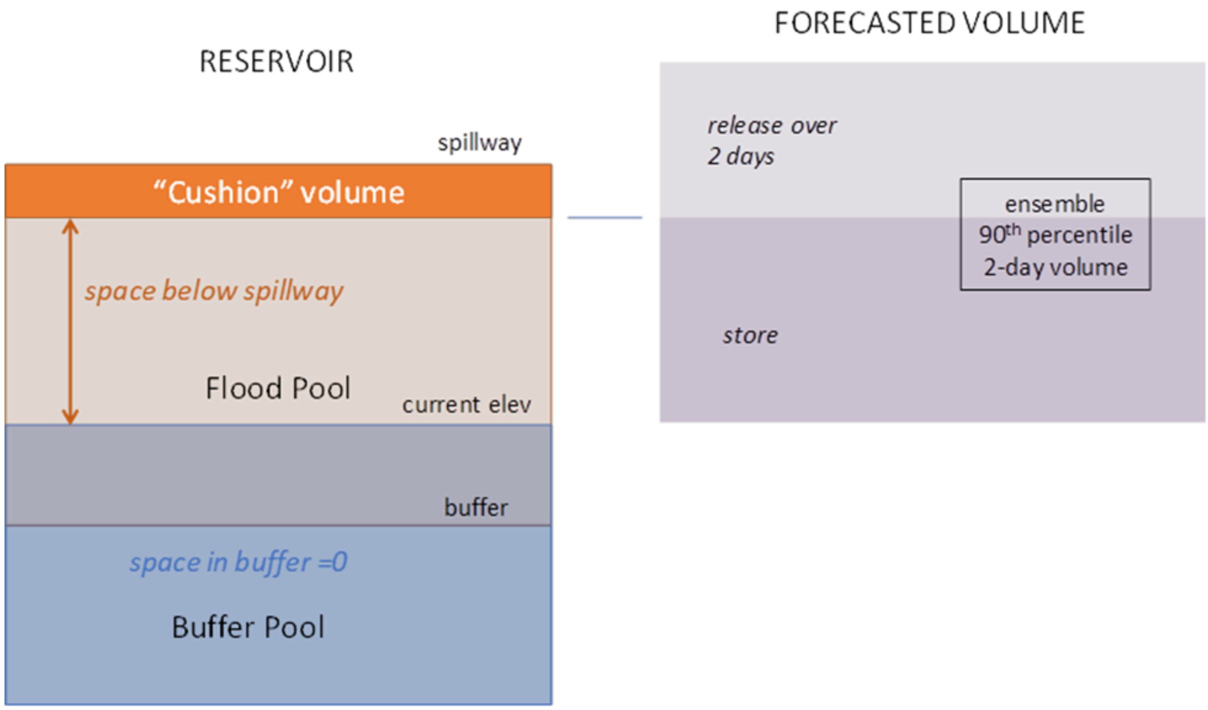


Figure 4-4. *Computed release while reservoir is in the flood pool for two-day volume. Release also computed for one-, three-, four-, and five-day forecast volumes.*

4.2.1.4 Flood Pool Computation

Plan to store the inflow volume that will fit below the spillway (or, below some cushion volume below the spillway) and release any that will not. Consider one-, two-, three-, four-, and five-day duration forecasted volumes (from start of forecast) using a non-exceedance probability that decreases with increasing lead time:

volume to release = forecasted inflow volume − volume below spillway minus cushion (space)
release rate = volume to release ÷ duration

For the results shown in Section 5, the non-exceedance probabilities selected for the one-, two-, three-, four-, and five-day volumes were 95, 90, 75, 50, and 25 percent, respectively. The results in Section 5 also reflect the selection of a "cushion" volume of 50, 000 ac-ft.

Compute the volume to release, and the release rate, for one-, two-, three-, four-, and five-day duration volumes. Choose the largest release of those five releases as the release to implement.

When the reservoir storage exceeds the Buffer Pool elevation, the release rate to bring the pool back down to the top of the Buffer Pool is guided by the WCM column in Table 4-7 below.

Note that another alternative was evaluated, in which another release limit was computed and applied. This second, lower release is intended to allow more use of the flood pool, thus decreasing release to the channel, and is based on the 90th percentile of the ensemble volumes (with 10 percent chance of being exceeded). The release is defined as a maximum, only releasing the volume that would not fit within the flood pool, and is based on a volume with a 10 percent chance of exceedance, providing a 90 percent chance it would in fact fit in the flood pool. The results including this maximum release in use are presented in Appendix B.

4.2.2 EFO Model for Prado Dam

The EFO model (Delaney et al. 2020) developed for Prado Dam is well documented in the PVA. The EFO model uses the full fidelity of the ensemble streamflow forecasts (through 15 days) to simulate an ensemble of projected reservoir storages with time that can be compared with the storage risk tolerance curve derived through calibration. The model identifies a recommended release that mitigates exceedances of the risk tolerance curve at all lead times. The model then considers release rules and physical constraints in order to refine the release. Release decisions are updated with each new forecast (daily).

The FVA EFO method is consistent with that used for the PVA, but there are key differences:

1. The risk tolerance curves were calibrated using the period of record hindcasts as well as the scaled hindcasts, as recommended in the PVA.
2. The EFO alternatives listed in Table 4-6 are "dual objective." Risk curves for exceeding the airport elevation (514 feet) and the spillway (543 feet or 563 feet) are both assessed with each forecast. The higher of the identified flows needed to mitigate the risk to the acceptable level is used to simulate operations until the next forecast cycle. An example EFO forecast using a scaled 200-year hindcast for February 19, 1998, is provided in Figure 4-5 below.

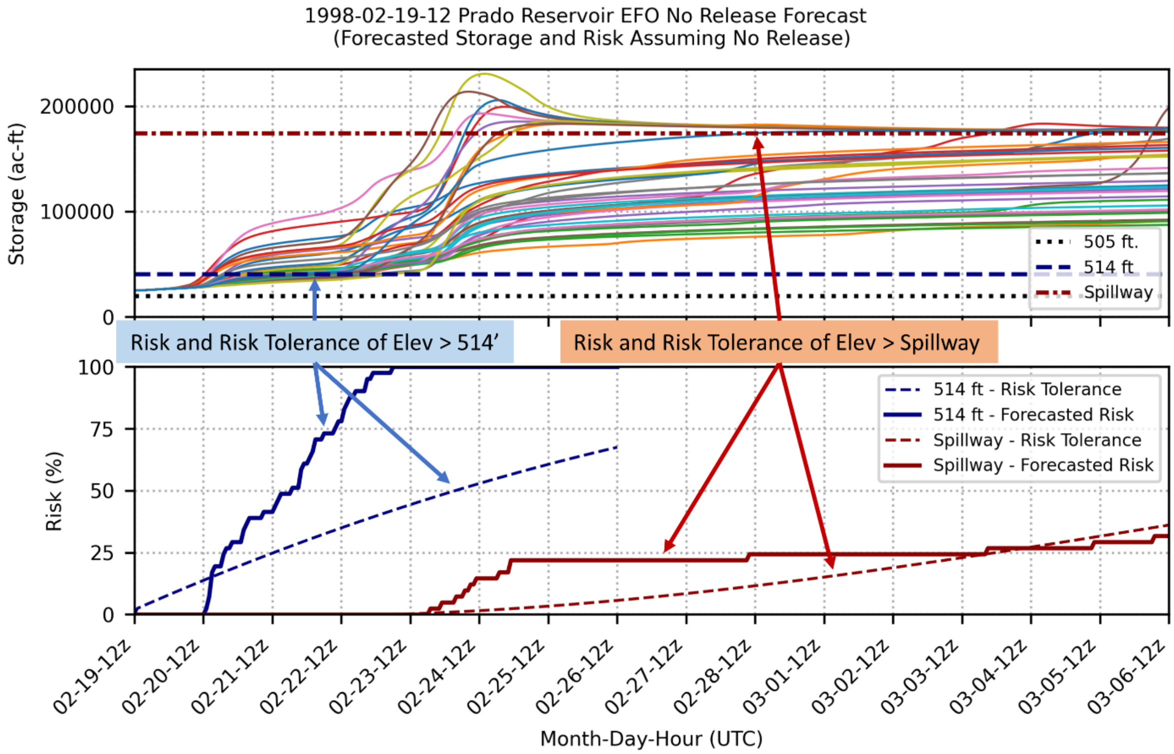


Figure 4-5. *Example EFO forecast for February 19, 1998, using the scaled 200-year hindcast prepared by the CNRFC.*

As with the SFO model, maximum releases are limited by the values shown in Table 4-7, and when risks are within acceptable bounds, the recommended release is consistent with the capacity of the recharge system to accept water (Section 4.2.4). When the reservoir storage exceeds the Buffer Pool elevation, the release rate to Table 4-7.

4.2.3 Reservoir Analysis Model for Prado Dam

HEC-ResSim was engineered to act as the "gate keeper" for all evaluated WCP alternatives as listed in Table 4-6. Passing the recommended releases through a common HEC-ResSim model ensured all alternatives were subject to the same constraints, which promoted an improved basis for comparison. Aside from basic information such as the storage elevation curve, spillway ratings, and outlet constraints, the maximum release schedule (Table 4-7) and the maximum release rate of change (Table 4-8) were enforced by HEC-ResSim during the simulations. "FIRO Pre-release for Spill" identifies the maximum release when the current forecast suggests that a spillway event needs to be avoided. "FIRO Pre-release for 514 feet" identifies the maximum release when the current forecast suggests that exceeding 514 feet (Corona Airport) needs to be avoided.

Table 4-7. *Prado Reservoir maximum release schedule for Interim WCM and alternative operations.*

Elevation (Feet, NGVD 29)	Maximum Release (cfs)		
	WCM (Non-FIRO)	FIRO Pre-release for Spill	FIRO Pre-release for 514 ft
470 to 490	600	600	600
490 to 505	5,000	10,000	5,000
505 to Top of Buffer Pool	5,000	10,000	5,000
Top of Buffer Pool to 514	10,000	10,000	5,000
514 to 520	15,000	30,000	n/a
520 to 540	25,000	30,000	n/a
>540	30,000	30,000	n/a

Note: Feet in elevation are measured based on the National Geodetic Vertical Datum of 1929.

Table 4-8. *Prado Reservoir rate of change constraints (increasing and decreasing).*

Release (cfs)	Rate of Change (cfs/hour)
0 - 300	200
300 – 1,000	500
1,000 – 2,500	800
2,500 - 5,000	1,250
>5,000	1,500

Alternatives 1–11 and 22–26 were simulated using HEC-ResSim. Alternatives 12–21 were simulated using the EFO model framework and then processed through HEC-ResSim to ensure they met all constraints.

4.2.4 Simulation of OCWD Diversions and Groundwater Recharge

The modeling needed to simulate operating the OCWD groundwater recharge facilities was developed for and documented in the Prado Dam PVA. For clarity, a brief description is provided here. For details, refer to PVA.

OCWD uses the Recharge Facilities Model (RFM) to simulate its recharge facilities for water supply planning. The RFM uses GoldSim software developed by Jacobs Engineering Group in 2009 and updated several times over the years. The model can handle complex operations with multiple rules and physical constraints to accurately simulate recharge operations on a daily time step. The complexities of the RFM made it awkward to integrate with the operations of the candidate WCPs.

Based on analysis of the OCWD RFM and input from OCWD staff, simulation of the recharge facilities operations was consolidated into four components: (1) Santa Ana River percolation; (2) the Anaheim, Warner, and Burris spreading basins; (3) the Santiago spreading basin; and (4) off-river systems. A simplified modeling framework was devised and parameterized using a 30-year RFM record. A comparison of results was performed for individual years and cumulatively over the full 30-year record. The results were remarkably close and deemed adequate for purposes of the PVA (see Figure 4-6).

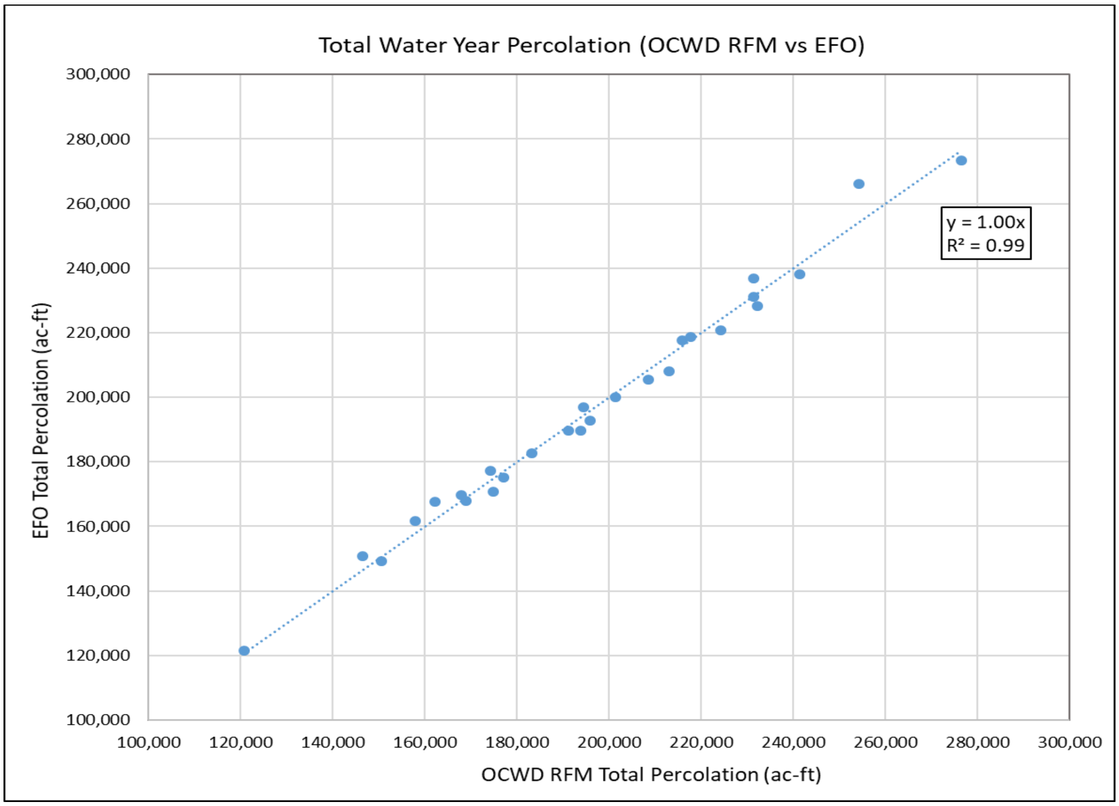


Figure 4-6. *Scatter plot of Prado Dam EFO model versus OCWD RFM total water year percolation. (From Prado Dam PVA).*

For the PVA, the percolation and recharge logic were integrated into the EFO framework. For the FVA, the logic was integrated into the HEC-ResSim model so it could be easily shared by both WCP modeling approaches (i.e., SFO and EFO).

4.3 Simulation Plan

The simulation plan defines and provides the observations and forecasts needed to simulate reservoir operations for each WCP identified in Table 4-6. Using forecasts complicates the WCP because, unlike observations, forecasts can be generated using any number of models and model sophistication, and they may or may not be available for the desired period of evaluation. This subsection describes the source of the model inputs (observations and forecasts) used to evaluate the FIRO WCPs, as well as the need to evaluate extreme events that are not adequately represented in the evaluation period of record.

4.3.1 Streamflow Observations

A primary input for simulating reservoir operations is the observed inflow into the reservoir. These data were provided by USACE for water years 1990 through 2019. The PVA noted that baseflows in the watershed above Prado Dam have declined by as much as 50 percent since the early 2000s due to water reuse and recycling by communities in the Prado watershed. Using historical data in the modeling work could overestimate the time to drain stormwater, which could affect buffer pool and potential environmental impacts. In response, the Water Resources Engineering (WRE) team created a revised historical time series of Prado Dam inflow that more closely reflects current baseflows. These revised observations were then provided to the CNRFC for recalibration of the hydrologic models that simulate inflow and generate the inflow hindcasts. The process used to revise the inflows is provided in Appendix B.

Natural flows downstream of Prado Dam to the OCWD diversion site on the Santa Ana River have not been consistently recorded. Gages have collected streamflow data at this location, but the period of record was not sufficient to be used for this study. Therefore, these natural flows were estimated by scaling flows recorded at the U.S. Geological Survey (USGS) gage Temescal Creek at Main Street (USGS 11072100). A scaling factor of 0.241 was calculated from the ratio of contributing watershed areas of these locations.

For reservoir modeling purposes, inflows to Prado Dam that were simulated using the CNRFC Community Hydrologic Prediction System (CHPS) model were used in lieu of the actual observations because the historical observations (adjusted for changes in baseflow) are only daily as opposed to hourly. Hourly flows are needed to properly simulate reservoir operations when the spillway is activated.

4.3.2 Streamflow Forecasts

Consistent with the PVA, streamflow forecasts from the CNRFC were selected for FVA evaluations. CNRFC streamflow forecasts are operationally available for the Santa Ana River watershed as both five-day deterministic values as well as 15-day ensembles. Both are generated using the CNRFC CHPS with common model parameters and states.

CHPS and the Hydrologic Ensemble Forecast System (HEFS), which is an ensemble generation within CHPS, are well-described in the PVA. The modeling framework used for the FVA was consistent with the PVA except for (1) CHPS recalibration based on additional historical data and the revised inflows as described in Section 4.3.1, and (2) a recalibration of HEFS based on the updated GEFSv12 reforecast from the National Centers for Environmental Prediction. The process for generating deterministic streamflow forecasts is shown in Figure 4-7 below. The process for generating ensemble streamflow forecasts is shown in Figure 4-8 below.

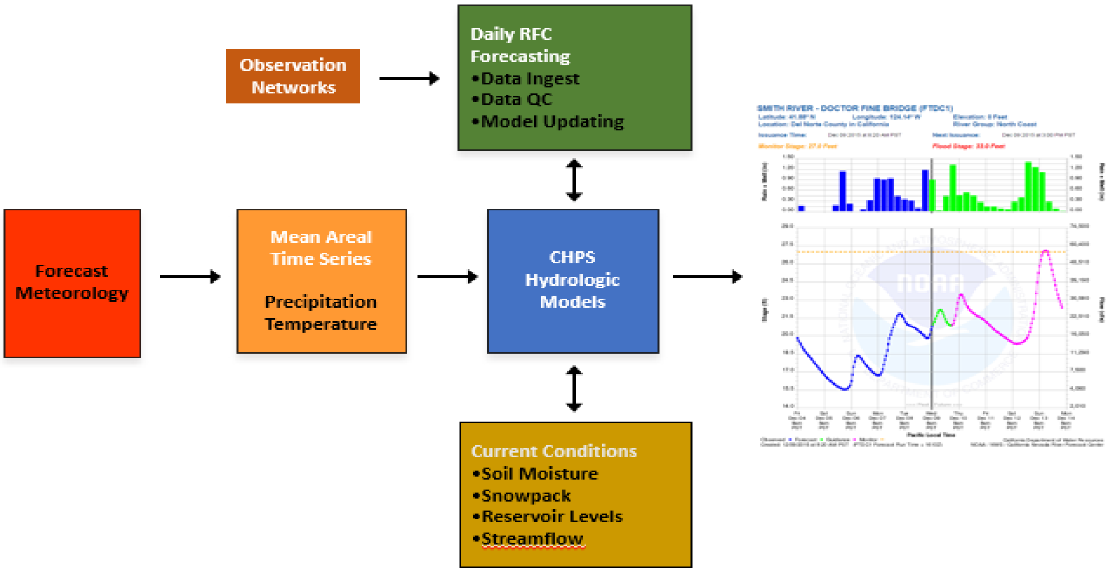


Figure 4-7. *Generalized forecast process used by the CNRFC to generate five-day deterministic streamflow forecasts.*

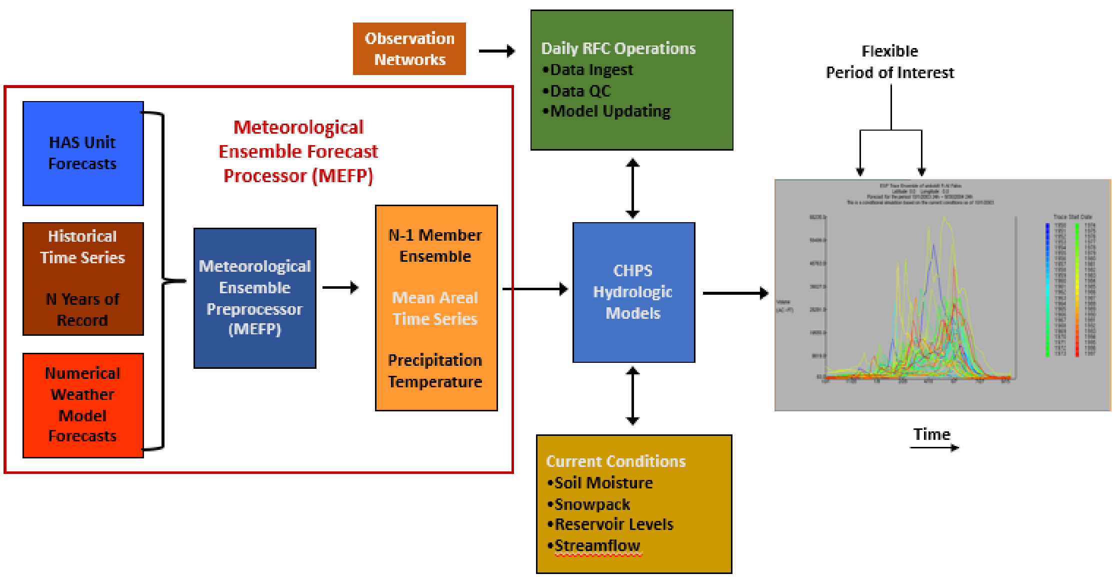
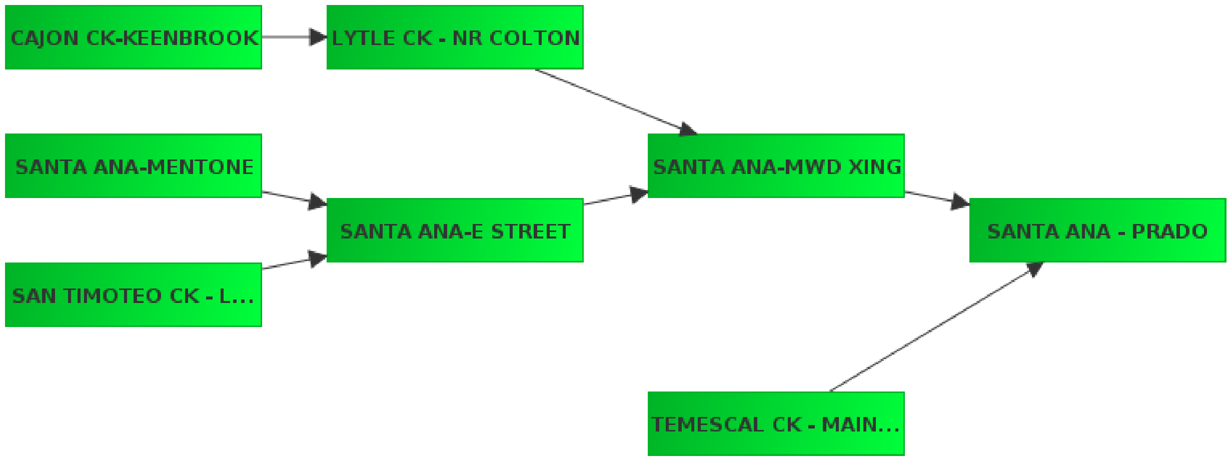


Figure 4-8. *CNRFC operational ensemble streamflow generation process (HEFS).*

The CNRFC model topology for simulating and forecasting the Santa Ana River watershed is shown in Figure 4-9 below. Seven Oaks Dam operations are not explicitly modeled and directly contribute to flow at Mentone, California. Potential contributions from the Lake Elsinore portion of the watershed were considered "non-contributing." Both these assumptions are reasonable for the purposes of this study.



Note: Current and archived river forecasts can be found on the CNRFC website (www.cnrfc.noaa.gov).

Figure 4-9. *CNRFC CHPS model topology for the Santa Ana River.*

4.3.2.1 Streamflow Hindcasts

The FVA evaluations used hindcasts generated with a HEFS and Meteorological Ensemble Forecast Processor calibration based on the GEFSv12 reforecast. Operational HEFS forecasts are likely to be slightly more skillful than the HEFS hindcasts for two reasons. First, in routine operations, there is an opportunity to tune model states and data before a forecast is generated (green box, Figure 4-8 above). In the hindcast process, the hydrology models are run without the benefit of review and tuning. Second, the operational HEFS ensembles use the Hydrometeorological Analysis and Support (HAS) weather forecaster's quantitative precipitation forecast (QPF) for the first three days, which has been shown to be slightly more skillful than the GEFS forecasts when evaluated during the overlapping period of record. Thus, the evaluations performed using the HEFS hindcasts reflect a conservative representation of forecast skill, and the results are therefore confidently transferable to actual operations. This distinction is important in reviews of model results because real-time operations may perform better than simulations due to this improved forecast skill.

Hindcasts are likely less skillful than operational forecasts because they don't benefit (1) from forecaster adjustments to (1) observations, (2) hydrologic model states, or (3) HAS Forecaster QPF for days 1-3. (Remove bright blue box (HAS Unit Forecast) and green box (Daily RFC Operations) from Figure 4-8).

The hindcast period of record generated for the WCP evaluations was 1990–2019. The ensemble forecasts, available daily throughout the period of record, had 41 members with a 15-day lead time. The daily issuance for the hindcast is another distinction from operations where deterministic and ensemble forecasts are available up to four times per day during extreme events.

4.3.2.2 Scaling of Extreme Events

The period of record hindcasts provide a limited timeframe to test reservoir management alternatives, and this period does not contain the Santa Ana River flood of record (1938).

Traditional USACE approaches of using historical information from the region to create synthetic events (e.g., storm centering) do not work well because of strong orographic influences; more importantly, they lack associated forecasts. To test the reservoir management alternatives under more extreme conditions than experienced within the hindcast period, scaled hindcasts were developed by the CNRFC to reflect the 100-, 200-, and 500-year three-day inflow volume to Prado Dam. Table 4-9 shows the three-day volume for the 100-, 200-, and 500-year design events provided by USACE LAD. The three-day period was selected through a "critical duration assessment" conducted by HEC in collaboration with the WRE team.

Table 4-9. *Three-day Prado Dam inflow volumes for 100-, 200-, and 500-year return frequencies.*

Return Frequency	3-day Inflow Volume
100-year	199,820 ac-ft
200-year	288,600 ac-ft
500-year	464,140 ac-ft

Nine scaled events were developed from the 1998, 2005, and 2010 flood events within the hindcast record. The 15-day duration scaled hindcasts were generated daily for each day of a 30-day period centered on the peak of the event. Event scaling factors were identified by increasing the observed precipitation until the model -simulated hydrograph reflected the desired three-day volume. Scaling of the precipitation was limited to the five-day period when precipitation was greatest. The scaling factor was applied to the precipitation ensembles generated by the Meteorological Ensemble Forecast Processor using the GEFSv12 ensemble mean during that same period of heaviest precipitation for each forecast day within the scaled hindcast period. The scaled ensemble precipitation time series were then processed through the CHPS modeling to generate the scaled streamflow ensembles for each forecast day. Figure 4-10 below compares the unscaled and scaled ensemble forecasts for the 2010 flood event. Because there are no actual observations for the scaled events, the flows simulated by CHPS were used as a surrogate. The scaled forecast for each day utilized the watershed conditions (initial model states) of the scaled simulation. Table 4-10 below provides the characteristics of the events that were scaled.

Note that all three of the events required substantial scaling of the precipitation to reach the return frequency three-day volumes shown in Table 4-9. A comparison of the observed and simulated maximum three-day volumes for each scaled event suggests the CHPS model works well but is not perfect.

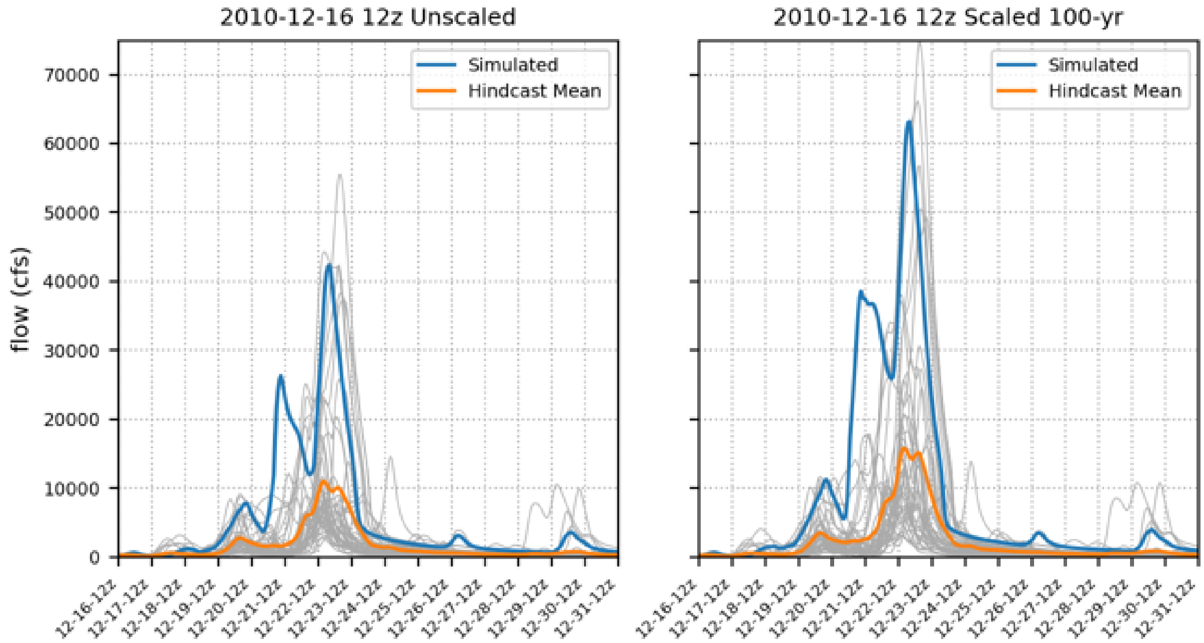


Figure 4-10. *Unscaled and 100-year three-day volume scaled ensemble forecasts for Prado Dam inflows for December 16, 2010. Simulated inflows are also included for reference.*

Table 4-10. *Selected hindcast periods for scaling to 100-, 200-, and 500-year three-day volumes.*

Scaled Event	Observed Max 3-day Volume (ac-ft)	Simulation Max 3-Day Volume (ac-ft)	Simulation Start	Simulation End
February 1998	69,461	81,054	2/9/1998	3/9/1998
January 2005	131,068	120,652	12/26/2004	1/25/2005
December 2010	106,907	119,351	12/7/2010	1/7/2011

Close examination of the 1998 scaled event revealed an inconsistency between the scaled and unscaled hindcast ensembles. Note that the 1998 scaled event was significantly under-forecast by the GEFSv12. As the event was scaled-up to 100-, 200-, and 500-year three-day volumes for the simulation, the scaled ensembles became significantly more biased. Ultimately, WRE developed a corrective process that forced the scaled and unscaled hindcast ensemble mean to have the same relationship with the simulated flow. While the corrections for the 2005 and 2010 scaled events were small, they were applied in the same way for consistency. The procedure, as well as the corrected and uncorrected ensembles, are provided in Appendix B. Note that this inconsistency has been identified in other FIRO evaluations and calls for investigations and development work to refine the representation of extreme events for WCP testing. Figure 4-11 below provides An example of the adjustments made to the scaled events.

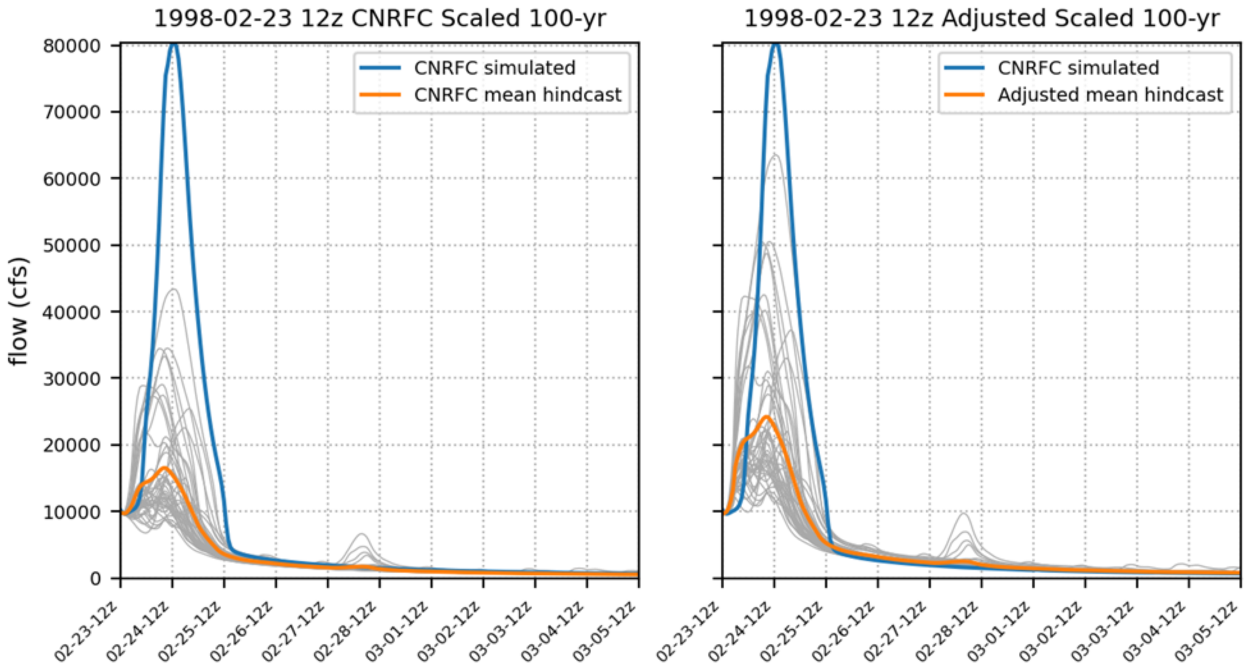


Figure 4-11. *Comparison of uncorrected (left) and corrected (right) ensemble streamflows for the 1998 event at the 100-year three-day volume level. Forecast date is February 23, 1998.*

Reservoir storage at the beginning of each scaled event hindcast simulation was set at the top of the buffer pool for the alternative being simulated. While this scenario is historically unlikely, it avoids the complications of integrating "incidental storage capacity" into the performance of the alternative strategies.

4.3.2.3 Perfect Forecasts

Two of the five WCP alternatives were simulated using "perfect forecasts." To mimic a perfect forecast, the observation time series was substituted for all ensemble members. HEFS was not used to generate the perfect forecasts used to simulate these alternative WCPs.

4.3.3 Simulation Plan Summary

Table 4-11 shows the body of hindcasts and observations developed for the evaluation and testing of the WCP alternatives in Table 4-6 above.

Table 4-11. *Hindcasts and observations used to evaluate WCP alternatives.*

Forecasts	Observations
POR (1990-2019) ensemble hindcasts	Adjusted for current baseflow conditions
Scaled 100-year ensemble hindcasts for 1998, 2005, and 2010	CHPS simulated to match 3-day volume
Scaled 200-year ensemble hindcasts for 1998, 2005, and 2010	CHPS simulated to match 3-day volume

Forecasts	Observations
Scaled 500-year ensemble hindcasts for 1998, 2005, and 2010	CHPS simulated to match 3-day volume

4.4 Potential Post-FVA Refinements

The weakest part of the evaluation strategy for the FVA relates to scaling events during the hindcast period of record. This scaling is necessary because there aren't any archived forecasts or hindcasts large enough to challenge the designed flood risk management objectives of Prado Dam. It is recommended that work continue on two fronts. First, the procedures to scale events in the hindcast period of record need to be evaluated and potentially sharpened. Second, early work on synthetic ensemble forecast generation based on a calibration of HEFS appears promising and has the potential to yield a much better foundation for rigorous WCP evaluations.

4.5 References

Delaney, C. J., Hartman, R. K., Mendoza, J., Dettinger, M., Delle Monache, L., Jasperse, J., Ralph, F. M., Talbot, C., Brown, J., Reynolds, D., & Evett, S. (2020). Forecast Informed Reservoir Operations using ensemble streamflow prediction for a multipurpose reservoir in Northern California. *Water Resources Research, 56*(9).

Section 5. Evaluation of FIRO Water Control Plan Alternatives

This section describes the process through which the five Water Control Plan (WCP) alternatives were simulated and evaluated. The alternatives, described in detail in Section 4 (Table 4-6), are:

- SFO (Simpler Ensemble Forecast Operations).
- SPFO (SFO with perfect forecasts).
- EFO (Ensemble Forecast Operations).
- PFO (EFO with perfect forecasts).
- NF (no forecast used).

The baseline alternative for comparison is a 505-foot buffer pool operation that does not consider forecasts. This is a surrogate for existing operations—though it does not fully replicate Los Angeles District (LAD) operations, because LAD considers multiple sources of information, including inflow forecasts, in its release decisions. Note that PFO, SPFO, and NF are not considered viable alternatives for potential implementation; they were simulated and evaluated to provide “bookends” on the potential benefits and risks of higher buffer pool elevations.

For each of the five WCP alternatives, five higher buffer pool operations (508, 510, 512, 514, and 520 feet) were simulated and evaluated. The perfect forecast simulations were completed to understand the maximum potential benefits. The NF simulations were completed to better define the relationship between buffer pool elevation and the onset of flood risk management (FRM) impacts. The 520-foot buffer pool is not likely to be a viable alternative given potential impacts on infrastructure, such as Corona Municipal Airport (514 feet) and Euclid Avenue (515 feet); however, it was evaluated to assess the maximum amount of groundwater recharge that could be obtained. Charts that include the 520-foot buffer pool are not included in this section but can be found in Appendix B.

The simulation plan described in Section 4.3 called for:

- Simulation of the period of record of the ensemble streamflow hindcasts (1990–2019).
- Simulation of historical data and hindcasts for February 1998, January 2005, and December 2010 scaled to 100-year, 200-year, and 500-year three-day inflow volume magnitudes.

In addition, the simulations of each WCP alternative run were configured with and without the Prado Dam spillway raise (543 feet and 563 feet).

A complete graphical summary of the results is provided in Appendix B.

The goals of this assessment were to:

- Gain refined insight on the range of benefits and potential impacts of FIRO for Prado Dam.

- Gain insight on the types of WCP alternatives and magnitude of buffer pools that may be appropriate for consideration in future WCM updates.

WCM updates are a U.S. Army Corps of Engineers (USACE) process. Accordingly, the findings and recommendations from this assessment are intended to inform, assist, and complement USACE efforts to include use of FIRO tools to update WCPs for future WCM updates. Additionally, given the timeline of the SARM project, these studies can serve to inform "alternative operation options" and the configuration of potential planned deviations from the approved WCP. Activities associated with this effort are described in Section 8.

5.1 High-Level Key Findings

- On average, forecast-informed reservoir strategies for elevations of 508 to 512 feet are estimated to yield 4,000 to 6,000 acre-feet (ac-ft) per year of additional groundwater recharge. Increasing the maximum elevation to 520 feet results in an *additional* average recharge of 6,000 ac-ft per year.
- Over the range of the hindcast period (1990–2019) and for scaled events (100-, 200-, and 500-year three-day volume), forecast-informed strategies (EFO and SFO) have a slight positive impact on flood risk management outcomes associated with reservoir spill and releases in excess of channel capacity for all buffer pools tested up to 520 feet.
- The selection of the buffer pool can affect the frequency of inundation at elevations of 514 feet and 520 feet, but all forecast-informed strategies at all buffer pools perform better than the baseline WCM when considering the frequency of exceeding 520 feet. The change in the inundation frequency of Corona Airport (514 feet) for EFO and SFO with buffer pools up through 512 feet is insignificant compared to baseline WCM operations.
- The environmental impacts of the tested alternatives at all buffer pool elevations appear to be negligible but need careful evaluation.
- The models and processes described in Section 4.2 were successful in simulating Prado Dam operations for the hindcast period of record and for scaled extreme events for the twenty-six alternatives listed in Table 4-6 and two spillway elevations (543 feet and 563 feet).
- Scaled events were needed to assess the effectiveness and impacts of the alternatives on flood risk management outcomes above elevations of 520 feet (no simulated spills in the period of record simulations).

Table 5-1 summarizes the evaluation outcomes for each of the WCP alternatives for the 543-foot spillway. The alternatives are described in Table 4-6, while the metrics are described in Table 4-5. The table provides some insight into how the alternatives compare, but a more detailed assessment is needed to understand how each alternative performed. This assessment is presented in Sections 5.2, 5.3, and 5.4. An identical table for the 563-foot spillway and additional graphics associated with each of the metrics and both spillway elevations can be found in Appendix B.

Table 5-1. *Outcomes for each evaluated WCP alternative (Table 4-6) for the metrics described in Table 4-5.*

Alternative	Metric (Table 4-5)											
	FRM			ENV					FRM/ENV		MAR	
(Table 4-6)	M1p	M1s	M2s	M3	M4	M5	M6	M7	M8	M9	M10	M11
WCM	1.84	34,288	544.2	2.14	2.09	0.87	0.58	0.33	0.19	0.05	106.7	45.8
508-NF	1.66	35,295	544.3	2.04	21.60	1.95	0.92	0.54	0.26	0.06	109.2	43.3
508-SFO	1.61	30,000	541.2	1.98	20.80	1.21	0.63	0.41	0.21	0.03	108.6	43.9
508-EFO	1.77	30,000	541.2	2.03	21.36	1.81	0.76	0.44	0.22	0.03	109.2	43.4
510-NF	1.50	36,348	544.5	1.79	26.88	18.45	1.80	0.77	0.35	0.06	111.1	41.5
510-SFO	1.48	30,090	541.7	1.85	26.28	17.66	1.10	0.53	0.27	0.04	110.5	42.0
510-EFO	1.73	30,000	541.8	1.79	26.48	17.47	1.54	0.57	0.28	0.03	110.9	41.6
512-NF	1.32	37,328	544.7	1.77	31.89	24.42	18.67	1.61	0.50	0.07	113.0	39.6
512-SFO	1.36	30,114	542.1	1.82	31.64	23.75	17.73	0.93	0.35	0.05	112.5	40.1
512-EFO	1.46	30,037	542.1	1.65	31.11	23.14	17.02	1.16	0.34	0.04	112.6	40.0
514-NF	1.16	37,915	544.8	2.25	37.35	29.19	23.71	17.55	1.23	0.09	114.7	37.8
514-SFO	1.25	30,252	542.6	1.82	36.98	28.88	23.05	16.56	0.69	0.06	114.2	38.3
514-EFO	1.31	30,000	542.0	2.04	33.48	25.64	20.23	12.68	0.67	0.04	113.4	39.1
520-NF	0.92	44,350	545.6	3.25	48.92	43.10	38.84	33.97	28.57	0.87	119.9	32.5
520-SFO	1.02	35,221	544.4	3.25	48.91	43.13	38.87	34.07	28.12	0.39	119.7	32.8
520-EFO	0.97	30,629	542.6	3.25	47.29	41.56	37.18	31.31	25.60	0.39	119.1	33.3

Note: Spillway elevation is 543 feet. M1p is the days/year > 5,000 cubic feet per second (cfs); M1s and M2s are taken from the 200-year scaled simulations and represent maximum release (cfs) and maximum reservoir elevation (feet). M3–M9 are average days per year. M10 and M11 are average volumes per year (1000 ac-ft/year). The colors describe how the alternatives vary from least (red) to most (green) desirable. FRM is Flood Risk Management, ENV is Environmental, and MAR is Managed Aquifer Recharge.

5.2 Flood Risk Management

The key FRM metrics identified in the hydraulic engineering management plan were the frequency of annual maximum water surface elevation and the frequency of annual maximum release from Prado Dam. more specifically, a negative FRM outcome is defined as an increase in the frequency of spillway use and/or an increase in the frequency of release in excess of the downstream channel capacity relative to the baseline WCM. a positive FRM outcome is defined as a decrease in the frequency of spillway use and/or a decrease in the frequency of release in excess of the downstream channel capacity relative to the baseline WCM. As described in Section 4.3, 100-year, 200-year, and 500-year scalings were simulated for three events within the hindcast period of record. These analyses were combined with the period of record analysis to create frequency plots that extended to the 500-year level.

Frequency graphics (maximum water surface elevation and discharge) for each buffer pool elevation (508 feet to 520 feet) and the two spillway elevations (543 feet and 563 feet) can be found in Appendix B.

Figure 5-1 below shows the frequency of annual maximum reservoir elevation for buffer pools of 508 to 520 feet with the 543-foot spillway elevation. As the figure shows, there are only very subtle differences in maximum annual reservoir elevation between the NF, EFO, and SFO alternatives. As expected, the difference between the baseline WCM and the alternatives increases as the buffer pool elevation increases. Note that the difference is only evident between about a three-year and 20-year return period. Below this, the events are not large enough to create pool elevations above 505 feet. Above this, the storage strategies of the alternatives are overwhelmed by the magnitude of the events. The lower right graph "zooms into" the 512-foot buffer pool maximum elevation frequency chart between two- and 20-year return periods. It shows that, with respect to annual maximum reservoir elevation:

- All 512-foot buffer pool alternatives (without perfect forecasts) increase the annual maximum pool elevation frequency over the baseline WCM (505 feet with no forecasts).
- NF 512 feet has the highest increase in annual maximum reservoir elevation frequency.
- EFO 512 feet and SFO 512 feet result in annual maximum reservoir elevation frequencies that are quite close.

The trend described above holds for all evaluated buffer pool elevations. While they do not strictly constitute an FRM outcome, there are impacts to Corona Airport and Euclid Avenue when the pool rises above 514 feet. The lower right plot in

Figure 5-1 shows a small increase in the frequency of exceeding 514 feet with the EFO and SFO alternatives, but it is very slight and likely related to the maximum release rates applied in the WCM alternative (Table 4-7). This small increase disappears for buffer pools at or below 510 feet (no impacts to the frequency of reaching 514 feet).

With a 543-foot spillway, the 200-year scaled events reach or nearly reach the spillway. The 563-foot spillway results are the same except that the spillway is reached only with the 500-year scaled events (see Appendix B). Spillway flows for these extreme events are slightly greater for the NF and WCM alternatives, suggesting that the FIRO alternatives provide some positive FRM benefits at all buffer pools evaluated.

One of the key reasons that the alternatives behave similarly for the larger and scaled events is the size of the buffer pool(s) in relation to storage available above them. Table 5-2 shows the reservoir storage at the evaluated buffer pool elevations in addition to the storage at the 543-foot and 563-foot spillway elevations. In comparison to the total reservoir storage, the buffer pools are small. In addition, the 200-year three-day volume (Table 4-9) is larger than the storage capacity at 543 feet and the 500-year three-day volume (Table 4-9) is larger than the storage capacity at 563 feet. Despite an aggressive maximum release schedule (Table 4-7) and prereleases (even down to streambed), the reservoir still spills regardless of the operation. This suggests that the scaled events evaluated cover the range associated with the design capacity of the dam.

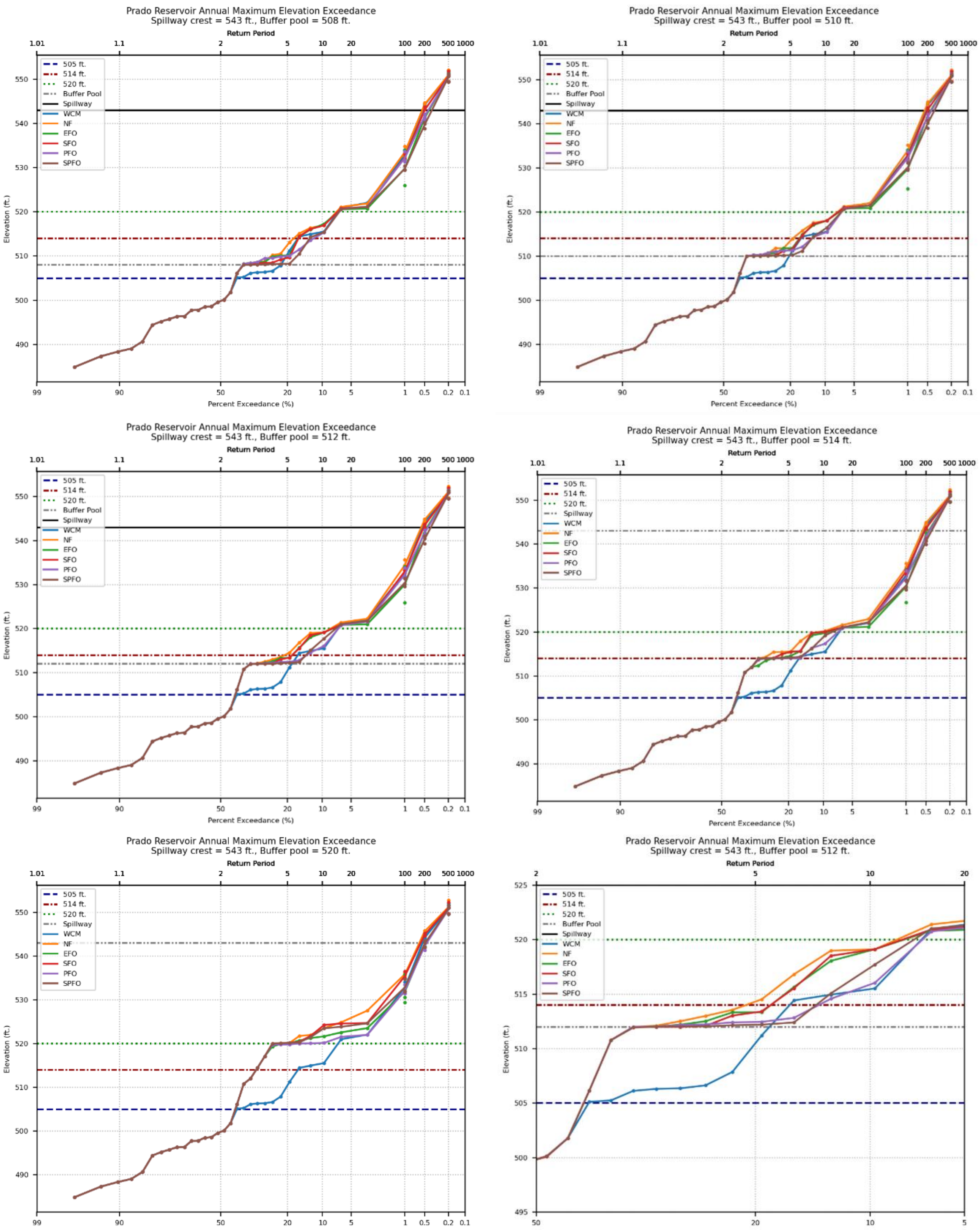


Figure 5-1. *Annual maximum reservoir elevation (feet) for Prado Dam plotted as annual exceedance probability, assuming a 543-foot spillway configuration and buffer pools of 508 to 520 feet. Lower right is an inset of 512-foot buffer pools between 50 and 5 percent exceedance probability.*

Table 5-2. *Prado Dam reservoir storage at considered buffer pool elevations and at the existing (543-foot) and planned (563-foot) spillway elevations.*

Elevation (ft)	Storage (ac-ft)	Storage Above 505 ft (ac-ft)	Percentage of 543 ft Storage	Percentage of 563 ft Storage
505	19,987	0	11.5	6.0
508	25,919	5,932	14.9	7.7
510	30,376	10,389	17.4	9.1
512	35,211	15,224	20.2	10.5
514	40,493	20,506	23.2	12.1
520	59,391	39,404	34.0	17.7
543	174,172	154,185	100.0	51.9
563	335,323	315,336	192.5	100.0

In addition to the maximum annual reservoir level, it is important to look at the frequency of the annual maximum reservoir release. Figure 5-2 shows the frequency of annual maximum reservoir release (cfs) for buffer pools of 508 to 520 feet with the 543-foot spillway elevation.

From Figure 5-2 we again see there are only very subtle differences in maximum annual reservoir release between the NF, EFO, and SFO alternatives. While small, the EFO and SFO alternatives have slightly lower maximum releases when the spillway is reached or nearly reached when compared to the NF and WCM alternatives. This represents a positive FRM outcome.

The most significant differences are again found in the middle of the plots. The lower right plot in Figure 5-2, below, "zooms into" the 512-foot buffer pool case between two- and 20-year return intervals. Here the baseline WCM reaches 10,000 cfs more often, primarily because of the discharge assumptions in Table 4-7. Other alternatives either have the benefit of forecasts or a higher buffer pool to limit the release to 5,000 cfs. This is more of an idiosyncrasy of Table 4-7 rather than representative of existing operations, in which decisions to increase releases above 5,000 are carefully considered. We can also see that the NF alternative reaches higher releases more often than the alternatives that use forecasts.

Along with maximum pool elevations and downstream discharges, the days of inundation at 514 feet and 520 feet are of interest. Figure 5-3 shows the average number of days per year above 514 feet (left) and 520 feet (right) for each of the alternatives from the period of record (1990–2019) simulations. The 520-foot buffer pool is omitted from Figure 5-3 below because its frequency overwhelms the others. Since the 543-foot spillway was never reached for non-scaled events, the results of the 563-foot spillway are nearly identical (also included in Appendix B).

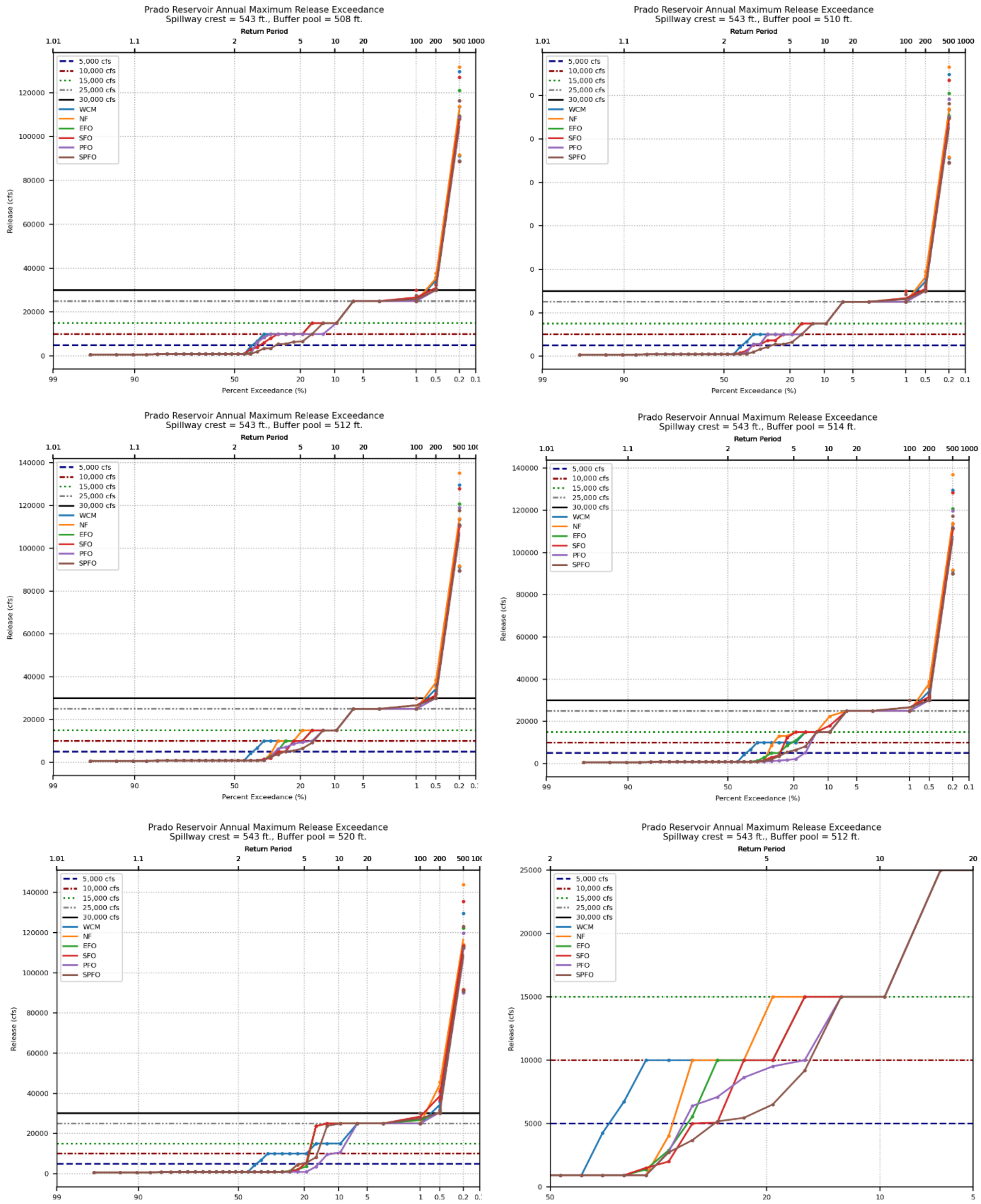


Figure 5-2. *Annual maximum reservoir release (cfs) for Prado Dam plotted as annual exceedance probability, assuming a 543-foot spillway configuration and buffer pools of 508 to 520 feet. Lower right is an inset of 512-foot buffer pools between 50 and 5 percent exceedance probability.*

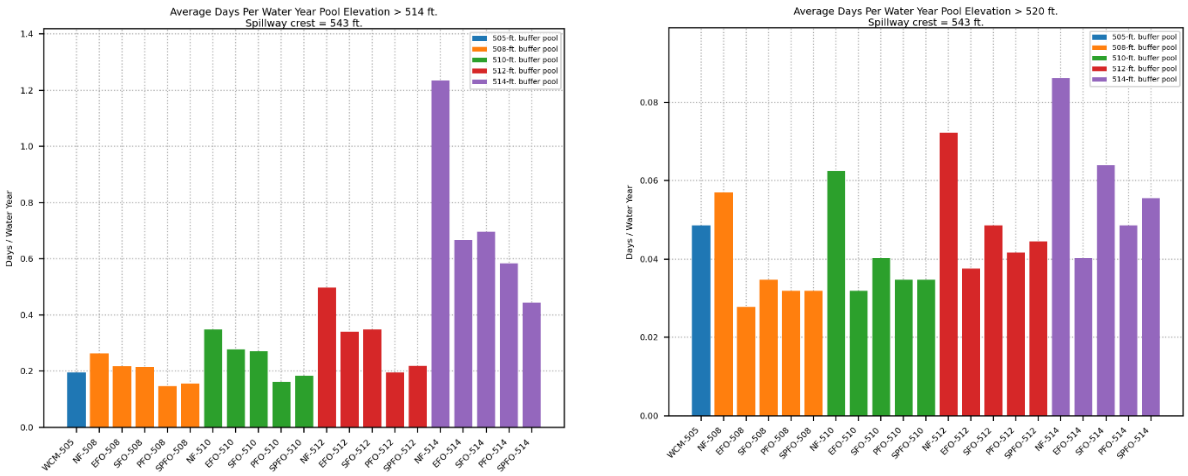


Figure 5-3. *Average number of days per year that Prado Reservoir surface water exceeds 514 feet (left) and 520 feet (right) for each of the alternatives during the period of record (1990–2019) simulation (543-foot spillway).*

The values are quite small (0.2 days/year is six days over the 30-year period), but there are differences between the alternatives. The NF approach consistently exceeds both 514 feet and 520 feet more commonly than the other alternatives. Note also that all approaches (other than NF) reach 520 feet less often than the baseline WCM, even for buffer pools up to 512 feet. Interestingly, the alternatives that use forecasts seem to do as well as those that use perfect forecasts when looking at the rate exceeding 520 feet. This phenomenon has been seen in other studies and has been attributed to the "margin of safety" afforded by the uncertainty in the forecast.

As noted earlier and as evident in

Figure 5-1, the frequency of reaching 514 feet is slightly greater for all alternatives that do not rely on perfect forecasts with buffer pools above 505 feet primarily because of the maximum release constraints shown in Table 4-7. This condition is not present for the 520-foot threshold, as all alternatives are permitted to release at higher rates (Table 4-7). Figure 5-3 supports the earlier conclusion that EFO and SFO alternatives up through 510 feet do not impact the frequency of Corona Airport inundation relative to the baseline WCM. Further, it appears that at 512 feet, the change is not significant.

It is also important to consider and review the performance of each alternative when presented with extreme events. The performance of each alternative for each of the scaled events is provided in Appendix B. Figure 5-4 below shows the 2005 event scaled to the 200-year level for the 512-foot buffer pool and 543-foot spillway.

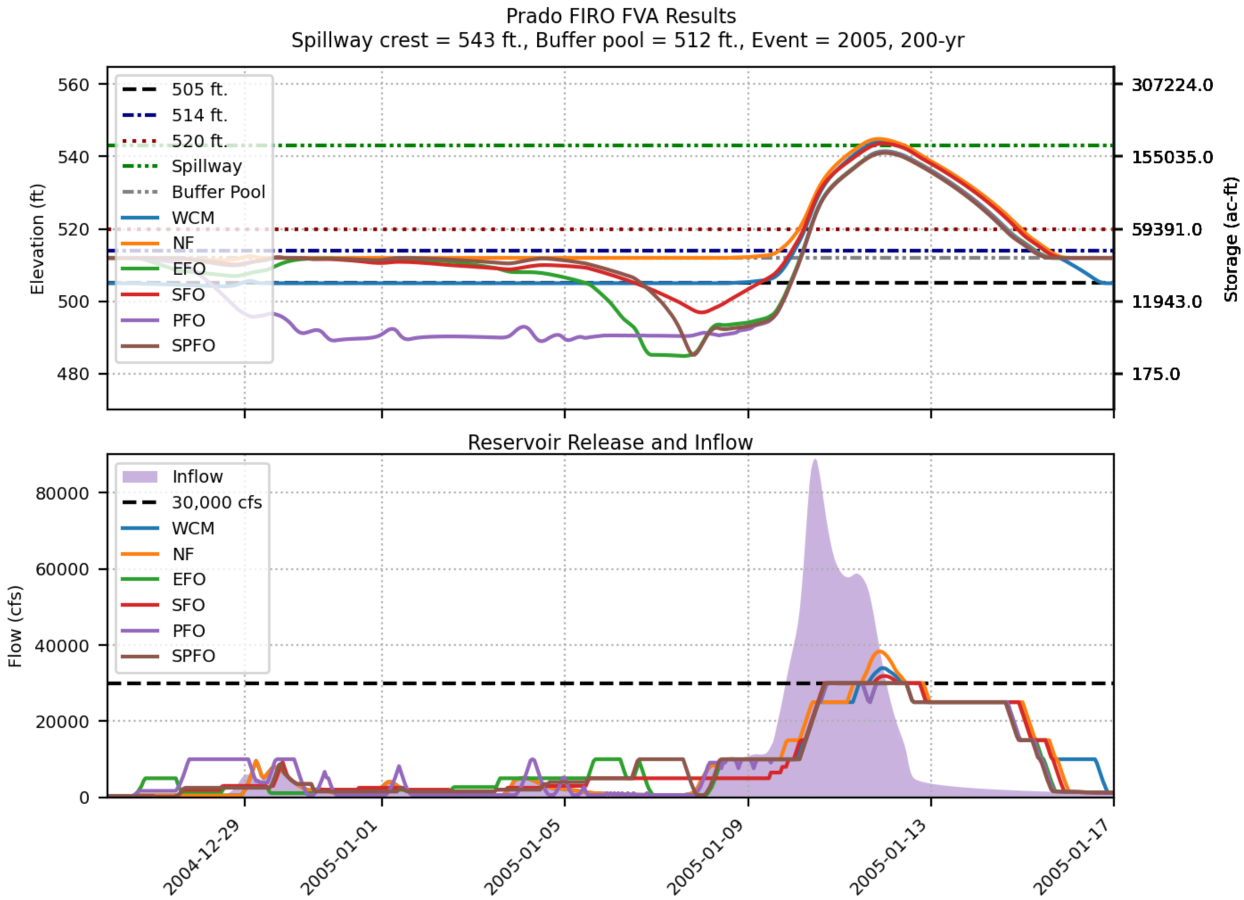


Figure 5-4. *2005 event scaled to a 200-year three-day volume with a 512-foot buffer pool and 543-foot spillway.*

Note that the NF-512 has the highest spillway flow with smaller spillway flows from baseline WCM and SFO-512 and no spillway flow for EFO-512. Note also that all alternatives resort to releasing 30,000 cfs at some point during the event. The spillway flows shown here are considered "minor," but it is acknowledged that any spillway flow is undesirable for this project.

Figure 5-5 below shows the 2005 event scaled to the 500-year level for the same 512-foot buffer pool and the 543-foot spillway. Here we can see that the inflows effectively overwhelm all the alternative WCPs because even a total evacuation of reservoir storage (see PFO storage) is not enough to control the inflows within the reservoir. As opposed to the minor spillway flows shown in Figure 5-4, the spillway flows are major and would result in very significant damage downstream of the dam. Note that the NF and baseline WCM alternatives begin spillway flow before the EFO and SFO alternatives, but all alternatives have similar peak reservoir releases.

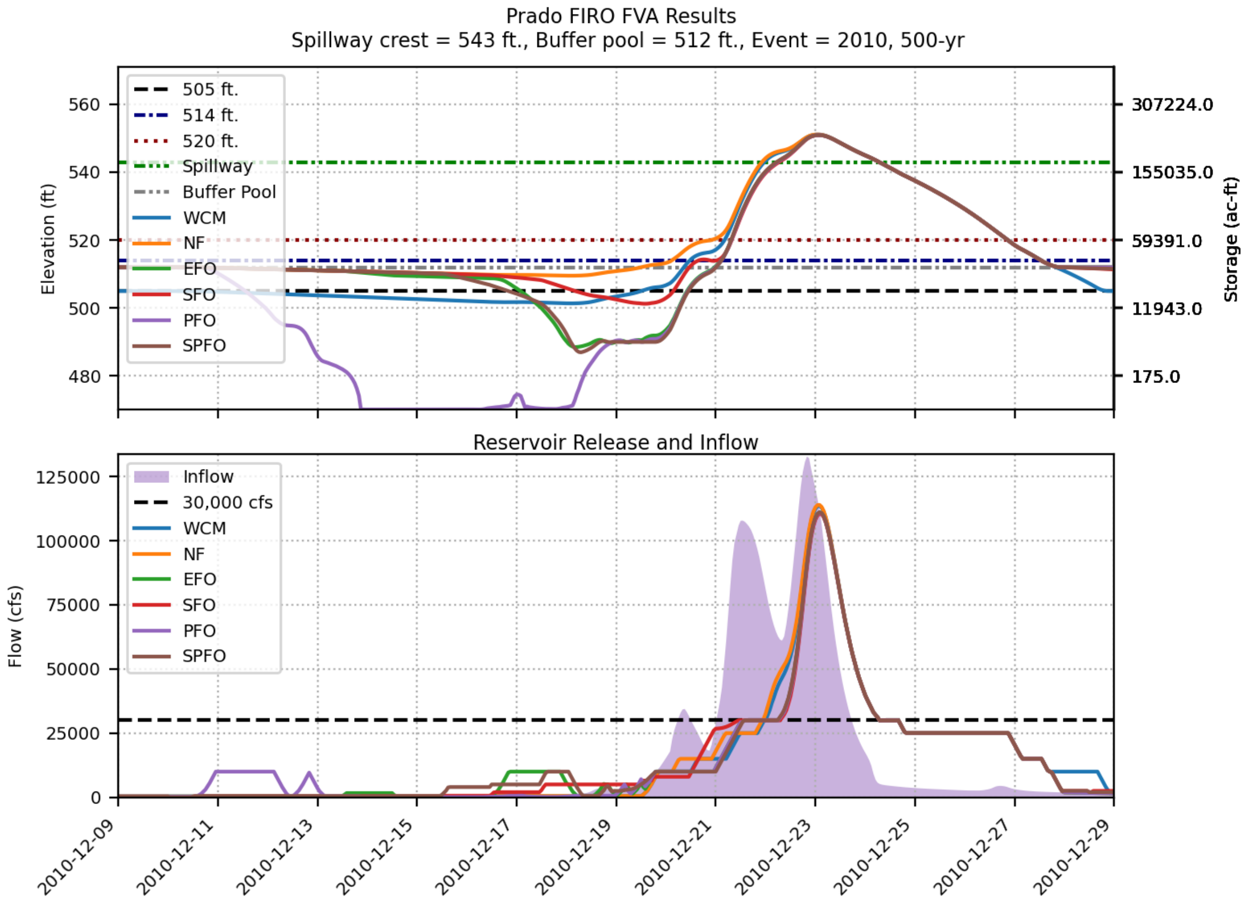


Figure 5-5. *2005 event scaled to a 500-year three-day volume with a 512-foot buffer pool and 543-foot spillway.*

Figure 5-6 below shows the 2005 event scaled to the 500-year level for the 512-foot buffer pool but with the 563-foot spillway. Here we can see all alternatives except baseline WCM and NF-512 evacuate storage in advance of the event, but the reservoir still fills to the spillway elevation. Only the perfect forecast alternatives and EFO alternatives with buffer pools less than 514 feet manage to avoid exceeding the spillway elevation. Again, these spillway flows are considered "minor," acknowledging that any spillway flow is undesirable for this project.

Appendix B provides identical graphics for all scaled events (1998, 2005, and 2010) at 100-, 200-, and 500-year levels for each buffer pool elevation (508 feet to 520 feet) and both spillway elevations (543 feet and 563 feet). The 563-foot spillway elevation and taking to 566 feet are based on the engineering analysis developed for the SARM project and are not subject to reconsideration by virtue of the analysis performed as a part of this FVA.

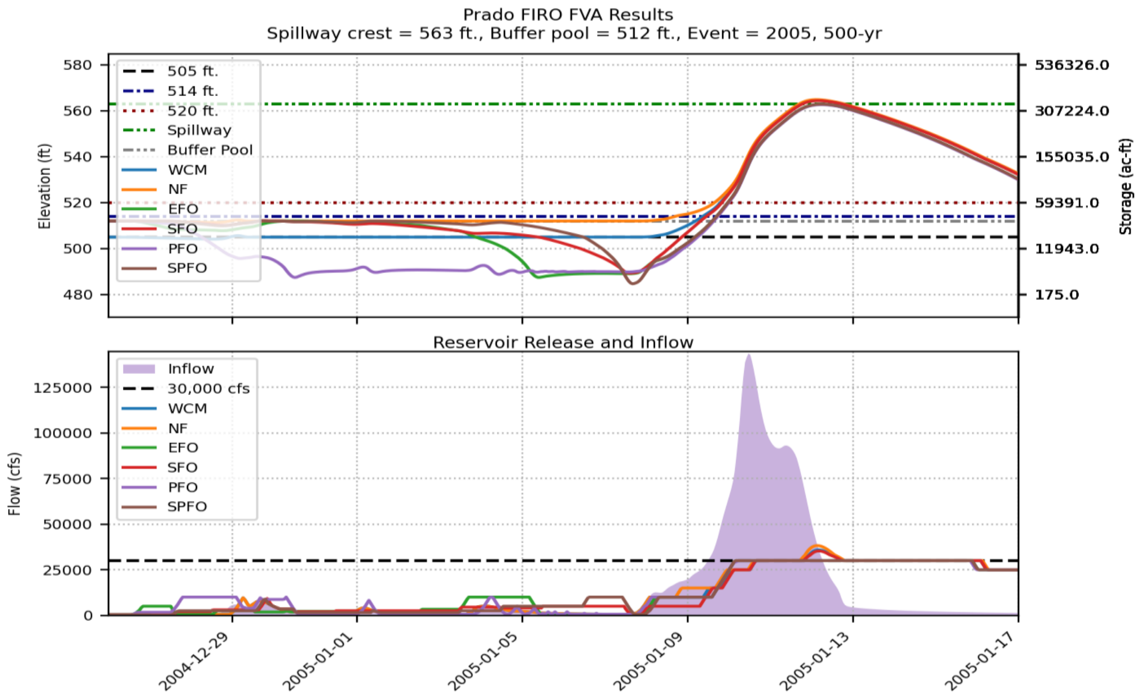


Figure 5-6. *2005 event scaled to a 500-year three-day volume with a 512-foot buffer pool and 563-foot spillway.*

5.2.1 Key Findings

From the assessments conducted, the following can be stated with respect to flood risk management objectives and alternative performance:

- The period of record simulations generated no spillway flows or channel capacity releases for any of the evaluated alternatives. This is consistent with the historical operation of Prado Dam, which has not reached the spillway elevation since construction.
- Scaled events were needed to assess the effectiveness and impacts of the alternatives on flood risk management outcomes (avoid total releases greater than 30,000 cfs).
- In the domain of extreme events (100-, 200-, and 500-year three-day volume simulations), there are only modest differences between the alternatives with respect to maximum reservoir elevation, spillway flows, and maximum reservoir release. But EFO and SFO (all buffer pools) reduce spillway flows and releases greater than channel capacity compared to baseline WCM operations.
- 200-year three-day volume simulations create minor spillway flows for baseline WCM, all NF, SFO-520, and EFO-520 with a 543-foot spillway elevation.
- 500-year three-day volume simulations create major spillway flows for all alternatives with a 543-foot spillway elevation.
- 500-year three-day volume simulations create minor spillway flows for baseline WCM, all NF, SFO-514, EFO-514, SFO-520, and EFO-520 with a 563-foot spillway elevation.

5.3 Groundwater Recharge Metrics

The evaluation described here is based on the 1990–2019 hindcast period of record simulations for each alternative for the 543-foot spillway configuration. None of the alternatives reached the spillway elevation of 543 feet during the period of record simulations, so it follows that they would not reach 563 feet either. Nevertheless, simulations of spillway elevations of 563 feet were completed, and the associated figures can be found in Appendix B alongside those for 543 feet.

As described in Section 4, optimal groundwater recharge is accomplished by releasing water from storage at or below the rate that can be diverted and recharged into the groundwater basin. When release rates exceed the maximum diversion or percolation rate, the excess release is uncaptured and is lost to the ocean. Alternatives with larger buffer pools that reduce the frequency of releases greater than what can be diverted or recharged will achieve better recharge results. Figure 5-7 compares average annual groundwater recharge for the alternatives and buffer pools with the baseline WCM.

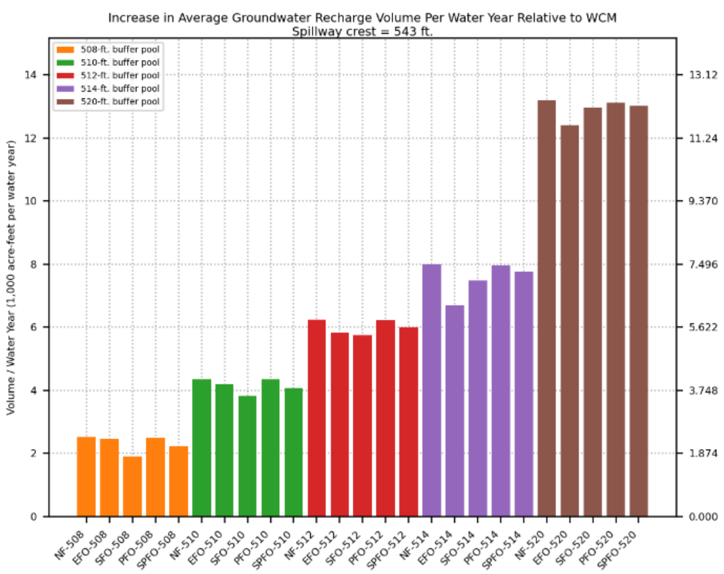


Figure 5-7. *Improvement in groundwater recharge over the baseline WCM alternative. From a 1990–2019 simulation with a 543-foot spillway.*

Figure 5-7 shows that larger buffer pools yield greater groundwater recharge and that, above 508 feet, each foot of buffer pool yields about 1,000 ac-ft per year of additional recharge on average. Figure 5-7, does not, however, show the important details associated with the intermittent opportunities for enhanced recharge. For example, in most years, the alternatives make no difference because there is no opportunity to fill the buffer pool. In other years, the buffer pool might be filled and drained several times. Figure 5-8 shows the frequency of groundwater recharge for the baseline WCM and the EFO and SFO alternatives with buffer pools ranging from 508 feet to 520 feet.

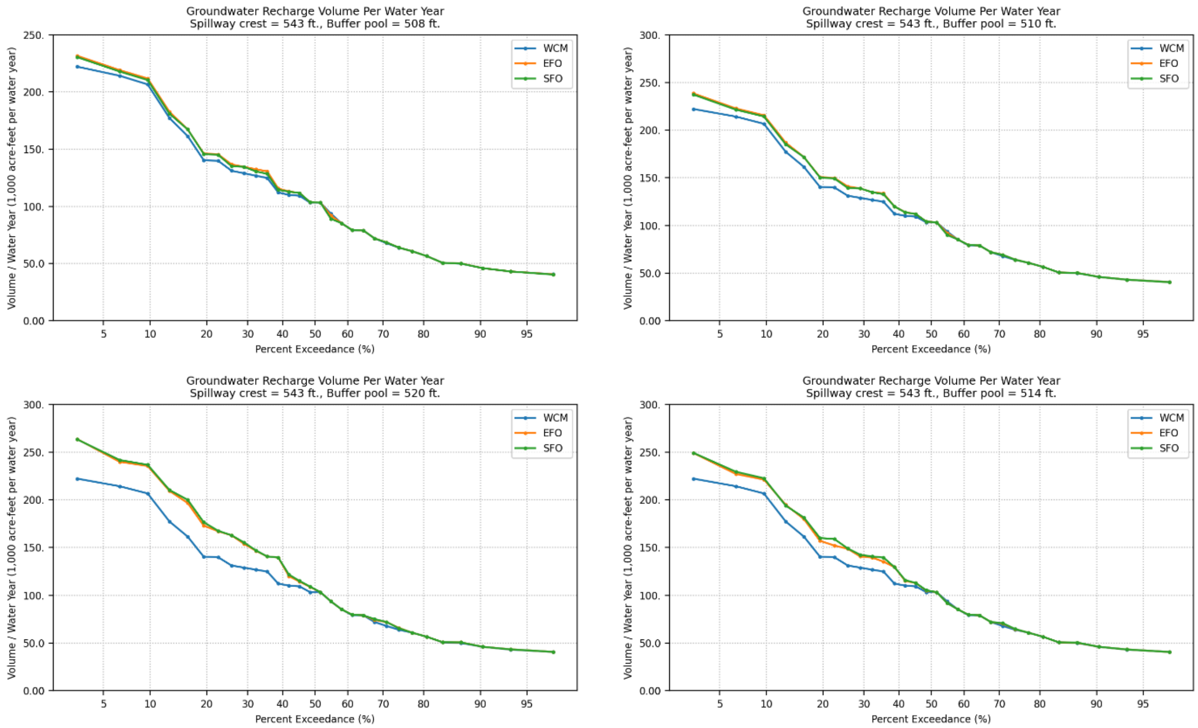


Figure 5-8. *Frequency of annual groundwater recharge with buffer pools ranging from 508 feet to 520 feet. This figure Compares baseline WCM with EFO and SFO alternatives for a 543-foot spillway crest (563 feet is essentially the same).*

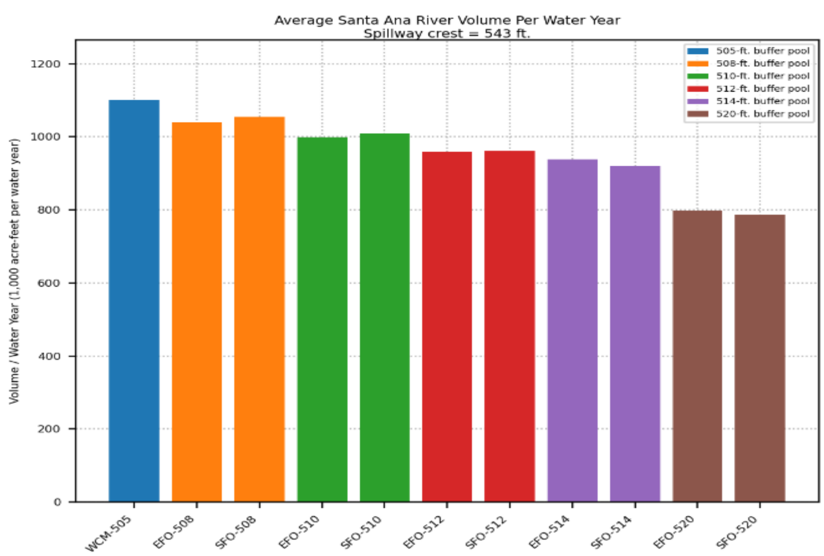


Figure 5-9. *Average Santa Ana River discharge to the Pacific Ocean per water year in 1,000 ac-ft per year. Only SFO and EFO alternatives compared with WCM baseline. From 1990-2019 simulation and 543 ft spillway.*

From Figure 5-8 shows that, in 50 percent of the years, there is no difference in groundwater recharge between the alternatives at any buffer pool because the reservoir inflow was insufficient. the difference begins to emerge in wetter years and becomes larger with larger buffer pools. Here the key factor seems to be filling the buffer pool at least once during the winter season —although, for the wettest years, the downstream recharge system capacity becomes the limiting factor.

Figure 5-9 below shows the average volume of Santa Ana River water that is *NOT* recharged into the groundwater basin. This is a result of releases (and local flows) that exceed the diversion and recharge capacity of the system at that time. Here only the WCM baseline, SFO, and EFO alternatives are shown across buffer pools of 508 feet to 520 feet. Consistent with other findings, increasing the buffer pool results in greater recharge compared to the WCM baseline and results in less water lost to the ocean.

Table 5-3 below lists the year-by-year total groundwater recharge as well as the difference in recharge from the baseline WCM for the EFO and SFO alternatives with 508-, 510-, 512-, and 520-foot buffer pools.

Table 5-3. *Annual percolation volumes for WCM and SFO and EFO alternatives at buffer pools from 508 feet to 520 feet. Mean water year percolation volumes and mean increases from baseline WCM are shown in bottom rows in ac-ft and percent. Color coding scales highest (green) to lowest (red).*

	Water Year Percolation Volume (ac-ft)										
Water Year	WCM	SFO-508	EFO-508	SFO-510	EFO-510	SFO-512	EFO-512	SFO-514	EFO-514	SFO-520	EFO-520
1990	72,026	72,040	72,026	72,040	72,026	72,040	72,026	72,040	72,026	72,040	72,026
1991	110,095	114,532	115,679	119,935	119,921	124,541	124,532	129,546	129,543	147,114	146,698
1992	140,451	145,900	146,340	150,380	150,822	155,668	152,927	160,076	152,143	162,933	162,850
1993	214,285	217,982	219,198	221,565	222,791	225,384	225,929	229,454	227,173	241,786	239,904
1994	112,281	112,919	113,079	113,758	113,935	114,735	114,766	115,901	115,122	121,648	120,015
1995	177,369	181,087	182,818	185,166	186,906	189,444	191,172	193,996	194,847	210,358	209,412
1996	109,355	111,759	111,757	112,025	112,023	112,430	112,427	112,933	112,835	115,053	114,348
1997	124,903	130,651	130,676	134,933	134,975	139,613	139,613	139,622	139,621	139,651	139,643
1998	206,726	210,547	211,881	214,378	215,687	218,463	219,784	222,694	221,263	236,773	235,530
1999	67,876	68,555	68,600	69,178	69,215	69,919	69,959	70,808	70,262	75,021	74,124
2000	79,074	79,074	79,074	79,074	79,074	79,074	79,074	79,074	79,074	79,074	79,074
2001	93,633	89,217	92,028	90,092	92,028	90,924	92,028	91,795	92,028	93,633	93,633
2002	40,709	40,400	40,604	40,468	40,604	40,528	40,604	40,589	40,604	40,709	40,709
2003	128,983	134,592	134,628	138,839	138,885	140,654	140,654	140,654	140,654	140,654	140,654
2004	79,148	79,364	79,357	79,532	79,525	79,592	79,592	79,592	79,592	79,592	79,592
2005	222,240	230,563	231,737	237,383	238,592	244,307	245,569	249,285	249,117	263,402	263,749
2006	103,335	103,796	103,779	104,130	104,116	104,490	104,477	105,322	104,908	109,176	108,797
2007	43,058	43,123	43,121	43,164	43,162	43,200	43,199	43,237	43,223	43,347	43,351
2008	103,300	103,300	103,300	103,300	103,300	103,300	103,300	103,300	103,300	103,300	103,300
2009	85,343	85,343	85,343	85,343	85,343	85,343	85,343	85,343	85,343	85,343	85,343
2010	131,223	135,246	136,776	139,414	140,970	144,019	145,599	149,094	148,724	167,565	167,113
2011	161,463	167,342	167,359	171,735	171,745	176,456	176,452	181,456	179,850	200,041	196,742
2012	63,899	64,008	63,978	64,168	64,136	64,356	64,311	64,672	64,517	65,486	65,795
2013	46,020	46,020	46,020	46,020	46,020	46,020	46,020	46,020	46,020	46,020	46,020
2014	50,657	50,657	50,657	50,657	50,657	50,657	50,657	50,657	50,657	50,657	50,657
2015	60,808	60,808	60,808	60,808	60,808	60,808	60,808	60,808	60,808	60,808	60,808
2016	56,587	56,587	56,587	56,587	56,587	56,587	56,587	56,587	56,587	56,587	56,587
2017	126,851	128,483	132,525	132,762	133,717	137,412	134,567	142,484	135,260	155,372	153,942
2018	49,987	50,050	50,169	50,188	50,206	50,340	50,232	50,497	50,254	50,874	50,829
2019	139,891	145,076	145,548	149,314	149,781	153,915	154,374	158,935	157,071	176,575	173,016
MEAN	106,719	108,634	109,182	110,545	110,919	112,474	112,553	114,216	113,414	119,686	119,142
INC from WCM		1,915	2,462	3,825	4,199	5,755	5,833	7,496	6,695	12,967	12,423
% INC MEAN		1.8%	2.3%	3.6%	3.9%	5.4%	5.5%	7.0%	6.3%	12.2%	11.6%

5.3.1 Key Findings

The period of record (1990–2019) simulations and analysis indicate that:

- Opportunities to improve groundwater recharge are tied to the prevailing hydrology, with enough water occurring in about half of the years.
- Recharge improvements with FIRO occur in years when the inflow is above average and the buffer pool is filled at least one time.
- In general, greater buffer pools lead to greater recharge, but forecasts are needed to avoid negative impacts to flood risk management outcomes above 508 feet.
- In general, strategies that leverage perfect forecasts perform better than those that use hindcasts. (Forecast skill improvements will lead to improved results.)
- In general, the EFO and SFO approaches provide for very similar recharge across the range of buffer pools tested.
- The average annual gain from implementing FIRO at 508 to 512 feet ranges from 4,000 to 6,000 ac-ft per year.
- The average annual gain from implementing FIRO at 520 feet is about 12,000 ac-ft per year.

5.4 Environmental Metrics

The key environmental concerns identified through the PVA are associated with least Bell's vireo habitat. Repeated long-duration inundation (especially in the spring) could affect the health of the riparian forest in the buffer pool. At the same time, infrequent inundation of the riparian forest can provide substantial habitat benefits associated with vegetation health, species recruitment, and insect production. The analysis provided here is based on the period of record hindcast analysis, not the scaled events. Since the alternatives did not reach the 543-foot spillway crest during the period of record analysis, only the 543-foot results are discussed and shown here. Figures associated with the analysis of the 563-foot spillway configuration are included in Appendix B.

Figure 5-10 below compares the number of days of inundation above 505, 508, 510, 512, 514, and 520 feet for the EFO and SFO alternatives. NF and perfect forecast alternatives were omitted here for the sake of simplicity. Charts that include NF and perfect alternatives can be found in Appendix B.

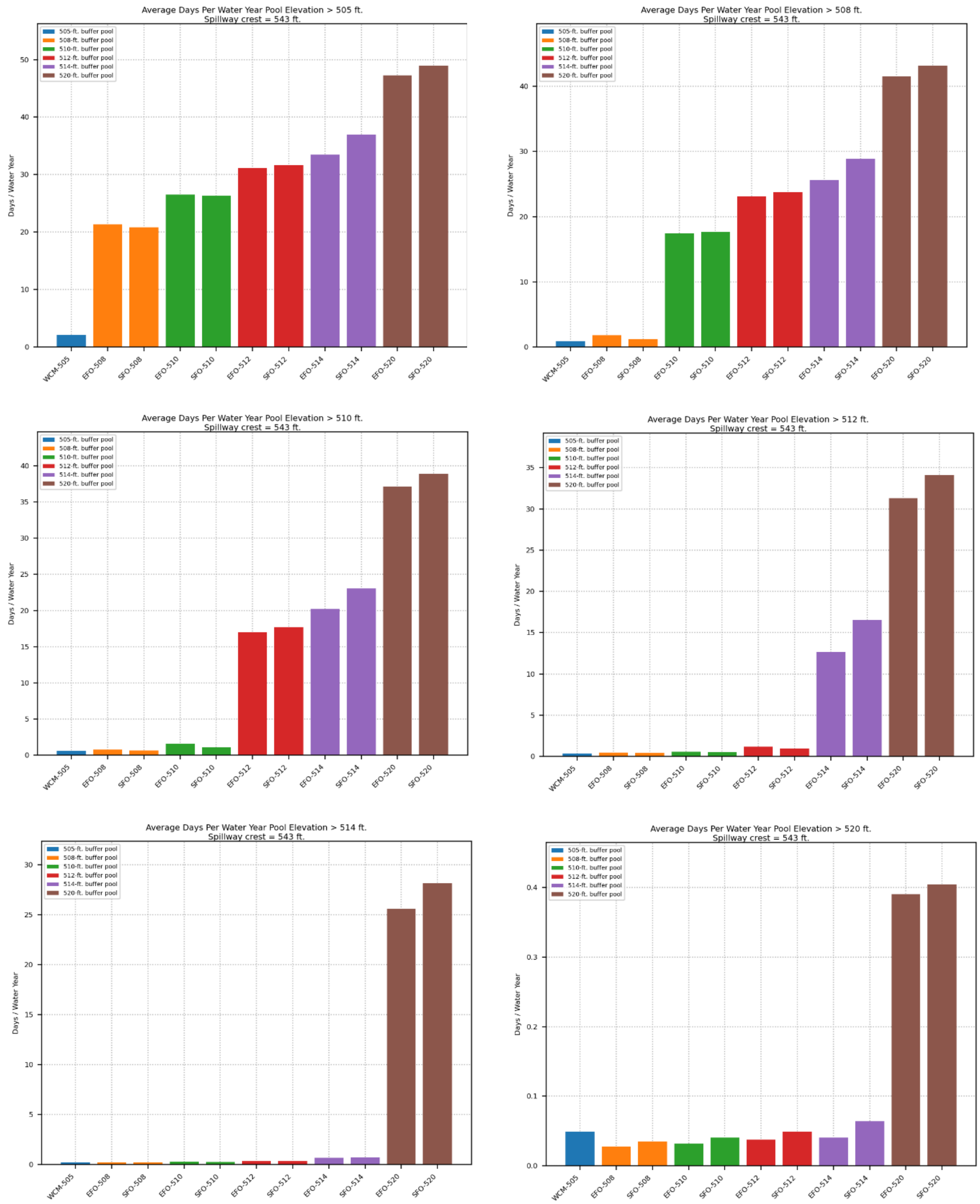


Figure 5-10. *Average number of days of inundation above the elevation shown (505 feet to 520 feet) for the baseline WCM operations and EFO and SFO alternatives with buffer pools of 508 feet to 520 feet. note that the scale of the charts is not consistent: in particular, the scale for the 520-foot chart (lower right) reflects a very rare exceedance of the 520-foot level within the 1990–2019 period.*

Figure 5-10 shows that the selection of the buffer pool elevation tends to severely limit the number of days per year that the reservoir elevation exceeds that level. It also indicates that higher buffer pools lead to more frequent inundation of vegetation within the buffer pool. Although higher buffer pools result in more inundation, this inundation will occur infrequently, as there is only enough water to fill the buffer pools half of the time

Figure **5-1**).

In addition, when vireos return to nest in the riparian forest in the spring, their nests could be damaged by reservoir rises, as they prefer to nest about 1 meter above the water surface elevation. Figure 5-11 compares the frequency of reservoir elevation rises greater than 1 meter within the March 21–May 1 period for the 543-foot spillway elevation during the simulation period of record.

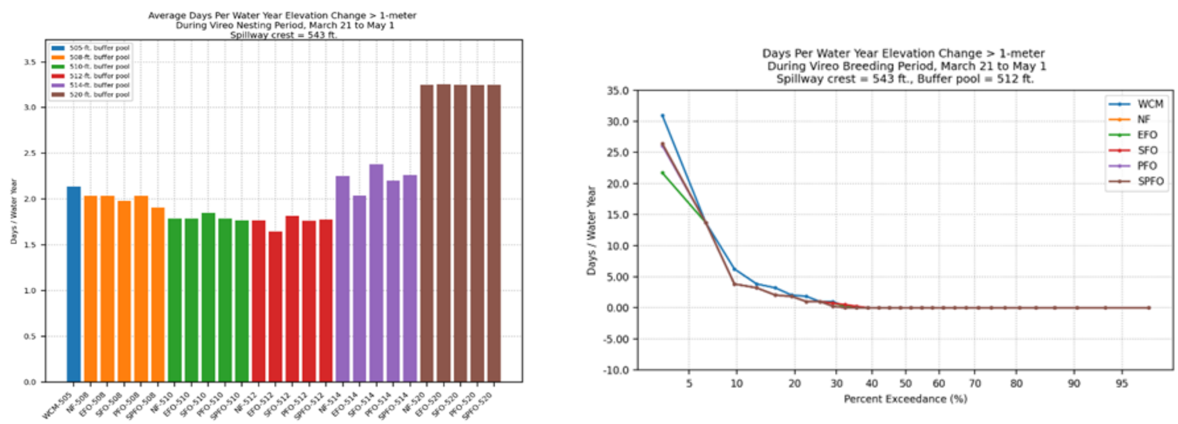


Figure 5-11. *Average days per water year when reservoir elevation increases by 1 or more meters between March 21 and May 1 for the baseline WCM and EFO and SFO alternatives with buffer pools ranging from 508 feet to 520 feet (left). Frequency of 1-meter reservoir rise during the vireo nesting season for the 512-foot buffer pool and 543-foot spillway case.*

Note from

Figure 5-11 that the EFO and SFO alternatives with buffer pools below 514 feet showed little difference in incidents of 1 meter or more rises during the vireo nesting season (March 21 to May 1) compared to the baseline WCM. From the figure on the right side of Figure 5-10, we can see that the 1-meter rises took place in less than 25 percent of the period of record years.

Note also that the evaluated alternatives did not contain logic or rules that attempt to limit or restrict the reservoir rise during the vireo nesting period. In operational practice, rises during this period of the year could be effectively managed in balance with flood risk management objectives. Depending on the circumstances, these releases could, however, significantly affect groundwater recharge outcomes.

The critical frequencies and duration of vegetation inundation are an area of ongoing research, explored and described in Section 6. Information from the simulations and evaluations associated with this study is available for use by others tasked with U.S. Fish and Wildlife Service coordination and/or National Environmental Policy Act requirements.

5.4.1 Key Findings

- Higher buffer pool elevations lead to more frequent inundation of vegetation within the buffer pool.
- EFO and SFO alternatives with buffer pools below 514 feet showed little difference the number of 1-meter or more rises during the vireo nesting season (March 21 to May 1) compared to the baseline WCM.
- The choice of the buffer pool elevation is a function of community/environmental tolerance for more frequent flood pool inundation in the winter through the range of the buffer pools tested (520 feet).

5.5 Conclusions and Recommendations

The engineering work done for the FVA was successful in showing that forecast-informed reservoir management strategies can be used to enhance the opportunities for managed aquifer recharge by the Orange County Water District.

On average, forecast-informed reservoir strategies for elevations of 508 to 512 feet are estimated to yield 4,000 to 6,000 ac-ft per year of additional groundwater recharge. Increasing the maximum buffer pool elevation to 520 feet yields an average of 12,000 ac-ft of recharge annually.

Over the range of the hindcast period (1990–2019) and for scaled events (100-, 200-, and 500-year three-day volume), forecast-informed strategies (EFO and SFO) have a slight positive impact on flood risk management outcomes associated with ungated reservoir spillway flows and releases in excess of channel capacity for all buffer pools tested up to 520 feet.

The selection of the buffer pool can affect the frequency of inundation at elevations of 514 feet and 520 feet, but all forecast-informed strategies at all buffer pools perform better than the baseline WCM when considering the frequency of exceeding 520 feet. The change in the inundation frequency of Corona Airport (514 feet) for EFO and SFO with buffer pools up through 512 feet is insignificant compared to baseline WCM operations.

The environmental impacts of the tested alternatives at all buffer pool elevations appear to be negligible but require careful evaluation (See Section 6.5).

5.5.1 Recommended Next Steps (Post -FVA)

Based on the work conducted for the FVA, the Prado Steering Committee recommends that a buffer pool of 510 ft to 512 ft be explored during the interim operations period before WCM update #2. Because the WCM update is years away, both the SFO and EFO approaches should be considered, refined, and integrated in decision support tools that USACE LAD can use.

The slightly difference in maximum release schedules (Table 4-7) for the baseline WCM and FIRO strategies partially confounded the source of change in Corona Airport (514 feet) inundation frequency. Additional testing with aligned maximum release schedules should be done to better understand the potential for Corona Airport inundation with buffer pools above 505 feet.

The study team recommends testing the SFO and EFO methodology and other decision support tools during the five-year minor deviation to increase the buffer pool to 508 feet (Section 8).

In developing this work, the Water Resources Engineering team noted a decrease in forecast skill for the Global Ensemble Forecast System (GEFS) version 12 reforecasts when compared with those from GEFSv10 for the years before 2000. The skill reduction translates directly to the Hydrologic Ensemble Forecast System (HEFS) streamflow hindcast skill. This has been noted elsewhere and is believed to be associated with the information used to initialize the GEFS model before 2000. As noted in Section 4, there were also problems associated with scaling the largest events during the hindcast period (1990–2019). These difficulties underscore the need to develop more representative and robust forecast datasets for WCP testing and evaluation. Current work on synthetic ensemble forecasts calibrated to (selected) HEFS hindcasts has the potential to provide significant improvements. Synthetic ensemble forecast generation can create multiple versions of "representative" hindcasts outside the hindcast period of record, thereby expanding the range of testing scenarios and the severe sampling limitations of the current scaling process.

The hindcast period of record ends in 2019. Since 2019, there have been several events that may provide more insight on the performance and robustness of the WCPs developed and tested as a part of the FVA work. Post-2019 forecasts presented cases of both over-forecasting and under-forecasting and raised questions about the performance and function of the hydrologic models themselves. These archived forecasts should be evaluated during the interim operations phase of the FIRO project.

Section 6. Studies, Research, and Development in Support of the FVA

6.1 Overview and Purpose

The Prado Dam Final Viability Assessment (FVA) stands on a foundation of extensive meteorological, hydrological, and biological research; decision support tools (DSTs); forecast skill assessment and enhancement; and real-world testing. This work has focused on the atmospheric river (AR) storms that produce most of the Santa Ana River watershed's precipitation—driving both beneficial water supply and flood hazards.

6.1.1 Scientific Advances That Contribute to FIRO's Viability at Prado Dam

The potential for Forecast Informed Reservoir Operations (FIRO) at a given reservoir is defined by the reservoir's operational constraints and the characteristics of the watershed's hydroclimate. Hydrologic forecasts, including inflow forecasts at Prado Dam, benefit from the predictability of regional precipitation. Short-range quantitative precipitation forecasts (QPFs) are more skillful in the West during the winter than in any other region in the United States (Sukovich et al. 2014). This forecast skill emerges from the dominance of ARs in the regional hydroclimate. More than two decades of studies on the sources of floods and water supply in California have consistently highlighted the dominant role of ARs (e.g., Ralph et al. 2006, 2013). For FIRO to succeed in this region, hydrologic prediction must be linked to ARs. The Prado Dam FIRO project is taking advantage of significant advances in AR predictability and hydrologic models focused on these extreme events.

This project has contributed to advances in understanding how ARs work physically (e.g., Cannon et al. 2020), what distinguishes ARs that are mostly beneficial to water supply from those that are hazardous (creation of the AR scale by Ralph et al. 2019), how ARs affect FIRO information requirements (Weihs et al. 2020), and what tools can best observe and predict ARs and the streamflow they induce (e.g., Ralph et al. 2020b). Knowing where ARs will hit and how much rain they may bring is essential for FIRO. Thus, FIRO at Prado Dam benefits from robust long-term investment in monitoring of ARs and associated precipitation as it moves through the watershed (White et al. 2013). A notable accomplishment in AR monitoring has been the development, testing, and operationalization of the AR Reconnaissance (AR Recon) Program (Ralph et al. 2020a). This program samples ARs offshore and transmits those data in real time to key global weather prediction models, including the National Centers for Environmental Prediction's (NCEP's) Global Forecast System (GFS), where the data are assimilated and contribute to improved forecast skill.

Modern precipitation and streamflow forecasts benefit from the availability of multiple prediction methods and models. The FIRO team has built weather and streamflow forecast tools and decision support systems that leverage ensemble predictions. Additionally, the development and application of an Ensemble Forecast Operations (EFO) method (Delaney et al. 2020) represents a major contribution to FIRO and a consideration for the Prado Dam Water Control Manual (WCM) update; it also enables continued research on improved forecast, and potential integration of those forecasts into future phases of FIRO. This framework improves forecast accuracy by quantifying the modulating effect of land-surface conditions, especially of soil moisture, using observations and specialized hydrologic modeling (Sumargo et al. 2020).

Sections 6.2 through 6.5 provide more detailed information about these efforts and additional advances in observations, weather forecasting, hydrology and water resources modeling, and biological investigations.

6.1.2 Research and Operations Partnership: A Blueprint for Success

The scientific advances discussed in this section center on improving forecasts and their application in decision making. Prediction improvements are made through technological advances (e.g., observation networks ingested into the forecasting system, updates to numerical forecasting and quantitative methods). Forecasts are made applicable to decision making through the design of robust decision support processes and tools with forecasters and operators, then through training and communication to ensure that those tools are widely usable. These advances benefit from a collaborative research and operations partnership (RAOP) approach.

The Prado Dam FIRO partnership has brought operational practitioners and their mission requirements together with scientists and their discoveries to advance the knowledge, methods, and tools that support FIRO. This RAOP approach (Ralph et al. 2020a) combines the rigor of established engineering testing protocols with the strengths of scientific studies and peer review to ensure the soundness of the technical foundation of FIRO at Prado Dam. At the core of this effort lies a well-established, successful operational framework (created by NWS's California Nevada River Forecast Center [CNRFC]); financial, human capital, and political support for scientific advancement; and a willingness to collaborate.

Figure 6-1 below shows a conceptual pathway from research to operations for improved observations, models, and DSTs. Beyond these information pathways, forecasters' and reservoir operators' expertise are essential to advancing FIRO. The RAOP approach has enabled research advances while also ensuring that this knowledge can be operationalized to help forecasters and operators interpret observation and model guidance during extreme events. This tight connection of research to operations is a foundational element of FIRO at Prado Dam.

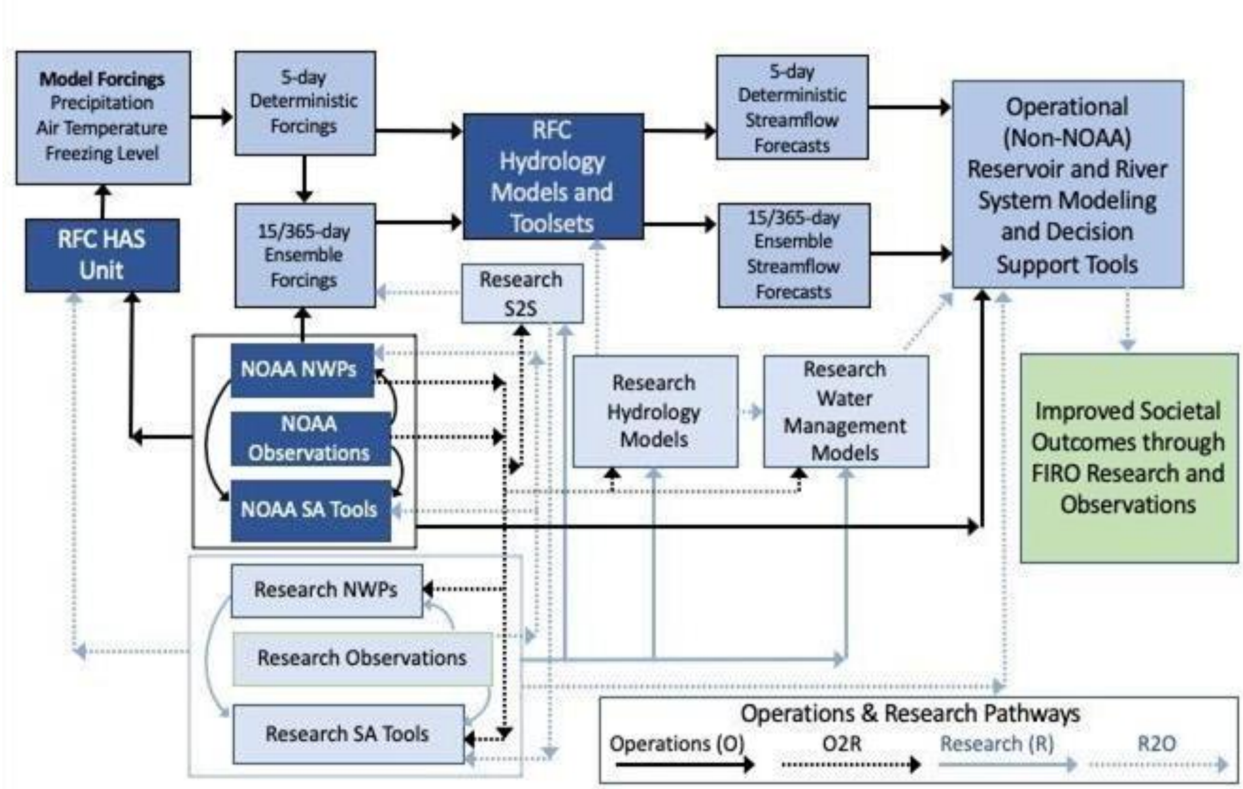


Figure 6-1. *Operations and research pathways concept as applied to Prado Dam FIRO.*

FIRO creates an environment where ongoing research investments in forecasts and their application lead to continually improving reservoir management outcomes. The RAOP approach is helpful in this regard. While many key tasks are defined by the specific technical requirements envisioned for FIRO, the RAOP approach also supports and empowers scientific inquiry that can lead to unexpected, transformative advances underlying future enhancements in forecast skill, and ultimately to greater reservoir operations flexibility. The current partnership can be extended to support additional WCM updates and push forecast skill forward to meet the requirements associated with enhanced reservoir operations goals. This section describes many opportunities to apply the RAOP framework for continued improvement of reservoir management outcomes.

6.2 Observations

6.2.1 Introduction

FIRO evaluation at Prado Dam included upgrades to and expansion of the existing observational network to enhance the real-time monitoring capabilities in support of FIRO objectives and address relevant research questions. Observational network expansion and upgrades were informed by recommendations from the Prado FIRO PVA (Ralph et al. 2021) and collaboration with project partners. These observations are used in atmospheric and hydrologic models both to answer process -based science questions and to improve model representations of the initial state of the system. The observations are also used to validate model forecasts, provide situational awareness through observations of antecedent watershed conditions, and evaluate the watershed response to precipitation events.

Major Accomplishments

- Ongoing collection and dissemination of near real-time (NRT) hydroclimatic observations on multiple public platforms.
- Installation of a new surface meteorological and soil moisture station, installation of a new radar meteorological station, and upgrades of existing stations to include radar meteorological observations.
- Santa Ana River streamflow monitoring enhancements.
- Ongoing radiosonde launch campaign at Catalina Island and Seven Oaks Dam, the new launch station for water year (WY) 2023.

6.2.2 Methods and Analysis

Observational network evaluation was performed during the FIRO Prado PVA (Ralph et al. 2021). results from the network evaluation were used to inform enhancements completed during the FVA.

Locations for the surface meteorological and soil moisture stations recommended in the Prado FIRO PVA were selected using a cluster analysis, which identified spatial groupings based on physical and hydroclimatic properties and organized them into discrete clusters. Clusters identified in the analysis were used to choose locations for five soil moisture stations representative of the discrete physical and hydroclimatic properties in the Santa Ana River watershed. The first Prado FIRO soil moisture station (YVW) was installed in November 2022 near Yucaipa, California. Four more sites are currently in the permitting process (Figure 6-1). Observations collected at the soil moisture stations include soil moisture and temperature, wind speed and direction, temperature, relative humidity, pressure, solar radiation, and precipitation. (See Appendix C.1 for details on soil moisture stations and their instrumentation.) Observations from the soil moisture stations will be used to support the existing Gridded Surface Subsurface Hydrological Analysis (GSSHA) developed for the watershed by the Engineer Research and Development Center of the U.S. Army Corps of Engineers (USACE) (Downer and Ogden 2004). Detailed methodology covering use of observations in hydrologic models can be found in Section 6.4.2.

Two radar meteorological (RADMet) stations, each with a vertically pointing micro-rain radar (snow-level), disdrometer (precipitation phase) and Global Positioning System receiver (for IWV) and a surface meteorological site, were installed and maintained near Seven Oaks Dam (SOD) and on Catalina Island (CAT) (Figure 6-2). Improvements in NRT data monitoring have resulted in increased consistency of data flow. This reduced data outages and resulted in SOD collecting data for 83 percent of the expected operational time since installation and CAT for 98 percent of the expected operational time since installation (see Appendix C.2 for additional information).

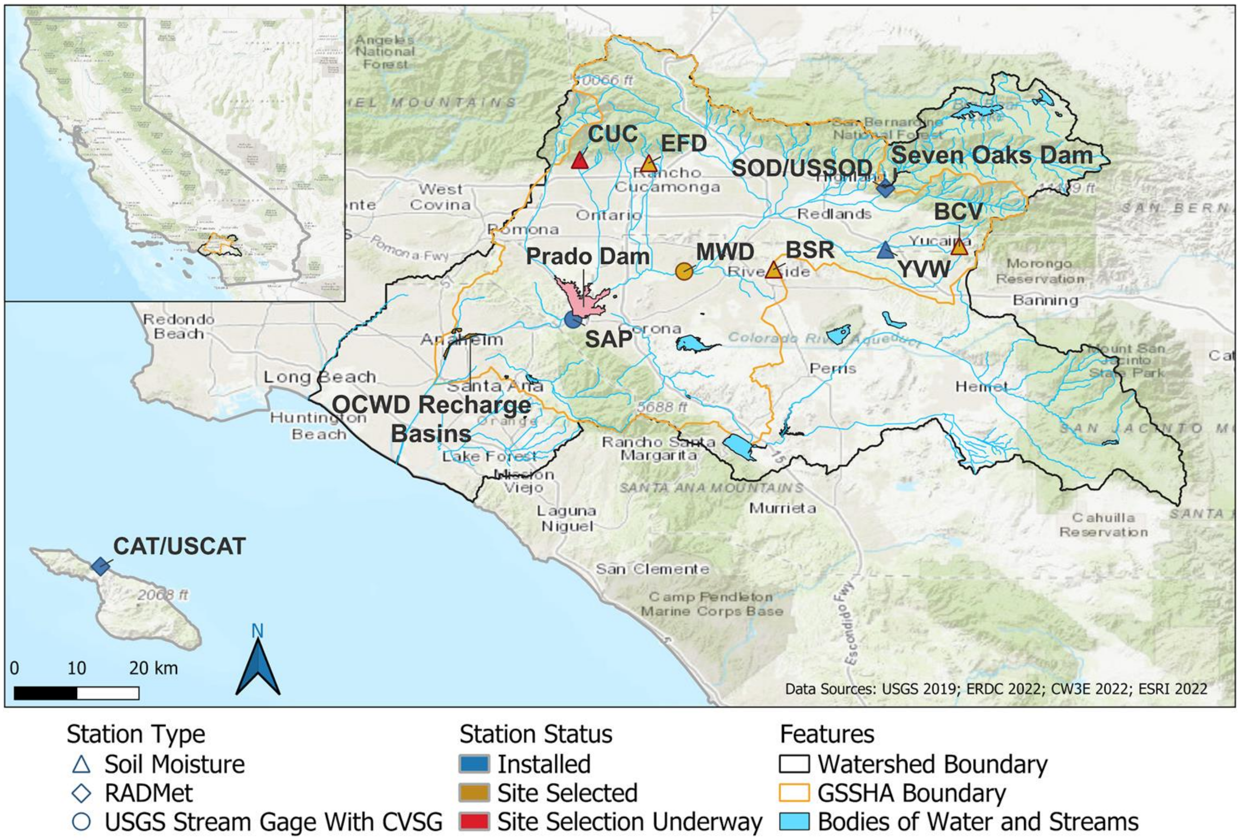


Figure 6-2. *The Prado FIRO Observation Network.*

There are two Prado FIRO radiosonde launch locations, collocated with the RADMet stations: Seven Oaks Dam (USSOD, activated Fall 2022) and Catalina Island (USCAT, activated Winter 2020). These are used to collect atmospheric observations during AR events. The radiosondes launched (see Figure 6-3 below) collect pressure, wind speed and direction, temperature, and humidity as they ascend into the atmosphere via weather balloon. As of March 16, 2023, USSOD has launched 65 radiosondes and USCAT has launched 67. (See Appendix C.3 for details on the radiosonde launches.) Data collected by the radiosondes are provided to the Global Telecommunications System, which is publicly available worldwide.

The Prado FIRO PVA identified a need for improved flow monitoring at key locations along the Santa Ana River to maximize FIRO benefits. Improved Prado Dam inflow monitoring at the Metropolitan Water District (MWD) Santa Ana River Pipeline Crossing Gage (MWD Crossing) (USGS 11066460) was recommended in support of model calibration and development and operations. Post-PVA discussions with FIRO project partners revealed that the stream gage below Prado Dam on the Santa Ana River (USGS 1107400) is important for Prado Dam and Orange County Water District (OCWD) recharge operations, as flows recorded at the stream gage are representative of outflow. However, USACE Reservoir Regulations reports that they do not currently use the USGS Prado Dam stream gage, as flows do not align with Prado gate rating flows. Both existing gage locations present operational challenges for traditional flow monitoring techniques (Ralph et al. 2021). Prado FIRO provided an opportunity to explore emerging flow monitoring technologies in these difficult -to -monitor locations.

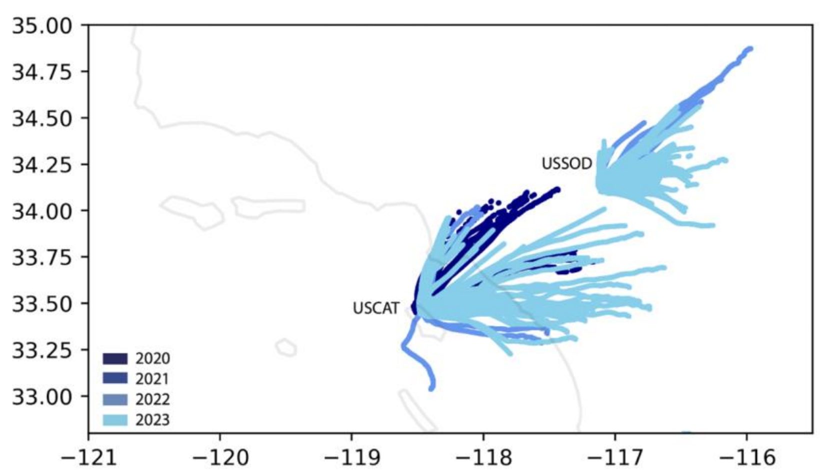


Figure 6-3. *Map of radiosonde trajectories from USCAT and USSOD since 2020.*

The existing USGS stream gage station below Prado Dam was supplemented with a prototype computer vision stream gage (CVSG) system, in development by Xylem INC., that uses space-time image velocimetry technology (CW3E station code SAP). (See Appendix C.4 for more details on CVSG.) Supplemental observations collected by the CVSG system provided a non-contact solution to collect velocity measurements during these difficult to monitor stages.

The computer vision stream gaging approach used below Prado Dam is being evaluated as a potential inflow monitoring approach for Prado Dam. Two Santa Ana River locations (USGS E Street and Hamner Avenue) have been identified as alternatives for inflow monitoring at the MWD Crossing location identified in the Prado PVA. Supplemental Prado Dam inflow monitoring will be completed post-FVA.

The AR Recon program has continued annually and provides offshore observations of key quantities (see Appendix D.7 for details). Data are provided via the Global Telecommunications System and ingested into multiple models. Regional models and reanalysis products assimilate AR Recon data as well.

Since the PVA was published in August 2021, AR Recon has collected data during 64 missions with 80 individual aircraft flights, for a total of 1974 vertical profiles of temperature, moisture, winds, and pressure, in January–March 2022 and November 2022–March 2023. Other datasets available via AR Recon are described in Appendix D.7. The earlier start for WY2023 was a direct result of the impactful storms during October and December 2021, before the start of the AR Recon campaign. In the current season, multiple Intense Observations Periods (IOPs) supported storms in California, many of which affected southern California and specifically the Santa Ana watershed. That includes IOPs 6–18 (00Z Jan 6–18), a 13-day sequence that is the longest conducted during AR Recon's history (Figure 6-4 below).

Assessments of forecast improvements attributable to AR Recon observations are a critical part of the mission, along with science advances enabled by the data (see Section 6.3.2 and Appendix D.7).

Observations by the Center for Western Weather and Water Extremes (CW3E) are sourced into a larger collection of available gage data provided by the Meteorological Assimilation Data Ingest System (MADIS). The spatial distribution of the MADIS data repository, including CW3E observations at Seven Oaks dam, is plotted against the West-WRF Reforecast seasonal total precipitation errors to (1) determine if the distribution of point observations would be enough to sample the basin errors and (2) determine if gaps exist in the spatial distribution to address particular sources of error in the numerical weather model.

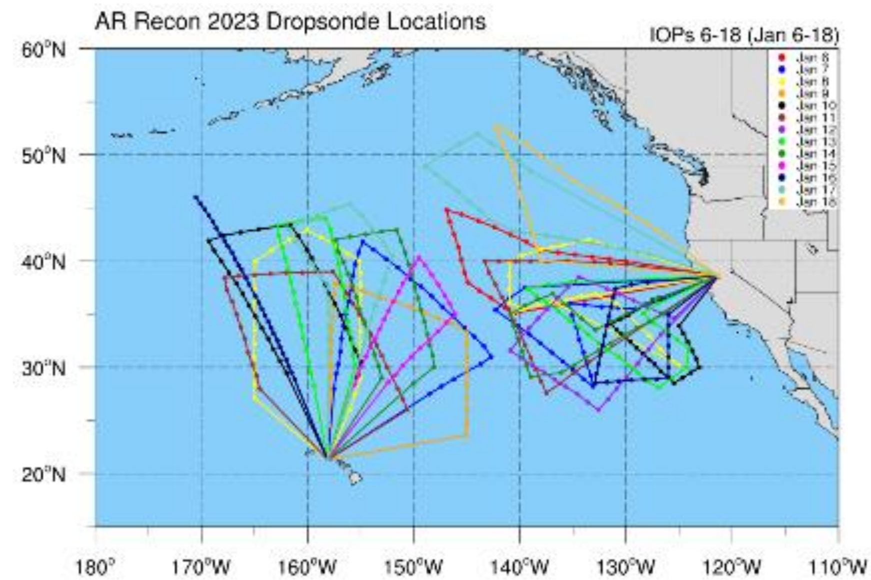


Figure 6-4. *Illustration of vertical profiles collected during IOPs 6–18 in AR Recon 2022–2023. Symbols indicate the dropsonde release points and the lines indicate flight tracks. The colors indicate the date of each IOP.*

Errors from the West-WRF reforecast within the Santa Ana River watershed are displayed against the available MADIS observation locations. The seasonal totals are aggregated from 24-hour totals at each individual lead time (all one-day 24-hour totals are summed across all valid times between December and March of each WY, and so on). Seasonal total errors are expressed as a percentage where the error between the observed and forecasted values are normalized by the observed precipitation. Seasonal errors are averaged over WY2008 through WY2019.

NRT Data from CW3E stations are available from the CW3E website, NOAA's Physical Sciences Laboratory (PSL) Profiler Network Data & Image Library the from the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory, NOAA's NOAA HMT (for surface meteorology and soil moisture), MesoWest (for surface meteorology and soil moisture), and CDEC the (for surface meteorology, soil moisture, snow level, and precipitation type). Additionally, observations are leveraged as calibration sources for hydrologic modeling experiments (see Section 6.4). These data are visualized via the USACE Model Interface Platform (UMIP) system.

6.2.3 Key Findings

Preliminary analysis of the CVSG system indicated that the approach was within a 19.5 percent root mean square error of traditional acoustic gaging methods (details are provided in Appendix C.4.). Analysis of CVSG flow observations will continue post-FVA. If deemed appropriate, USGS rating curve adjustments will be made based on CVSG observations.

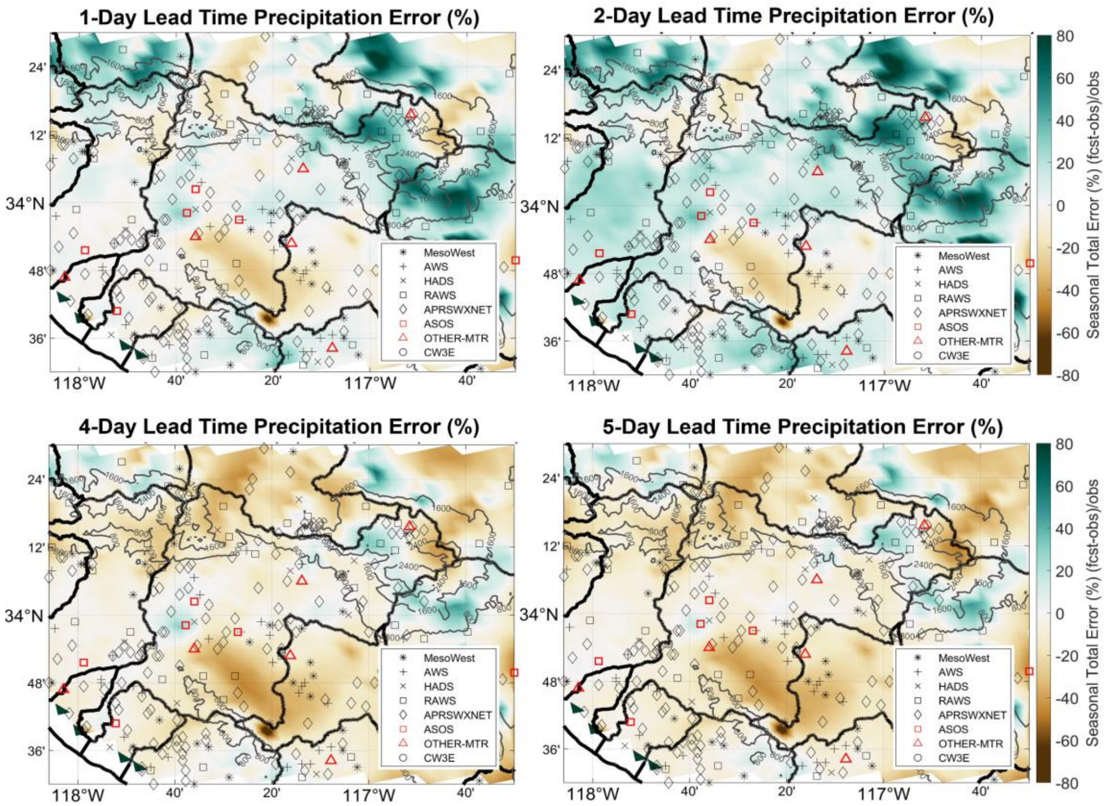


Figure 6-5. *Composite seasonal precipitation errors (percent of seasonal total) from the West-WRF Reforecast between 2008 and 2019 at one-day (top left), two-day (top right), four-day (bottom left), and five-day (bottom right) lead times centered on the Santa Ana basin. The Hydrologic Unit Code (HUC)-8 watershed boundaries are drawn in dark black contours and the USGS Digital Elevation Model elevation is plotted in the light gray contours at 800-meter levels. MADIS-sourced station locations are denoted by markers associated with their sources in the legend. Red markers represent locations from the METAR sub-repository.*

Composite precipitation errors from the West-WRF reforecast and the spatial distribution of MADIS-sourced precipitation locations within the Santa Ana watershed are shown in Figure 6-5. In each panel, the shading represents the percentage of seasonal precipitation error (green represents overestimation of seasonal precipitation and brown represents underestimation) using one-day, two-day, four-day, and five-day lead time forecasts. At one- and two-day lead times, the largest seasonal precipitation errors tend to be overestimations in the San Bernardino mountains. However, four- and give-day lead times exhibit underestimation of seasonal precipitation on average over the basin, particularly over the Santa Ana mountains and through the San Gabriels and lower foothills. The MADIS-sourced station locations are overlaid to determine what observation distribution exists within the Santa Ana watershed and how they might align spatially to address localized forecast model behavior. In comparing these spatial distributions, several recommendations can be made: (1) to better understand the errors in the San Bernardino mountains and orographic precipitation efficiency, place additional precipitation gages with high temporal sampling where errors in the forecast are largest; (2) target an additional precipitation gage with high temporal sampling below 800 meters just south of the San Gabriels to understand implications of overestimated precipitation in the foothills and its possible implications for faster runoff generation, and (3) identify the value of observations along the mean integrated water vapor transport (IVT) direction and perpendicular to topography gradients within the Santa Ana basin, particularly in the San Bernardino mountains, to further expand precipitation processes during AR events. See Appendix C.5 for discussion.

- Preliminary analyses of CVSG technology show discharge is within 19.5 percent of traditional gaging methods at SAP.
- Observations collected from CVSG at SAP indicate that the existing rating may need adjustment.
- Data from the AR Recon program have been useful in a variety of ways. See Section 6.3.2 and Appendix D.7 for details.

6.2.4 Recommendations

These recommendations are intended to optimize the potential benefits of FIRO as the project transitions to interim operations and WCM Update #2.

Recommendations for future upgrades to and expansion of the existing observational network include installation of the remaining surface meteorology and streamflow monitoring equipment and continued evaluation of the network for improvements. If appropriate, stream rating curves should be adjusted using observations collected by CVSG technology to more accurately characterize flow at USGS stream gages.

Event-based sampling of impactful events through AR Recon and radiosonde launches should be continued to support forecasting efforts in support of FIRO Prado Dam operations and AR research. Watershed -scale assessments of the impact of airborne reconnaissance data and the radiosonde data on precipitation forecasts should continue in order to improve sampling strategies in future campaigns. Collaboration with the meteorology and forecast verification teams should be continued to assess and improve outcomes for the Santa Ana River watershed (see Section 7.1.3 for details). In particular, the AR Recon program continues to refine strategies for flight track design, using essential atmospheric structures and sensitivities computed at the watershed scale for the Santa Ana River. Continued improvement in targeting strategies and in model capacity to use collected data is expected to enhance FIRO at Prado Dam.

6.2.5 Recommendations

- Install the remaining surface meteorological and soil moisture stations.
- Continue to integrate observational data into models and analysis to improve understanding of the impacts of atmospheric rivers in the Santa Ana River watershed.
- Continue storm-based sampling and ground-based radiosondes and incorporate the data into operational weather models.

- Continue evaluation of emerging technologies to support inflow and outflow monitoring at Prado Dam.
- Utilize enhanced streamflow observations to update rating curves at USGS streamflow stations.
- Continue airborne reconnaissance. Ensure that season length allows for sampling of all storms impactful for the Santa Ana River watershed. Work with Meteorology and Forecast teams to continue to assess and improve outcomes for the Santa Ana watershed (see section 7.1.3 for details).
- Support ongoing refinements to AR Recon observing strategies (specifically, flight track design) to benefit precipitation forecasts in the Santa Ana River watershed. These annual improvements are a part of the AR Recon Research and Operations Partnership and are important to continue to enhance FIRO benefits at Prado Dam.
- Continue to conduct watershed scale assessments of the impact of airborne reconnaissance data on precipitation forecasts, in order to improve sampling strategies in future campaigns.

6.3 Meteorology

6.3.1 Introduction

Although the cool-season climate of the Santa Ana River watershed is predominantly dry (only 6 percent of days are meaningfully wet), an overwhelming majority of precipitation occurs in association with landfalling ARs. The overarching goal of the meteorological studies, research, and development in support of the FVA at Prado Dam was to better understand the role of landfalling ARs in precipitation events in southern California and their predictability as it pertains to the “F” in FIRO. The following subsections provide additional high-level information; further details on the methods and analysis for each subsection are in Appendix D.

6.3.2 Methods and Analysis

6.3.2.1 Creation of an AR and Precipitation Catalog

A daily catalog of IVT and landfalling ARs, spanning about 12 years, was created from the hourly European Centre for Medium Range Weather Forecasting (ECMWF) ERA5 dataset following the methodology of the AR Scale from Ralph et al. (2019) at 33.5°N, 118°W near Irvine, California. This 12-year AR catalog is a subset of a longer-term AR catalog described in Appendix D. The precipitation data in this analysis were derived from both daily mean-areal Stage-IV precipitation observations averaged within the HUC-8 boundary of the Santa Ana River watershed and hourly observations from select stations within the same boundary. The data contained in the Catalog were used to subsequently identify relationships among landfalling AR characteristics, precipitation, and forecast verification (discussed in Section 3) over the Santa Ana River watershed for WY2012 through WY2023 (through January).

The Catalog observations serve as validation to subsequently identify potential systematic sources of forecast error as a function of lead time. The Catalog also included both (1) AR-related forecast characteristics derived from the West-WRF model (e.g., landfall location, intensity, direction) and (2) daily mean-areal quantitative precipitation forecasts from the California–Nevada River Forecast Center and the West-WRF model for leadtimes up to five days. With these forecasts and observations, different methods, including the Method for

Object-Based Diagnostic Evaluation tool, were used to identify AR-related and precipitation forecast errors discussed in Section 3 of the FVA.

6.3.2.2 Linking ARs to Precipitation in the Santa Ana River Watershed

The precipitation climatology from the AR Catalog over the Santa Ana River watershed during the October–March cool-season period contains 75 percent dry days and 25 percent wet days (i.e., days with precipitation above 0.0 inches). Only 6 percent of days contain meaningful precipitation (above 0.25 inches). The odds of a precipitation day over the watershed increases with increasing IVT magnitudes to over 70 percent with maximum daily IVT magnitudes of 300–350 kg /m/s and to nearly 100 percent for IVT magnitudes over 450 kg /m/s. The odds of precipitation also increases to over 50 percent on days with IVT directions that are between 170° and 220° (south-southwest; Figure 6-6 below).

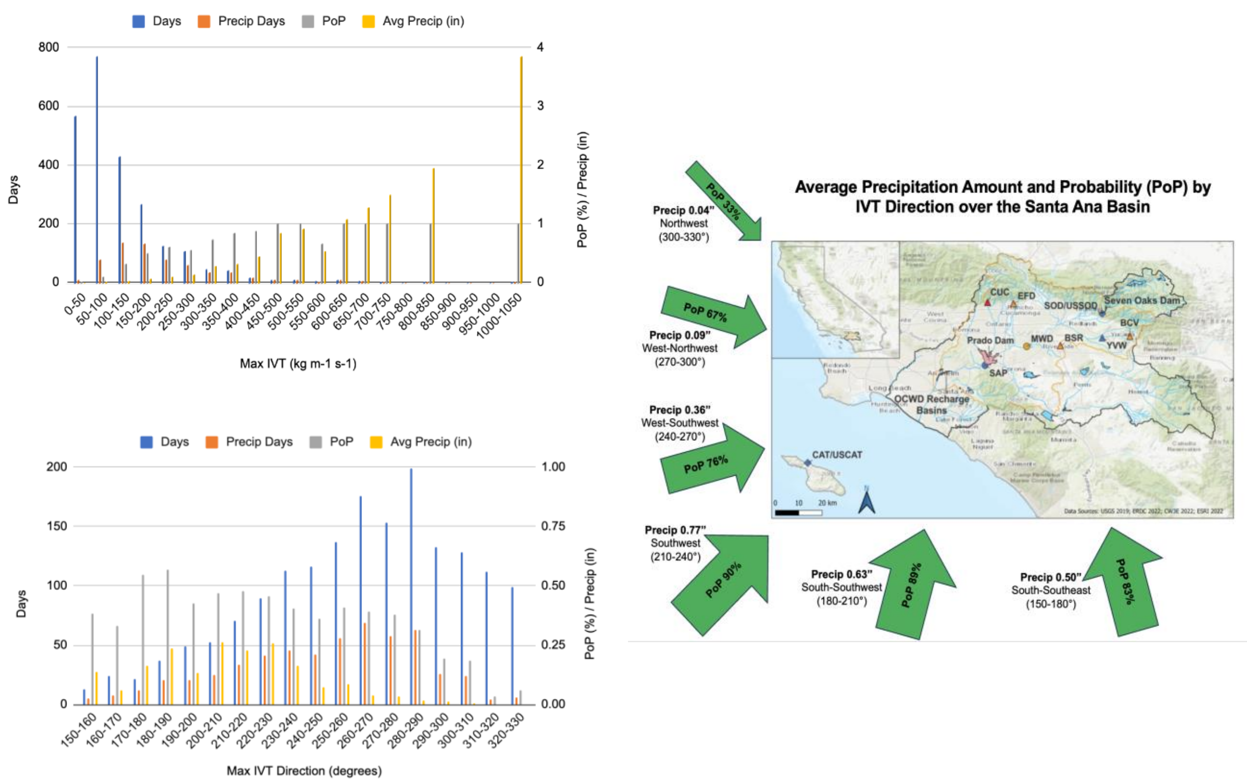


Figure 6-6. *Left: The number of days (blue); days with precipitation (orange); probability of precipitation, or PoP; gray); and average daily precipitation (yellow) as a function of daily maximum IVT for cool season (October–April) days in October 2010–January 2023. Right: as in the left panel, except as a function of IVT direction. Note that the y-axis is PoP (percent) for gray bars* ***or*** *precipitation (inches) for orange and yellow bars. Bottom: PoP and average precipitation over the Santa Ana Watershed when IVT exceeds 250. Results are shown as averages over 30° of direction. The arrow sizes correspond to PoP. Note that average precipitation varies more than PoP as a function of direction.*

On days with IVT above 250 kg /m/s (i.e., during ARs), a large group of IVT directions have a northwest-to-west wind direction with high probability of precipitation (PoP) and low average precipitation, while a smaller group have a southwest-to-southeast wind direction with high Pop and high average precipitation (see Appendix D). In other words, enhanced IVT associated with landfalling ARs, from nearly any direction, increases the likelihood of precipitation across the Santa Ana Watershed, but enhanced IVT from the south-southwest is responsible for the highest precipitation events.

6.3.2.3 Orographic Precipitation in the Santa Ana River watershed

Daily mean areal precipitation (MAP) in the Santa Ana River watershed is maximized for 925 millibars, or mb (~1 km above sea level), of water vapor flux directed from 210° (south-southwest; $r^2 = 0.78$) as shown by Ricciotti and Cordeira (2022), is reproduced in Appendix D, and is similar to the average precipitation results shown in Figure 6-6. This dependence of precipitation within the watershed on the orientation of water vapor flux suggests that the orographic distribution of precipitation is important to FIRO in the Santa Ana River watershed. The orographic distribution was further investigated by comparing the observed precipitation in the lower 25 percent and upper 25 percent hypsometry of the watershed. Precipitation in the upper 25 percent of the watershed is primarily concentrated in the San Gabriel and San Bernardino Mountains (see Appendix D). During WY2012–2022, the annual MAP was 455 millimeters (17.9 inches) in the upper portion of the watershed and 223 millimeters (8.8 inches) in the lower portion. Overall, 37 percent of the total precipitation fell in the upper 25 percent of the watershed; only 18 percent fell in the lower 25 percent of the watershed. Years with higher contribution from the lower portion of the watershed are characterized by lower contribution from the upper portion of the watershed (Figure 6-7). The orographic precipitation ratio (defined as the ratio of MAP in the upper 25 percent of the watershed to MAP in the lower 25 percent) varies from year to year, with a minimum of 1.8 in WY2015 and a maximum of 2.7 in WY2018.

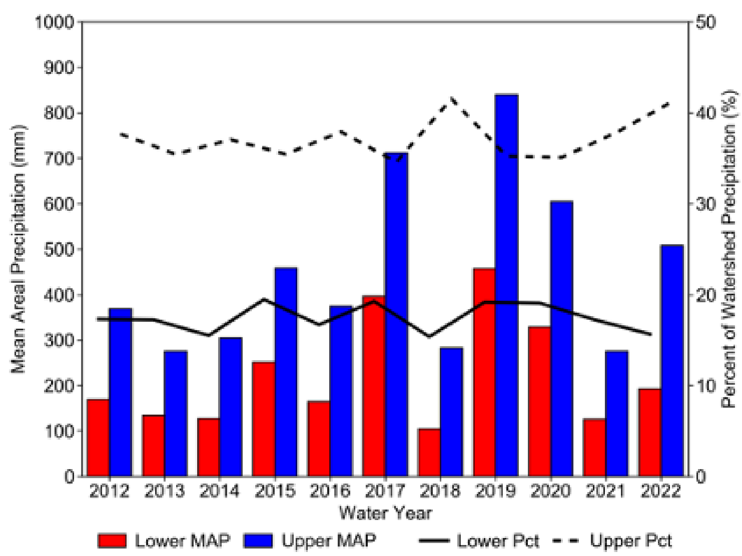


Figure 6-7. *Time series showing total MAP in the lower (red bars) and upper (blue bars) portions of the Santa Ana River watershed during WY2012–2022. The Solid (dashed) line represents the percent of total WY precipitation that fell in the lower (upper) portion of the watershed.*

6.3.2.4 Precipitation Intensity and ARs in the Santa Ana River watershed

A climatology of hourly precipitation observations was gathered for seven ASOS/AWOS stations distributed across the Santa Ana River watershed for WY2012–2023 through January 2023 to further understand the role of ARs in modulating the precipitation intensity within the watershed. The hourly data were used to calculate the daily maximum precipitation rate and the daily precipitation totals for each day. Hourly station precipitation observations were analyzed for each AR event during the period by isolating the observed precipitation between the start and end of each hour. Note that the timing information is part of the data (mentioned in Appendix D) from which the AR Catalog is derived.

Error! Reference source not found. shows that, As the maximum daily precipitation rate at stations in the watershed increases from (>0 to ≤2.5 millimeters) to (>10.0 to ≤12.5 millimeters), the percent that occurred on AR days increased from 9 to 57 percent. Similarly, as the daily precipitation total at stations in the watershed increases from (>0 to ≤10 millimeters) to (>40 to ≤50 millimeters), the percent that occurred on AR days increased from 9 to 42 percent (not shown in the figure). These relationships demonstrate that ARs are on average more frequently associated with the highest daily maximum precipitation rates and daily precipitation totals at stations in the Santa Ana River watershed; however, the most extreme daily maximum hourly rates do appear to occur in association with non-AR storms worth additional investigation.

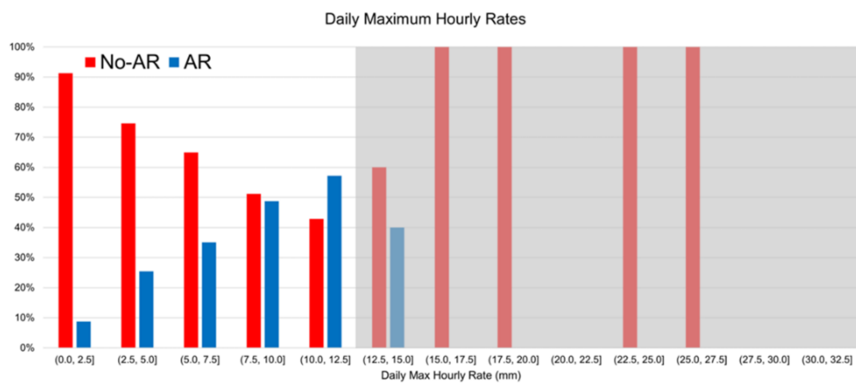


Figure 6-8. *A histogram of the percent of daily maximum precipitation rates above 0 inches that occurred on AR (blue) and No-AR (red) days during the cool season (October–March) across all stations between WY2012 and WY2023. The gray-shaded region indicates a sample size below 10 occurrences.*

6.3.2.5 Diagnostic tools that provide guidance on the influence of key storm mechanisms in forecast models

While precipitation in the Santa Ana River watershed is largely governed by landfalling ARs, different ingredients during the landfall are known to affect the intensity, duration, distribution, and forecast skill of precipitation—for example, narrow cold-frontal rainbands (NCFRs), upslope flow, and synoptic-scale forcing. Based on diagnostics used to study these phenomena in Cannon et al. (2020) and de Orla-Barile (2022), additional forecast tools were developed from the GFS, ECMWF, and West-WRF forecast models to display quantities such as "frontogenesis and temperature advection" to aid in the prediction of NCFRs during landfalling ARs (see Appendix D), the "irrotational wind" to aid in identifying upstream processes that can lead to forecast uncertainty, and the "Q-Vector" to aid in visualizing the role of synoptic-scale forcing on precipitation.

6.3.2.6 AR Recon Program and data assimilation in Numerical Weather Prediction

A leading source of California precipitation forecast error and uncertainty in numerical weather prediction models exists within ARs and nearby conditions offshore. AR Recon fills this observation gap. Global weather models operated by NWS, the U.S. Navy, and the European Union assimilate AR Recon data with evidence showing that collected observations improve representation of ARs over the North Pacific, improve forecasts of precipitation downstream over western North America, and provide both complementary and additive benefits to satellite-derived data collection techniques. Three examples of specific results involving the impacts of data collected by AR Recon on forecasts published in peer -reviewed literature are listed below (Appendix D offers more examples).

- AR Recon dropsonde observations improve the three-dimensional structure of ARs and water vapor transport in ECMWF model forecasts (Lavers et al. 2018).
- AR Recon dropsonde observations reduce overall errors in AR water vapor flux and inland precipitation at forecast lead times from one to six days, with the largest improvement of inland precipitation forecast skill associated with back-to-back flights with dropsonde observations every other day (Zheng et al. 2021).
- AR Recon observations improve geographical distribution of forecasted precipitation at lead times of about three to five days by 5–15 percent over the full western United States and by 10–20 percent over the Pacific Northwest and Northern California when dropsonde data are assimilated into the NCEP Operational GFS model (Lord et al. 2022).

6.3.2.7 High-resolution probabilistic precipitation forecasts and data visualizations

The development and implementation of the 200-member West-WRF ensemble is a significant milestone in CW3E's ability to provide NRT forecast information and allows for additional probabilistic forecast capabilities. CW3E developed a suite of forecast products using the West-WRF ensemble output to produce percentile -based and probabilistic forecasts of ARs, IVT, the AR Scale, precipitation, snowfall, wind, temperature, and atmospheric moisture. One such example displays the forecast probability of 24-hour precipitation above 3 inches. (See Appendix D.) These maps are available for multiple variables, domains, and accumulation times ranging from 15minutes to 72hours for lead times up to seven days. Similar maps are also produced for percentiles to allow the user to see the full spread of ensemble members and forecasted extremes. Probabilistic forecasts for specific locations have also been developed displaying the AR Scale, precipitation, snowfall, temperature, and wind speeds. These products display a time series of the chosen variable, forecasts from each ensemble member, and a probabilistic forecast of various thresholds being exceeded (See Appendix D). In addition to these new tools, several previously deployed using global NWP models have been adapted and designed to display the West-WRF ensemble. These include the CW3E AR Landfall tool, IVT plume diagrams, and multiple AR Scale diagnostic tools. Products are available online at https://cw3e.ucsd.edu/west-wrf_ensemble/.

6.3.2.8 Machine learning to improve reliable probabilistic predictions

A significant portion of NWP model errors can be recovered in a post-processing framework using artificial intelligence (AI) and machine learning (ML). These AI/ML techniques make it possible to train algorithms that learn the dynamic model behavior over a historical period and can lead to improved forecasts and reliable uncertainty quantification. An AI/ML technique using a CW3E deep learning architecture called Unet was applied to zero- to five-day daily accumulated precipitation forecasts from the 34-year West-WRF Reforecast dataset. For the intense wet period of December 2022 through January 2023, which featured several landfalling ARs in California, the West-WRF model post-processed with Unet produced about 25 percent less precipitation error over the Santa Ana River watershed and outperformed both the GFS and ECMWF forecast models, including the West-WRF model without post -processing (Hu et al. 2023). Similarly, deep learning using an Artificial Neural Network applied to CW3E's 200-member West-WRF ensemble (Ghazvinian et al. 2022) outperformed the ECMWF model by about 15 percent when aggregated over the watershed for WY2022. For more information, see Appendix D.

6.3.2.9 Evaluation of forecast products

The evaluation of forecast products fell into three categories:

- A report summarizing the skill of the AR Landfall Tool in GFS and ECMWF ensemble forecasts for southern California following the publication of Stewart et al. (2022), which can be found in Appendix D.
- Case study and longer-term assessments of probabilistic precipitation forecasts, including the December 2021 "cutoff" event and the December 2022–January 2023 "Deep Dive" (see Appendix A).
- Case study and longer-term assessments of probabilistic AR forecasts, including the lead-time prediction of ARs during the December 2022–January 2023 "Deep Dive" (see Appendix D).

6.3.2.10 RAOPs

A key part of CW3E's decision support services is interaction between CW3E and key stakeholders in RAOPs. For example, a CW3E meteorologist was embedded into the California Department of Water Resources' (DWR's) Hydrology and Flood Operations Branch to work directly with DWR and the CNRFC. This position is supported by other state and locally funded projects. This collaboration has been a key development in fostering RAOPs across the water enterprise, including offering multiple trainings; information sessions; and briefings before, during, and after events. CW3E has hosted many of these meetings focused on DSTs for several water agencies and decision makers. Of interest to the Santa Ana River watershed, these include DWR (Division of Flood Management and State Water Project), USACE's Los Angeles District, CW3E's Water Affiliates Group, OCWD, and the CNRFC.

6.3.3 Key Findings

- Landfalling ARs play a primary role in precipitation and precipitation extremes in the Santa Ana River watershed.

- Smaller-scale phenomena during landfalling ARs (e.g., NCFRs) and the unique characteristics of the AR landfall (e.g., orientation/duration) are responsible for the spatial distributions of precipitation and storm-total accumulations within the watershed.
- Specialized diagnostic and probabilistic forecast tools can improve situational awareness and characterize risk of smaller-scale phenomena, unique characteristics, and precipitation associated with landfalling ARs.
- AR Recon and improved observations of ARs before landfall improve NWP model forecasts of precipitation for the Santa Ana River watershed.
- ML and AI techniques improve NWP model forecasts of precipitation over the Santa Ana River watershed.
- RAOPs serve as a focus for communication, training, and development of tools and information necessary for using forecasts as part of reservoir operations.

6.3.4 Recommendations

- Conduct case studies and ongoing assessments of forecast skill as additional landfalling ARs produce precipitation challenges within the Santa Ana River watershed.
- Evaluate the success and utility of new forecast tools derived from specialized diagnostics and probabilistic information.
- Continue to explore and develop watershed-specific ML/AI methods to improve AR-related and non-AR-related precipitation forecasts in the Santa Ana River watershed.
- Sustain AR Recon each year as an RAOP with continued focus on improvement in flight targeting techniques, assimilation methodologies, and demonstration of forecast improvements for Southern California.

6.4 Hydrology

6.4.1 Introduction

Existing operations at Prado Dam are supported by streamflow forecasts issued by the CNRFC. The CNRFC uses a well-tested set of semi-lumped models developed in the 1970s to simulate and predict flows upstream of Prado as well as Prado reservoir inflows. The models are calibrated to current watershed conditions and executed in a modern forecasting framework; the resulting forecasts are described in Section 3. Nonetheless, there remains a potential to improve streamflow forecasts using a contemporary physics-based, gridded hydrologic model that can be coupled with a mesoscale NWP model run on a similar scale (West-WRF), which may perform better in an arid region like the Santa Ana River Watershed where there are a limited number of events for model tuning. Additional benefits for reservoir operations may be derived from integrated simulation of the watershed, streams, and reservoir. To test this hypothesis, the Santa Ana River watershed and Prado Dam were simulated with the GSSHA model, as an alternative to other watershed models such as those used by the CNRFC. The GSSHA model simulates larger storms in the basin that might cause flooding. The model is calibrated/verified to observed streamflows and changes in reservoir volume using observed rainfall data, then tested against observed reservoir inflows for an extended simulation period.

An experimental operational model has been developed to run on the CW3E computer resources using a West-WRF forecast; output is downloaded to and displayed on the UMIP system, which shows all types of measured and simulated hydrologic data online.

6.4.2 Methods and Analysis

6.4.2.1 Data Analysis

Input and assessment data are critical to developing, calibrating, and assessing model performance. Precipitation is a key input to the simulation of hydrology, while streamflow and reservoir level/volume are key performance criteria. The study team assessed the adequacy of these data for use in modeling and operations:

- Data for about 200 rainfall gages, in and within 10 miles of the watershed, were downloaded from the Synoptic Public Benefit Corporation. Gages with hourly or sub hourly recording intervals for the periods of interest were used for modeling. The locations of gages are shown in the PVA.
- There are 134 historical USGS stream gaging stations in the Santa Ana River watershed that have collected data at some point in time. Data were available for the chosen calibration/verification periods from 21 gages (Figure 6-8, green circles).

6.4.2.2 Integrated Hydrologic Model

A GSSHA watershed model was prepared for the Santa Ana River watershed. GSSHA is a fully distributed, physical-process-based, gridded hydrologic numerical tool suitable for engineering analysis and design that simulates the hydrologic response of a watershed subject to given hydrological and atmospheric inputs (USACE 2020).

As Figure 6-8 shows, the model domain extends from the San Gabriel and San Bernardino Mountains to below OCWD's recharge basins, terminating at the USGS gaging station at Santa Ana, California. The model domain excludes areas that are considered extremely unlikely to contribute significant flow to the Santa Ana River during a large event, including Lake Elsinore and portions of the watershed above the Seven Oaks and San Antonio dams. Similar assumptions were made in the development of other watershed models of the Santa Ana River (Santa Ana River Watermaster 2019). For times when conditions cause these regions to contribute significant flow to the SAR, flows can be added to the model as specified hydrographs on the stream network. Lake Elsinore is a non-contributing sub-catchment to Prado Dam, so a specified hydrograph is not necessary for most cases. Seven Oaks Dam is operated in tandem with Prado Dam and generally attenuates inflows into Prado Dam, and specified hydrographs should be included in the model when water surface elevation equals or exceeds 2,565 feet (in relation to the National Geodetic Vertical Datum [NGVD] of 1929) and the pool is falling as discharges can reach up to 7,000 cubic feet per second (cfs). San Antonio Dam is operated so that floodwaters are released as soon as available downstream channel capacity permits, and specified hydrographs should be included in the model when water surface elevation equals or exceeds 2,165 feet (in relation to the NGVD). The model domain encompasses 1,460 square miles. At a model resolution of 820 feet, the model grid contains 60,526 computational cells. A one-dimensional stream network was developed within the two-dimensional overland flow surface, as shown in Figure 6-8.

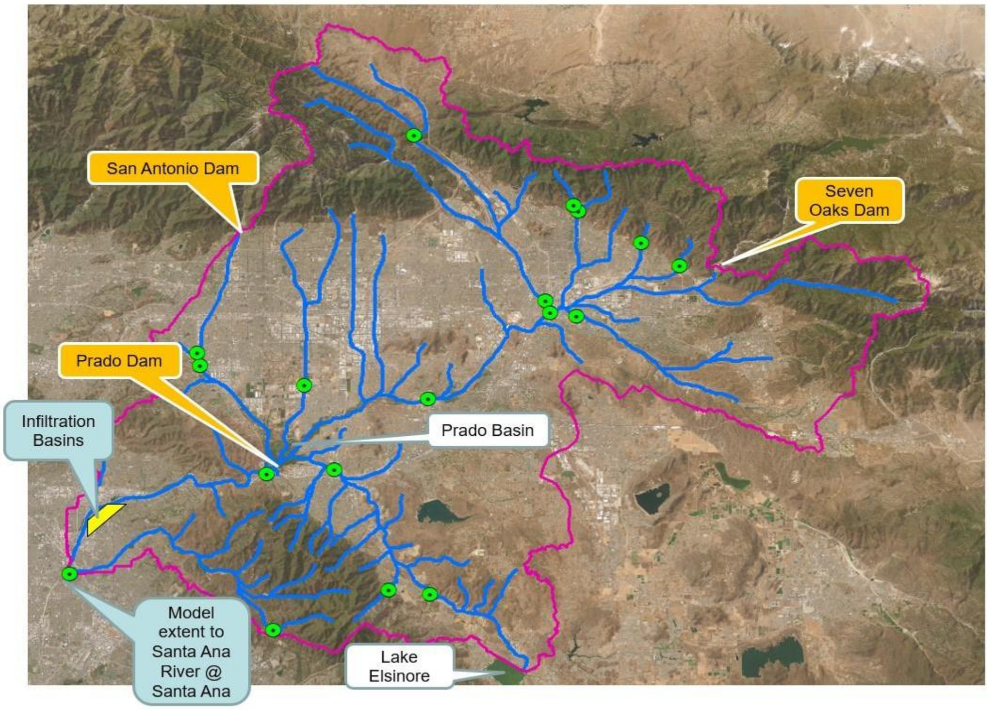


Figure 6-8. *Santa Ana River watershed model with USGS gage locations.*

6.4.2.3 Calibration

The watershed model was calibrated for large flooding events using two of the largest events in the last 50 years, January 2005 and 2010. The model was calibrated to a combination of three-hourly cumulative flow at the USGS stream gages (Figure 6-8) and daily changes in reservoir volume. Three calibrations were performed: one for 100 percent streamflows, one for 100 percent reservoir volume changes, and one for an even split between the two measures. The 50/50 split allows both reservoir volume and streamflows to be used in the calibration with equal weight. The Nash-Sutcliffe efficiencies (NSEs) for daily change in reservoir volumes and streamflows at MWD Crossing are shown in Table 6-1. NSE compares the model to the mean of the measured metric. A score of 1.00 is a perfect match. Anything less than 0.00 indicates the model result is a worse fit than the mean of the observed metric for the period simulated. As seen in Table 6-1, the 2005 and 2010 calibration efforts produced good results. Other results for the 2005 calibration period are shown in Figure 6-9 below. In general, adding the changes in reservoir volume as a calibration metric increases the ability to simulate the reservoir without a large penalty in simulating stream gage flows.

Table 6-1. *Santa Ana River watershed model calibration results.*

Calibration Period	Streamgage Weight (%)	Reservoir Volume Weight (%)	NSE Change in Reservoir Volume	NSE Flow @ MWD Crossing
2005	100	0	0.76	0.85
2005	0	100	0.97	0.75
2005	50	50	0.96	0.81
2010	100	0	0.71	0.71
2010	0	100	0.95	0.22
2010	50	50	0.93	0.72

6.4.2.4 Verification

To verify the model with the calibrated parameter set, the 2005 calibration period was extended for another two months, which included another series of precipitation events. The three-hour change in reservoir volume (which Reservoir operators indicate is an important metric in reservoir operations) was used as the target metric. Results are shown in Figure 6-9 below. As the figure shows, the model with parameter sets derived using the daily change in reservoir volumes—especially the set derived using *only* the daily reservoir volume change as the calibration metric—shows considerable skill in matching the three-hour change in reservoir volume, at least for this period. This indicates the model has potential to aid operations. For the 2010 period, NSEs for the three-hour change in reservoir volume are 0.77 for calibration, 0.40 for verification, and 0.61 overall.

6.4.2.5 Precipitation/HMET Data Source

CW3E collects a set of NRT operational data products, including Stage-IV (4-kilometer hourly, NRT), NLDAS-2 (0.125° hourly, 3.5 days lag), PRISM (4-kilometer daily, one month lag), and High-Resolution Rapid Refresh (3-kilometer hourly, NRT), and merges/downscales them into a 1-kilometer hourly surface meteorological forcing dataset. Eight variables (precipitation, 2-meter air temperature, downward shortwave/longwave, specific humidity, and wind speed with direction) are provided. NLDAS-2, Stage-IV and PRISM, the backbone and High-Resolution Rapid Refresh, are used only for the most recent 3.5 days. The CW3E West-WRF model provides daily five-day weather forecasts during the rainy season.

6.4.2.6 Testing with NRT Precipitation

The NRT data will be used to initialize the forecast model runs for the experimental operational model. The model, calibrated to the network of rainfall gages, was used with the NRT data to test the capability of the model/rainfall to simulate the change in Prado reservoir volumes. First, the 2005 calibration/verification period was repeated using the NRT data. The results with the NRT precipitation were compared to both the observations and the gage-calibrated model results. Both models used the parameter set derived from both the change in reservoir volume and stream gages (50/50) because it provides the best overall fit to the calibration data, as shown in Table 6-1. While there is some deterioration of the results when switching between rainfall types (NSE 0.60 vs 0.69), the model can still reproduce the reservoir volume change at the three-hour interval, as shown in Figure 6-10. Next, the 2000–2022 period was simulated using the NRT precipitation for testing. Fifty-two periods with “significant” rainfall events (with peak discharge at MWD crossing greater than 50 cubic meters per second [1,764 cfs] were analyzed. Results were compared to the three-day moving total inflow into the reservoir (calculated as USACE observed change in reservoir volume plus discharge). The overall NSE for all events combined is 0.6658, a fairly accurate result. Table 6-2 shows the mean flow, mean absolute error (MAE), and NSE calculated overall and, for the groupings consistent with Section 3, non-AR, AR, and top 5 percent ARs.

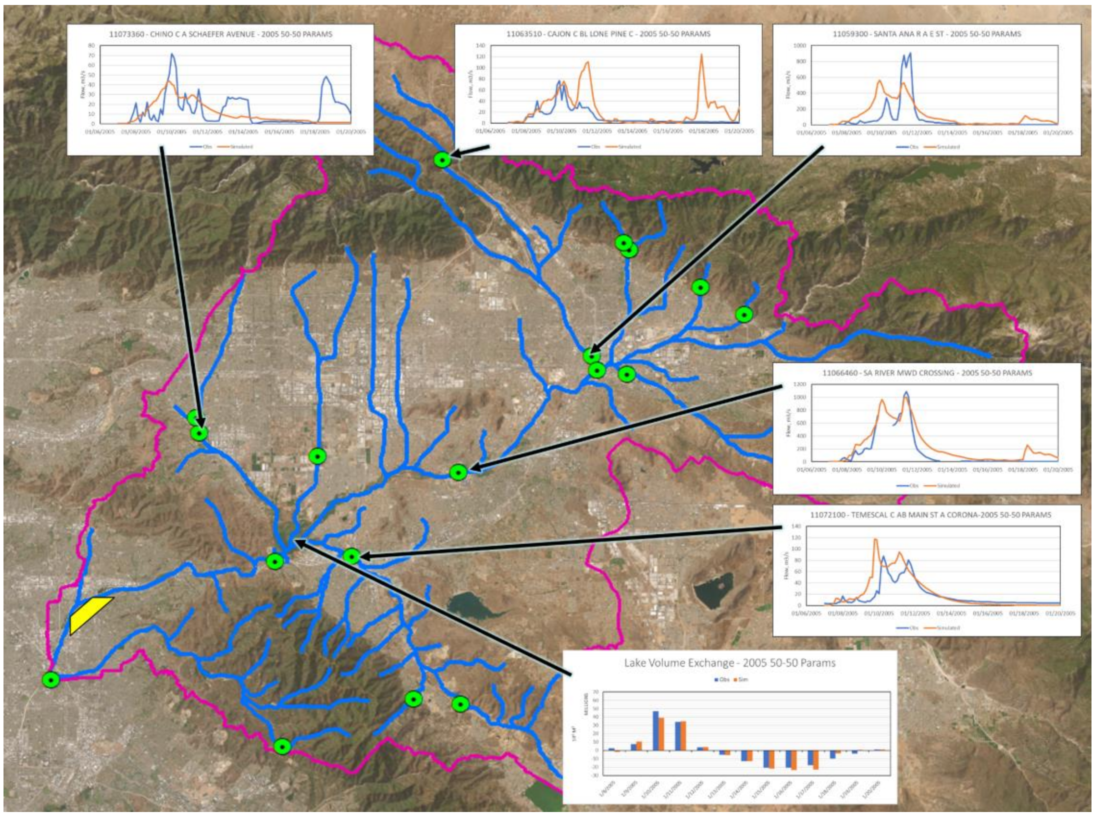


Figure 6-9. *Calibration results: daily change in reservoir volume and three-hour streamflows.*

As Table 6-2 shows, the overall model results are good. AR events dominate flow -producing events in the Santa Ana River Watershed, and the model does a good job of simulating reservoir inflows. Results for non-AR events, while still positive, are not as good. These events tend to be infrequent and small, and probably of not great significance for Prado Dam. Adding smaller events to the calibration, if desirable, would likely improve results for these events. Overall results can possibly be improved by recalibrating with the NRT data.

Section 3 discusses the ability of the CNFRC Community Hydrologic Prediction System (CHPS) model to simulate total reservoir inflows. While a direct comparison between GSSHA and CHPS is difficult, due to differences in how the models were assessed, one thing does stand out: while the CHPS model overall gives good results, its results tended to be least accurate for large AR events. As Table 6-2 shows, the GSSHA model functions well for large AR events, indicating that it may be capable of adding value beyond CHPS for simulating reservoir inflows for these larger events.

6.4.2.7 Experimental Operational Model

An experimental operational hydrologic model has been developed by linking West-WRF weather forecast to the Santa Ana River watershed GSSHA model. This operational model is set up to run on Comet at the San Diego Supercomputer Center every eight hours. A set of scripts control the operational model. The scripts locate the latest West-WRF operational models, run the GSSHA model with the West-WRF forecast, and then provide the latest forecast to the FIRO Data Viewer on the UMIP system.

The FIRO Data Viewer is a Tethys web app that allows a user to view and download all outputs from a selected GSSHA model forecast simulation, including maximum depth in each computational cell, reservoir levels, and stream hydrographs, as shown in Figure 6-11.

Simulations using the five-day West-WRF forecast for a December 2019 event, with good West-WRF precipitation results, indicate that the model can simulate the peak reservoir stage reasonably accurately for this event—within 0.5 meters, or about 1 foot. More rigorous assessment of the West-WRF/GSSHA forecast will be completed as a future effort.

Table 6-2. *Testing results: NSE for three-day moving total reservoir inflow (2000–2022).*

Statistic	All Events	Non-AR Events	AR Events	>5% AR Events
Mean inflow (1,000 ac-ft)	25	17	27	63
MAE (1,000 ac-ft)	12	9	13	35
NSE	0.67	0.11	0.69	0.62

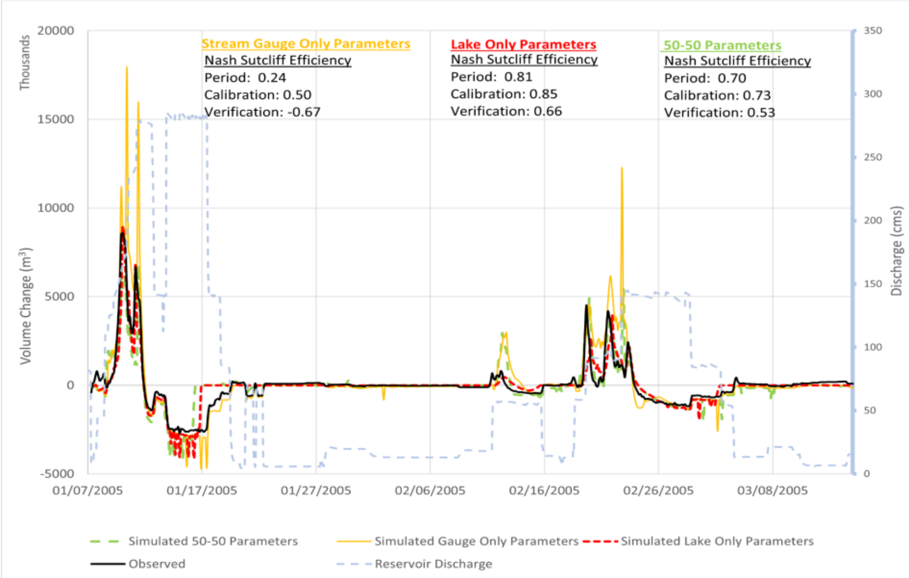


Figure 6-10. *Three-hour change in reservoir volume simulations for the calibration/verification period.*

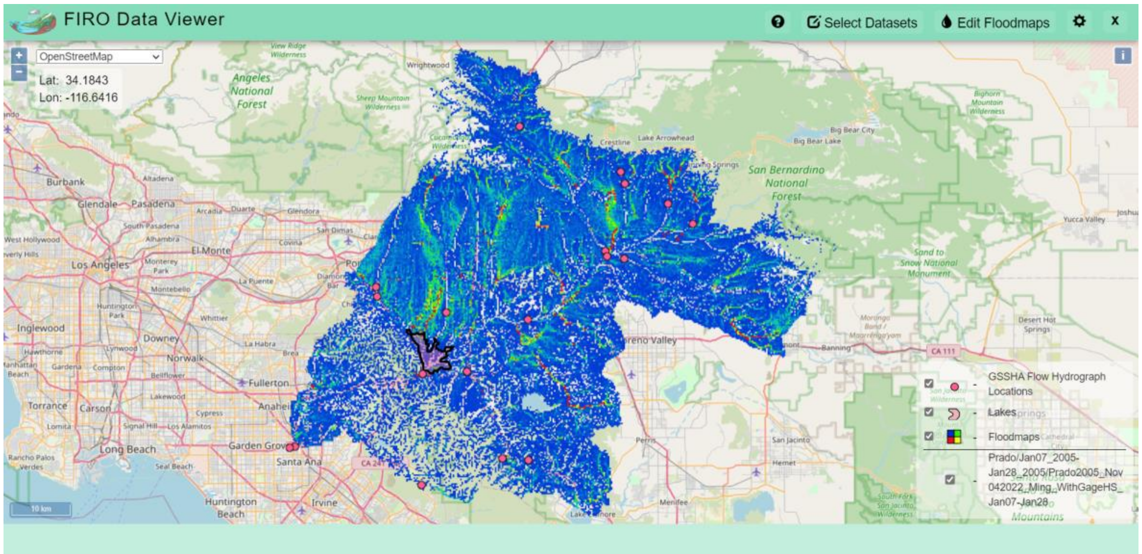


Figure 6-11. *Screenshot of the FIRO data viewer.*

6.4.3 Key Findings

- The precipitation and stream gaging network in the Santa Ana River watershed was sufficient to support the development and calibration of a contemporary hydrologic model.
- An integrated GSSHA model was developed, covering the Santa Ana River watershed, the Santa Ana River, and Prado Reservoir.
- The model was calibrated and verified to both streamflow and change in reservoir volume.
- Including the change in reservoir volume as a calibration metric improved the model's ability to simulate the change in reservoir volume without a significant reduction in streamflow simulation capability. This is seen as an advantage to using a fully integrated model.
- When driven by CW3E NRT precipitation data, the model remained capable of simulating a key metric for operational considerations: three-hour change in reservoir volume.
- Using the model with the CW3E NRT precipitation data, the GSSHA model was able to simulate inflows into Prado Reservoir during the 2000–2022 period. The model performs best for AR events, including large AR events, indicating that it may add some value to estimates from CNRFC, which performs worst for large AR events.
- An experimental operational GSSHA Santa Ana River watershed/Prado Dam model that uses the West-WRF 10-day forecast has been developed on the CW3E network, with results downloaded and displayed by the FIRO Data Viewer on the USACE UMIP system.

6.4.4 Recommendations

- Enhance the robustness of the GSSHA model by expanding the calibration period and range of event sizes.
- Further develop the experimental operational model at Prado to maximize potential utility for operational support.
- Use the NRT data for model spin-up before simulating the West-WRF forecast.
- Process downscaled (post-processed) West-WRF ensembles through GSSHA to create ensemble streamflow forecasts.
- Assess the accuracy of the GSSHA/West-WRF reservoir inflows as results become available.
- Consider making the results available on the CW3E environment.
- Process the forecast streamflow ensembles through the Prado Dam EFO model and HEC-ResSim as a proof of concept.
- Use additional field data to assess and improve the GSSHA model as these data become available.

6.5 Least Bell's Vireo

6.5.1 Introduction

USACE, OCWD, and the U.S. Fish and Wildlife Service (USFWS) have a long-standing partnership balancing flood control, water conservation, and environmental stewardship at Prado Dam. The Prado Basin contains the single largest forested wetland in coastal Southern California, supporting an abundance and diversity of wildlife, including listed and sensitive species. The least Bell's vireo (*Vireo bellii pusillus*) is a federally endangered bird species that has been the focus of environmental considerations at Prado Dam. When evaluating the viability of implementing FIRO to safely increase water conservation behind Prado Dam, it is critical to develop a more complete understanding between water conservation and the riparian habitat on which the vireo depends. Too much water can damage habitat; too little water will desiccate it.

Baseflows into the Prado Basin, which are dominated by discharges from wastewater treatment facilities, have steadily declined since the early 2000s (Figure 6-12). Multiple factors, including wastewater recycling, water conservation, and long-term drought, have contributed to decreases in baseflow. Baseflows may continue to decline. Groundwater levels in the Prado Basin have also declined. This is a concerning trend for riparian vegetation, which needs continual access to shallow groundwater.

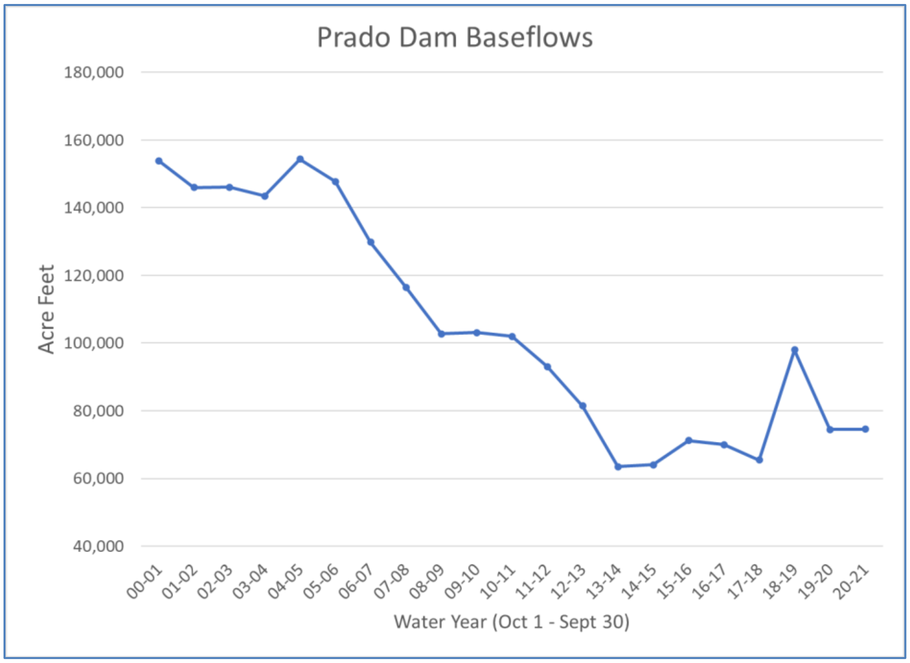


Figure 6-12. *Prado Dam Baseflows from 2000–2021.*

Infrequent wet years like 2023 represent an opportunity to study and understand the effect of both short- and long-term inundation on riparian habitat and the vireo. Observations from 2023 indicate that short -term inundation, even in the spring, can have a net positive impact on riparian vegetation by providing moisture for recruitment of important understory habitat as well as perennial species such as mulefat and willows. Short -term inundation has induced widespread natural recruitment of riparian vegetation. Initial vireo nesting data indicate that, while the extended water conservation pool may have delayed mate selection and nesting, the vireo adapted by nesting at higher elevations in the basin. The preliminary count of vireo territories in the Prado Basin shows that vireo numbers were not negatively affected by water conservation in 2023. In fact, there was a near -record- breaking number of vireo territories in 2023. With changing hydrology behind Prado Dam, a robust environmental monitoring program and adaptive management strategy are paramount to the success of the vireo. This section describes enhancements to the existing monitoring program, adaptive management strategies, and habitat experiments that will occur to support FIRO implementation. A summary of OCWD's current monitoring program can be found in the 2021–2022 *Prado Basin Water Conservation and Habitat Assessment* Report (see Appendix E).

Riparian habitat in the Prado Basin

The Prado Basin is the largest forested wetland in coastal Southern California, supporting an abundance and diversity of wildlife including many listed and sensitive species, including the federally endangered least Bell's vireo. Threats to riparian habitat in the Prado Basin, including water availability, have changed dramatically with urbanization of the upper watershed. FIRO is expected to have overall positive effect on riparian habitat in the Prado Basin by balancing human and environmental needs, but a robust monitoring and adaptive management program will be necessary to ensure a positive effect for the vireo.

6.5.2 Methods and Analysis

Water conservation at Prado Dam has occurred in lockstep with OCWD's ongoing environmental monitoring and adaptive management program, which has led to a remarkable recovery of vireo in the Prado Basin. With the implementation of FIRO, OCWD will expand on its environmental monitoring and adaptive management program. To evaluate the viability of new monitoring tools and habitat studies proposed in the PVA, a FIRO Environment Work Team was established with stakeholders from USACE, CW3E, OCWD, USFWS, and the California Department of Fish and Wildlife.

The following sections detail some of the key components that the FIRO Environment Work Team developed, evaluated, and intend to incorporate into the environmental monitoring and adaptive management program to allow FIRO to increase water conservation without negatively affecting (and hopefully improving) the environment and the species supported within the Prado Basin.

6.5.2.1 Pre-establishment of Habitat Values above 505 Feet

Fire is emerging as the largest factor affecting habitat and species in the Prado Basin; its effects on habitat health are extremely detrimental, and possibly catastrophic, with increasing frequency. In April 2015, the Highway Fire burned 1,049 acres across the center of the Prado Basin, including about 450 acres of Arundo. Immediately following the fire, Arundo regrowth was rampant and the OCWD Board approved funding to treat the regrowth and monitor habitat recovery on 400 acres to establish riparian values that could offset potential habitat losses. Most of this parcel was burned a second time in December 2020 during the Airport Fire that consumed 1,087 acres.

This 400-acre habitat recovery parcel is above the water conservation pool and has been monitored and surveyed to quantify natural recruitment and the development of viable habitat (Figure 6-13). Results to date have been encouraging, and vireo territories now occur within the 400-acre parcel.

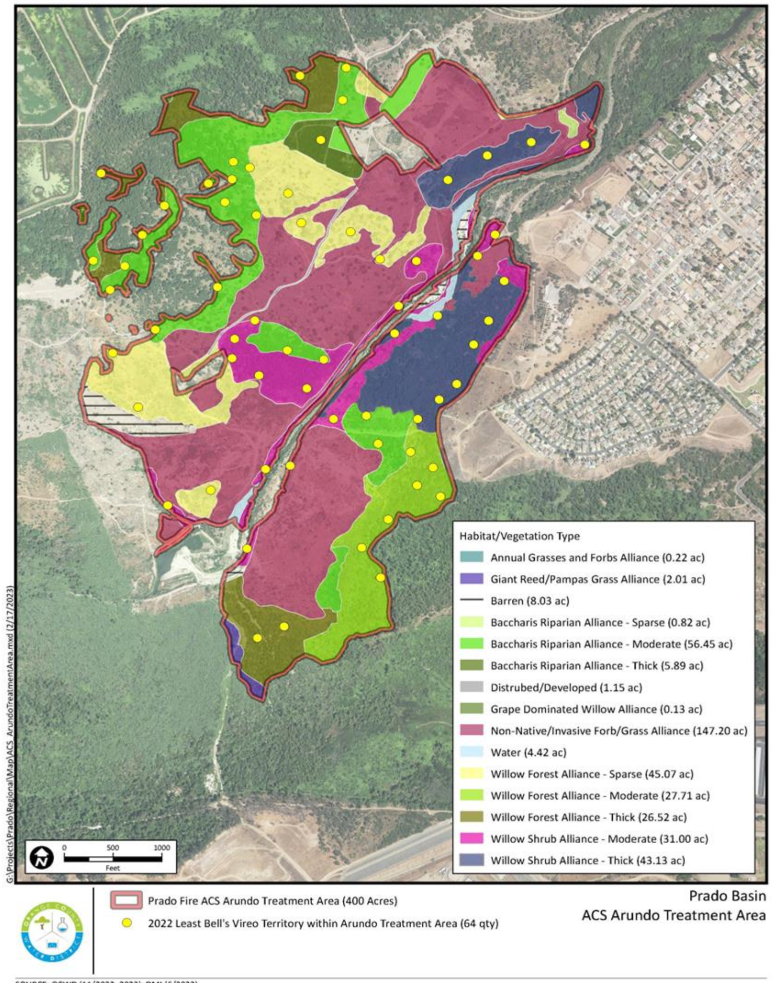


Figure 6-13. *The 400 -Acre Arundo Treatment/preemptive habitat restoration site.*

6.5.2.2 Vegetation Map of the Prado Basin

A "baseline" of the vegetation in the Prado Basin is necessary to understand environmental effects (both positive and negative) associated with higher water levels under FIRO operations. In July 2022, OCWD undertook a mapping effort using high -resolution aerial imagery. Areas to the west of the 71 Freeway and in the higher elevations outside the extent of the aerial photograph (shown in Figure 6-13) were not included in the mapping effort. These areas are well outside the buffer pool's influence. The acreage of each of the cover types and vegetation classes was calculated as shown in Table 6-3. Additional vegetation mapping efforts will be performed to document potentially impactful events like FIRO -enabled high water levels or other large-scale changes, such as fire, in the basin. The results of these subsequent mapping efforts will be compared to the 2022 baseline conditions. Mapping efforts will be updated as conditions warrant and accompanied by observations on the ground.

Table 6-3. *2022 Prado Basin Vegetation Map: Vegetation Type by Acreage.*

Habitat/Vegetation Type	Sum of Acres
A - Agriculture	720.43
AGF - Annual Grasses and Forbs Alliance	16.90
ARU - Giant Reed/Pampas Grass Alliance	231.07
BAR - Barren	238.81
BRM - Baccharis Riparian Alliance - Moderate	164.07
BRS - Baccharis Riparian Alliance - Sparse	61.02
BRT - Baccharis Riparian Alliance - Thick	29.96
CDW - Cocklebur Dominated Willow Alliance	138.30
CMH - Coastal Mixed Hardwood Alliance	13.34
CSB - California Coastal Sagebrush Alliance	217.76
DD - Distrubed/Developed	2,040.33
DWF - Developed Water Features	101.14
EUC - Eucalyptus/Non-Native Trees Alliance	152.50
FPA - Fan Palm Alliance	9.59
GDW - Grape Dominated Willow Alliance	83.24
NIG - Non-Native/Invasive Forb/Grass Alliance	3,174.30
OVG - The Olive Grove	96.05
REC - Recreation	415.42
TUL - Tule - Cattail Alliance	44.19
WAT - Water	587.44
WFM - Willow Forest Alliance - Moderate	521.74
WFS - Willow Forest Alliance - Sparse	341.04
WFT - Willow Forest Alliance - Thick	1,120.93
WSM - Willow Shrub Alliance - Moderate	323.36
WSS - Willow Shrub Alliance - Sparse	125.08
WST - Willow Shrub Alliance - Thick	822.89
Total Sum of Acres	**11,790.90**

6.5.2.3 Experimenting with Riparian Enhancement Sites above 505 feet

In recent years, perennial flows in the Santa Ana River have steadily declined and groundwater levels in the Prado Basin have receded. Healthy tree and shrub growth, as well as recruitment of young plants, depends on continued perennial plant access to shallow groundwater. During the FIRO evaluation period, the elevation of the buffer pool will be higher, increasing the days of inundation for vegetation within the buffer pool area. By storing water behind Prado Dam at these higher elevations, FIRO presents an opportunity to increase the area exposed to short-term flood irrigation, potentially expanding the riparian forest upward. To evaluate this potential benefit, OCWD will gently contour sediment high in the buffer pool to expand the area benefiting from short -term flood irrigation made possible by FIRO. These areas will be monitored closely to determine the riparian habitat and vireo response.

Increasing the days of inundation at the lower elevations could result in temporary decrease in foliage volume at these elevations. To date, no long-term habitat loss of the established willow forest has been observed associated with water conservation activities. Monitoring for vegetation and vireo response will continue to occur in the lower and higher elevations. It is anticipated that the short-term flood irrigation at the higher elevations may support renewed growth and vigor of the riparian forest to offset any foliage volume loss at the lower elevations. OCWD will consider weeding non-natives in experimental sites to encourage natural recruitment in areas newly inundated by FIRO to determine if riparian forest habitat can be expanded higher in the basin.

The experimental riparian habitat enhancement sites will be in the central part of the Prado Basin south of OCWD's constructed wetlands. The sites were mostly burned in the recent fires and some are part of recent Arundo removal activities, devoid of native plants. The experimental sites are subject to inundation if the buffer pool reaches elevations above 505 feet. On the experimental sites, OCWD will gently contour sediment to maximize the effects of occasional inundation at elevations. Contouring will create connectivity to the buffer pool and allow the lower points to become inundated when the buffer pool approaches maximum elevation. Following contouring of sediment, OCWD will consider weeding non-natives and will monitor the sites for habitat values. The experimental sites provide an opportunity to learn how riparian vegetation responds to changes in water availability. If successful, these experimental sites could inform efforts to expand the riparian forest within the Prado Basin.

6.5.2.4 Vireo Habitat Pilot Study using LiDAR

OCWD commissioned a pilot study to explore the use of LiDAR (Light Detection and Ranging) to assess the structure and health of vegetation and its suitability as nesting habitat for vireos.

The primary objective of the study was to assess whether LiDAR data could provide information comparable to data produced using the field- based stacked cube method developed by Barbra Kus at USGS (and currently used by OCWD for field-based vegetation studies in the lower Prado Basin). Stacked cube field protocols involve estimating vegetation cover within a sequence of stacked 2×2×1-meter cubes visualized from the ground to the canopy (Kus 1998). The purpose of the stacked cube method is to determine if density and structure of riparian habitat is suitable to support vireo. These methods are labor intensive and can only represent a limited area, making their effectiveness as a habitat monitoring tool questionable.

Another objective was to explore how LiDAR data might be used to provide a more general assessment of riparian habitat conditions and help define appropriate spatial scales for LiDAR vegetation structure across the lower basin. The approach categorizes the density and height of LiDAR returns into biologically significant cells (20–50 meters) that represent intrinsically similar or dissimilar groups (Figure 6-14). This method, called cluster analysis, is designed to find a "natural" assignment of these cells based on their structural similarities compared to vireo nest selection data to see if this classification could represent community structure and ecological function. Figure 6-15 shows a map generated by using cluster analysis to assign 25-meter cells into structurally similar groups.

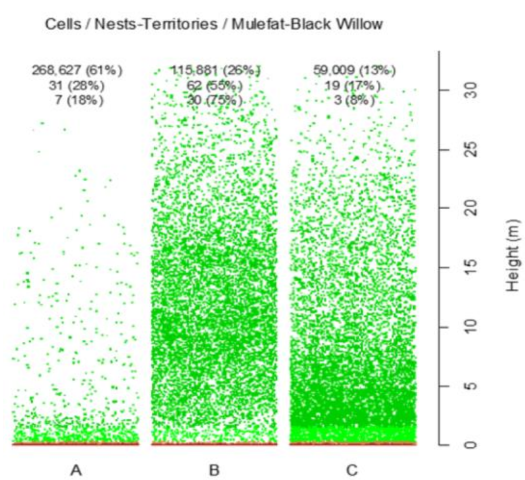


Figure 6-14. *Grouping of Vertical LiDAR Returns and Vireo Nest Locations.*

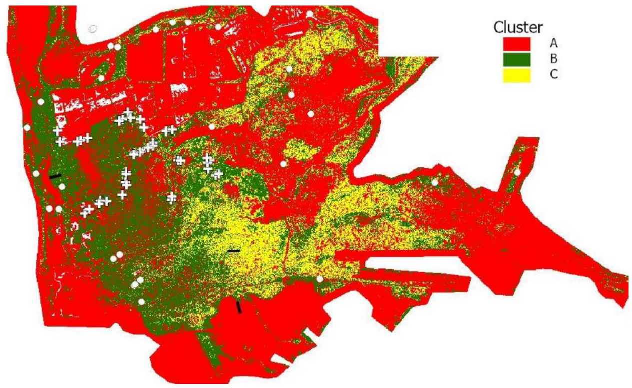


Figure 6-15. *Prado Basin Map created using Cluster Analysis.*

The LiDAR pilot study determined that commercially available LiDAR collected by aircraft does not currently have the density and penetration of returns needed to replicate the stacked cube method. However, the LiDAR study did demonstrate that using cluster analysis to develop a larger -scale (25-square-meter) video territory map has potential. Subsequent pilot studies are being considered to determine if cluster analysis could be a valuable tool to measure changes to habitat and vireo attributed to increased water conservation from FIRO.

6.5.3 Key Findings

Baseflows in the Santa Ana River, which are predominantly discharges from wastewater treatment plants, have been steadily declining since the early 2000s as the upper watershed continues to construct more recycling projects and advance water use efficiency. This means less water arriving in the Prado Basin for environmental needs. In addition, in recent years fires are emerging as the largest potential factor affecting habitat and species in the Prado Basin. Its effects on habitat health are extremely detrimental, even catastrophic, with increasing frequency.

Although temporary impacts to the understory due to higher water levels have been observed, there have been no irreparable long-term impacts to the willow forest from water conservation. Observations from 2023 indicate that short -term inundation, even in the spring, can have a net positive impact on riparian vegetation by providing moisture for recruitment of important understory habitat as well as perennial species such as mulefat and willows. Potential environmental effects caused by higher water levels will be closely monitored. OCWD has over 2,000 acres of land behind Prado Dam and will actively monitor and adaptively manage the habitat to stay ahead of potential environmental impacts associated with increased water conservation made possible by FIRO. Before starting FIRO at elevations above 505 feet, OCWD has pre-established riparian habitat values on 400 acres at higher elevations in the Prado Basin. pre-establishing these habitat values higher in the basin gives the vireos 400 acres of suitable habitat to adaptively use if/when FIRO affects water levels in the lower elevations.

- Since water conservation began in the early 1990s, vireo populations have steadily increased as water conservation has expanded. Data indicate that vireos can adapt to the presence of standing water, and the highest populations have been observed during years with above-average water levels.
- Baseflows in the Santa Ana River have been steadily declining since the early 2000s as the upper watershed continues to construct more recycling projects and advance water use efficiency. This

means less water arriving in the Prado Basin for environmental needs. Further study is needed to evaluate if FIRO can offset habitat effects caused by decreases in baseflow.

- Data suggest that wetter conditions improve vireo habitat through natural recruitment. Except for the understory, there are no data to support that irreparable forest damage has occurred due to prolonged inundation from water conservation. Further research is needed to understand how habitat responds to both short- and longer-term inundation.
- OCWD owns over 2,000 acres in the Prado Basin, which are managed to maximize natural resource values. If mitigation is needed to offset impacts to riparian habitat attributed to FIRO, sufficient lands are available. The proposed action includes adaptive management measures that could be implemented if habitat loss occurs.

6.5.4 Recommendations

To monitor and understand the effects of higher water levels under FIRO, it will be important to expand monitoring of habitat above 505 feet to determine if the additional water can be used to enhance and expand riparian habitat to benefit the forest and vireos. OCWD has established habitat values that will be monitored and managed to ensure that additional water conservation under FIRO results in no net loss—and, hopefully, a net gain —for the Prado Basin forest and its inhabitants.

- Expand the existing monitoring program above 505 feet and implement the monitoring program to identify any mitigation needed to offset impacts.
- Preemptively and adaptively manage adequate riparian habitat to offset potential temporary or long-term impacts associated with FIRO.
- Explore and study opportunities for habitat value creation made possible by FIRO. For example, continue experimenting with habitat islands and flood irrigation pathways above an elevation of 505 feet to expand the area benefiting from temporary flood irrigation, which could offset potential environmental impacts in the lower elevations associated with FIRO.
- Develop new methods to study riparian habitat responses to prolonged dry and wet conditions.
- Create operational procedures based on observed field conditions to maximize viable vireo habitat and success.

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Section 7. Findings and Recommendations

The execution of this Final Viability Assessment (FVA) involved an array of efforts to address the feasibility of Forecast Informed Reservoir Operations (FIRO) for Prado Dam and the pathways through which FIRO outcomes can be supported and improved in the future. This section identifies and describes Specific findings and recommendations within the research areas of forecast skill assessment and enhancement (Section 3), water resources engineering (Section 4 and Section 5), observations (Section 6.2), weather forecasting (Section 6.3), hydrologic modeling (Section 6.4), understanding and managing environmental objectives (Section 6.5), and interim operations and FIRO Implementation (Section 8).

7.1 Forecast Skill

7.1.1 Findings

24-hour precipitation errors:

1. Forecasts of 90th percentile events are skillful out to four days ahead of time using Global Ensemble Forecast System (GEFS) version 12 using two different metrics (critical success index [CSI] vs. relative forecast error and climatology).
2. West-WRF has additional skill in predicting mean areal precipitation (MAP) under 1 inch out to three days in advance over the GEFSv12 control member.
3. Under-forecasts of integrated water vapor transport (IVT) at Prado often coincide with underestimations of MAP in West-WRF.

72-hour Inflow Volume Forecast Errors:

1. Forecast accuracy tends to deteriorate with longer lead times, except in the all -non-atmospheric-rivers (ARs) subset.
2. Brier scores are generally best in the all -time subset and worst in the all -ARs subset, indicating lower forecast accuracy under AR conditions.
3. Ensemble forecasts are still more skillful than the reference forecast based on climatology.
4. The Community Hydrologic Prediction System (CHPS) model (used by the California Nevada River Forecast Center [CNRFC]) has skill in simulating non-AR, all -AR, and top 5 percent AR flows (Nash-Sutcliffe efficiency above 0.53).

AR landfall:

1. Generally, there is a northerly bias in AR landfall using GEFS and objects above 250 kg /m/s IVT.
2. Errors are about 100 kilometers at a one-day lead time and about 400 kilometers at a seven-day lead time using West-WRF.

3. West-WRF can skillfully predict AR landfall out to at least seven days (critical success index above 0.5, probability of detection above false alarm ratio).

Prado December 2021 Case Study:

1. Global Forecast System/National Weather Service (NWS) forecasts of precipitation events were very volatile through two- to five-day lead times.
2. The NWS local point precipitation forecast for Prado was reduced by half from a two-day to a one-day lead time.
3. Alignment of forecast errors and decision making timelines proved to be an extremely valuable exercise. It resulted in:
   - Improved understanding of how forecasts are leveraged.
   - Understanding limitations of operational flexibility with critical decision making markers (e.g., notifying local agencies).
   - Investigating sources of forecast uncertainty and meteorological predictability of cutoff low.

7.1.2 Recommendations Post-FVA

1. Continue to evaluate forecast skill, particularly for epochs of marked improvements to model development.
2. Expand the inflow verification to include metrics that describe starting times of increased hydrographs during precipitation events. These represent important triggers for operational decisions.
3. Continue research into localized impacts/behavior of ARs and extreme precipitation and feedback of key mechanisms to forecast predictability.
4. Continue to work with stakeholders and operational decision makers to understand key aspects of forecasts used or leveraged in the decision making process.
5. Conduct case studies of quantitative precipitation forecast inflow error analysis to understand the role of atmospheric forecast uncertainty to hydrologic sensitivity.
6. Continue to evaluate potential improvements and advances in meteorological and hydrologic forecasting models for additional FIRO benefit.

7.2 Water Resources Engineering/Alternatives Assessment

7.2.1 Findings

Flood Risk Management:

1. The period of record simulations generated no spillway flows or channel capacity releases for any of the evaluated alternatives. This is consistent with the historical

operation of Prado Dam, which has not reached the spillway elevation since construction.

2. Scaled events were needed to assess the effectiveness and impacts of the alternatives on flood risk management outcomes (avoid total releases greater than 30,000 cfs).
3. In the domain of extreme events (100-, 200-, and 500-year three-day volume simulations), there are only modest differences between the alternatives with respect to maximum reservoir elevation, spillway flows, and maximum reservoir release. But Ensemble Forecast Operations (EFO) and Simpler Ensemble Forecast Operations (SFO) (all buffer pools) reduce spillway flows and releases greater than channel capacity compared to baseline Water Control Manual (WCM) operations.
4. 200-year three-day volume simulations create minor spills for baseline WCM, all NF (no forecast used), SFO-520, and EFO-520 with a 543-foot spillway elevation.
5. 500-year three-day volume simulations create major spillway flows for all alternatives with a 543-foot spillway elevation.
6. 500-year three-day volume simulations create minor spillway flows for baseline WCM, all NF, SFO-514, EFO-514, SFO-520, and EFO-520 with a 563-foot spillway elevation.
7. NF (all buffer pools) and baseline WCM result in slightly higher maximum reservoir elevations and maximum releases than alternatives that use forecasts. These higher maximum reservoir elevations and maximum releases increase with increasing NF buffer pool elevations.
8. The change in the inundation frequency of Corona Municipal Airport (514 feet) for EFO and SFO with buffer pools up through 512 feet is insignificant when compared to baseline WCM operations.
9. For non-extreme flood events, the EFO and SFO alternatives provide for lower releases and less likely inundation at 520 feet compared to baseline WCM operations.

Groundwater Recharge metrics:

1. Opportunities to improve groundwater recharge are tied to the prevailing hydrology, with enough water occurring in about half of the years.
2. Recharge improvements with FIRO occur in years when the inflow is above average and the buffer pool is filled at least one time.
3. In general, greater buffer pools lead to greater recharge, but forecasts are needed to avoid negative impacts to flood risk management outcomes above 508 feet.
4. In general, strategies that leverage perfect forecasts perform better than those that use hindcasts. (Forecast skill improvements will lead to improved results.)
5. In general, the EFO and SFO approaches provide for very similar recharge across the range of buffer pools tested.
6. The average annual gain from implementing FIRO at 508 to 512 feet ranges from 4,000 to 6,000 acre-feet (ac-ft) per year.

7. The average annual gain from implementing FIRO at 520 feet is about 12,000 ac-ft per year.

Environmental metrics:

1. Higher buffer pool elevations lead to more frequent inundation of vegetation within the buffer pool.
2. EFO and SFO alternatives with buffer pools below 514 feet showed little difference in the number of 1 -meter or more rises during the vireo nesting season (March 21 to May 1) compared to the baseline WCM.
3. The choice of the buffer pool elevation is a function of community/environmental tolerance for more frequent flood pool inundation in the winter through the range of the buffer pools tested (520 feet).

7.2.2 Recommendations Post-FVA

1. Procedures to scale events in the hindcast period need to be evaluated and potentially sharpened.
2. Early work on synthetic ensemble forecast generation based on a calibration of the Hydrologic Ensemble Forecast System (HEFS) appears promising and has the potential to yield a much better foundation for rigorous WCP evaluations.
3. Based on the work conducted for the FVA, the Prado Steering Committee recommends that a buffer pool of 510 ft to 512 ft be explored during the interim operations period before WCM update #2. Because the WCM update is years away, both the SFO and EFO approaches should be considered, refined, and integrated in decision support tools that can be used by the U.S. Army Corps of Engineers' Los Angeles District.
4. The slight difference in maximum release schedules (Table 4-7) for the baseline WCM and FIRO strategies partially confounded the source of change in Corona Airport (514 feet) inundation frequency. Additional testing with aligned maximum release schedules should be done to better understand the potential for Corona Airport inundation with buffer pools above 505 feet.
5. The study team recommends testing the SFO and EFO methodology and other decision support tools during the five-year minor deviation to increase the buffer pool to 508 feet (Section 8).
6. In developing this work, the Water Resources Engineering team noted a decrease in forecast skill for the GEFSv12 reforecasts when compared with those from GEFSv10 for the years before 2000. The skill reduction translates directly to the Hydrologic Ensemble Forecast System (HEFS) streamflow hindcast skill. This has been noted elsewhere and is believed to be associated with the information used to initialize the model before 2000. As noted in Section 4, there were also problems associated with scaling the largest events during the hindcast period (1990–2019). These difficulties underscore the need to develop more representative and robust forecast datasets for WCP testing and evaluation. Current work on synthetic ensemble forecasts calibrated to (selected) HEFS

hindcasts has the potential to provide significant improvements. Synthetic ensemble forecast generation can create multiple versions of "representative" hindcasts outside the hindcast period of record thereby expanding the range of testing scenarios and the severe sampling limitations of the current scaling process.

7. The hindcast period of record ends in 2019. Since 2019 there have been several interesting events that may provide more insight on the performance and robustness of the WCPs developed and tested as a part of the FVA work. Post-2019 forecasts presented cases of both over-forecasting and under-forecasting and raised questions about the performance and function of the hydrologic models themselves. These archived forecasts should be evaluated during the interim operations phase of the FIRO project.

7.3 Observations

7.3.1 Findings

1. Preliminary analyses of CVSG technology show discharge is within 19.5 percent of traditional gaging methods at SAP.
2. Observations collected from CVSG at SAP indicate that the existing rating may need adjustment.
3. Data from the AR Recon Program have been useful in a variety of ways. See Section 6.3.2 and Appendix D.7 for details.

7.3.2 Recommendations Post-FVA

1. Install the remaining surface meteorological and soil moisture stations.
2. Continue to integrate observational data into models and analysis to improve understanding of the impacts of atmospheric rivers in the Santa Ana River watershed.
3. Continue storm-based sampling and ground -based radiosondes and incorporate the data into operational weather models.
4. Continue evaluation of emerging technologies to support inflow and outflow monitoring at Prado Dam.
5. Use enhanced streamflow observations to update rating curves at USGS streamflow stations.
6. Continue airborne reconnaissance. Ensure that season length allows for sampling of all storms impactful for the Santa Ana River watershed. Work with the Meteorology and Forecast Verification teams to continue to assess and improve outcomes for the Santa Ana watershed (see Section 7.1.3 for details).
7. Support ongoing refinements to AR Recon observing strategies (specifically, flight track design) to benefit precipitation forecasts in the Santa Ana River watershed. These annual improvements are a part of the AR Recon Research and Operations Partnership and are important to continue to enhance FIRO benefits at Prado Dam.

8. Continue to conduct watershed -scale assessments of the impact of airborne reconnaissance data on precipitation forecasts in order to improve sampling strategies in future campaigns.

7.4 Meteorological Analysis

7.4.1 Findings

1. Landfalling ARs play a primary role in precipitation and precipitation extremes in the Santa Ana River watershed.
2. Smaller-scale phenomena during landfalling ARs (e.g., Narrow Cold -Frontal Rainbands) and the unique characteristics of the AR landfall (e.g., orientation/duration) are responsible for the spatial distributions of precipitation and storm-total accumulations within the watershed.
3. Specialized diagnostic and probabilistic forecast tools can improve situational awareness and characterize risk of smaller-scale phenomena, unique characteristics, and precipitation associated with landfalling ARs.
4. AR Reconnaissance and improved observations of ARs before landfall improve numerical weather prediction model forecasts of precipitation.
5. Machine learning and artificial intelligence techniques improve numerical weather prediction model forecasts of precipitation over the Santa Ana River watershed.
6. Research and Operations Partnerships serve as a focus for communication, training, and development of tools and information necessary for using forecasts as part of reservoir operations.

7.4.2 Recommendations Post-FVA

1. Conduct case studies and ongoing assessments of forecast skill as additional landfalling ARs produce precipitation challenges within the Santa Ana River watershed.
2. Evaluate the success and utility of new forecast tools derived from specialized diagnostics and probabilistic information.
3. Continue to explore and develop watershed-specific ML/AI methods to improve AR-related and non-AR-related precipitation forecasts in the Santa Ana River watershed.
4. Sustain AR Recon each year as an RAOP with continued focus on improvement in flight targeting techniques, assimilation methodologies, and demonstration of forecast improvements for Southern California.

7.5 Hydrologic Modeling

7.5.1 Findings

1. The precipitation and stream gaging network in the Santa Ana River watershed was sufficient to support the development and calibration of a contemporary hydrologic model.
2. An integrated Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model was developed, covering the Santa Ana River watershed, the Santa Ana River, and Prado Reservoir.
3. The model was calibrated and verified to both streamflow and change in reservoir volume.
4. Including the change in reservoir volume as a calibration metric improved the model's ability to simulate the change in reservoir volume without a significant reduction in streamflow simulation capability. This is seen as an advantage to using a fully integrated model.
5. When driven by CW3E NRT precipitation data, the model remained capable of simulating a key metric for operational considerations: 3-hour change in reservoir volume.
6. Using the model with the CW3E NRT precipitation data, the GSSHA model was able to simulate inflows into Prado Reservoir during the 2017–2022 period. The model performs best for large events, typically caused by ARs, indicating that it may add some value to estimates from the CNRFC.
7. An experimental operational GSSHA Santa Ana River watershed/Prado Dam model that uses the West-WRF 10 -day forecast has been developed on the CW3E network, with results downloaded and displayed by the FIRO Data Viewer on the U.S. Army Corps of Engineers' UMIP system.

7.5.2 Recommendations Post-FVA

1. Enhance the robustness of the GSSHA model by expanding the calibration period and range of event sizes.
2. Further develop the experimental operational model at Prado to maximize potential utility for operational support.
3. Use the NRT data for model spin-up before simulating the West-WRF forecast.
4. Process downscaled (post-processed) West-WRF ensembles through GSSHA to create ensemble streamflow forecasts.
5. Assess the accuracy of the GSSHA/West-WRF reservoir inflows as results become available.
6. Consider making the results available on the CW3E environment.
7. Process the forecast streamflow ensembles through the Prado Dam EFO model and HEC-ResSim as a proof of concept.

8. Use additional field data to assess and improve the GSSHA model as these data become available.

7.6 Least Bell's Vireo

7.6.1 Findings

1. Since water conservation began in the early 1990s, vireo populations have steadily increased as water conservation has expanded. Data indicate that vireos can adapt to the presence of standing water, and the highest populations have been observed during years with above -average water levels.
2. Baseflows in the Santa Ana River have been steadily declining since the early 2000s as the upper watershed continues to construct more recycling projects and advance water use efficiency. This means less water arriving in the Prado Basin for environmental needs. Further study is needed to evaluate if FIRO can offset habitat effects caused by decreases in baseflow.
3. Data suggest that wetter conditions improve vireo habitat through natural recruitment. Except for the understory, there are no data to support that irreparable forest damage has occurred due to prolonged inundation from water conservation. Further research is needed to understand how habitat responds to both short- and longer-term inundation.
4. OCWD owns over 2,000 acres in the Prado Basin, which are managed to maximize natural resource values. If mitigation is needed to offset impacts to riparian habitat attributed to FIRO, sufficient lands are available. The proposed action includes adaptive management measures that could be implemented if habitat loss occurs.

7.6.2 Recommendations Post-FVA

1. Expand the existing monitoring program above 505 feet to identify potential environmental impacts from increased water conservation, as needed implement the adaptive management program to offset impacts.
2. Preemptively and adaptively manage adequate riparian habitat to offset potential temporary or long-term impacts associated with FIRO.
3. Explore and study opportunities for habitat value creation made possible by FIRO. For example, continue experimenting with habitat islands and flood irrigation pathways above an elevation of 505 feet to expand the area benefiting from temporary flood irrigation, which could offset potential environmental impacts in the lower elevations associated with FIRO.
4. Develop new methods to study riparian habitat responses to prolonged dry and wet conditions.
5. Create operational procedures based on observed field conditions to maximize viable vireo habitat and success.

Section 8. Interim Operations and FIRO Implementation

This section describes the decision support needs for implementing Forecast Informed Reservoir Operation (FIRO) through deviation requests to the U.S. Army Corp of Engineers (USACE) Los Angeles District (LAD), and for permanent implementation through modifying the water control manual (WCM). One of the central needs for FIRO implementation is a water control plan (WCP) that utilizes forecasts to inform reservoir release decisions. Section 8.1 describes The importance of a FIRO Decision Support System (DSS) for Prado Dam and the process used to evaluate DSS needs, Section 8.2 describes the current DSS used by USACE LAD, Section 8.3 describes virtual operations for FIRO at Prado Dam, Section 8.4 describes data gaps identified for FIRO implementation, and Section 8.5 provides recommendations and findings.

8.1 Decision Support Systems

At the beginning of the Final Viability Assessment (FVA) process, a multidisciplinary decision support team was assembled, composed of members from the Orange County Water District (OCWD), USACE's LAD and Engineer Research and Development Center, the Center for Western Weather and Water Extremes (CW3E), and consultants. This team included experts in Prado Dam operations, operations of OCWD's groundwater recharge facilities, atmospheric science, hydrology, and data collection.

Decision support tools (DSTs) are an essential component of reservoir operations and are widely applied to support release decisions associated with reservoirs. WCPs used to manage USACE flood control space have traditionally been engineered to use observations ("water on the ground") as the basis for release decisions. Observations, while not perfect, are relatively certain. Forecasts have proven adequately skillful and are considered in the decision making process, but until recently they have never been formally used. FIRO shifts the operational paradigm, where forecast information is integrated as an essential component of the decision making process.

A decision support system (DSS) is an information system from a related set of tools that supports decision making. A DSS is a necessary part of FIRO that functions to provide operators and decision makers with current and forecasted information about a reservoir system. The DSS enables confident and well-informed operational decisions. Operating reservoirs can be very dynamic as weather and weather forecasts can change very rapidly, and reservoir operators and decision makers may need to respond to these changes multiple times per day. To support these needs, a DSS must be able to ingest and process data quickly, and therefore cannot utilize information with long latency or that is too cumbersome for current processing methods. However, a DSS must use the best available information and provide a complete picture of the forecasted environment to implement all components of a FIRO WCP.

To understand what a DSS needs in order to support FIRO implementation at Prado Dam, the DST team conducted four workshops covering the following topics:

- **Workshop 1.** Review existing tools used by USACE LAD to support operations for Prado Dam. This workshop evaluated two case study events to investigate how tools are utilized:

  - February 2019 atmospheric river (AR) event.
  - December 2021 non-AR event.
- **Workshop 2.** Review AR and watershed tools that could support FIRO.
- **Workshop 3.** Review operational reservoir management tools that could support FIRO.
- **Workshop 4.** Review forecasts and operations from the January 2023 AR Events.

These workshops were very useful to allow the study team's scientists and engineers to better understand the operational needs and challenges to implement FIRO at Prado Dam, and for USACE LAD engineers to learn how new tools might be used to support real -time operations under FIRO. The information gathered during these workshops provided the foundation for the analysis provided in this section. Meeting agendas, notes, and selected presentation slides from the workshops are included in Appendix F.

8.2 Existing DSS for Prado Dam

Prado Reservoir is a multi-purpose facility that was primarily constructed to reduce flood risk to downstream reaches of the Santa Ana River. Prado Reservoir contains a flood pool (elevation 490–543 feet) where, during high -inflow events, water can be detained to reduce flooding downstream. After peak inflows of the event have occurred, the water detained in the flood pool is then released at a rate that will not cause flooding downstream. Following the construction of Prado Dam, municipal infrastructure was constructed within the flood pool of the reservoir. When water is impounded in the flood pool as part of the semi-routine flood control operations of the reservoir during the wet season, these structures can be temporarily flooded. Corona Municipal Airport is most notably impacted when water elevation exceeds 514 feet. Additionally, Euclid Avenue becomes flooded at 515 feet and is closed when water elevation exceeds 510 feet. High releases from Prado Dam of water encroaching the flood pool can also impact downstream reaches. Releases that exceed conservation release rates to support OCWD groundwater recharge operations can impact downstream golf courses, unsanctioned encampments, and channel conditions. Due to the potential downstream impacts, USACE LAD tries to limit releases to 5,000 cubic feet per second if possible.

In order to minimize impacts from high water levels in the reservoir flood pool or high releases to downstream reaches, USACE LAD maintains tools to help notify affected stakeholders of potential impacts of upcoming flood events. USACE LAD maintains a document (the Orange Book) to track the contact information of permanent landowners and residents who are at risk of flooding due to reservoir operations. LAD tracks Correspondence with Orange Book contacts in a database to record the success or failure of each outreach attempt. In addition, LAD maintains a site access notification system to track entities, such as contractors completing work in the reservoir flood pool and downstream in the Santa Ana River, that may be temporarily impacted by Prado Dam operations. These entities are required to fill out a form with their contract information and information on where and when they will be working. LAD uses These systems to notify affected stakeholders at least 24 hours in advance of a potential flood event to allow them to make necessary preparations. LAD also coordinates with emergency responders in case there are encampments of people experiencing homelessness that could be impacted.

A significant amount of planning and management regarding forecasted flood events can help prepare for potential high releases and encroachment of storage into the reservoir flood pool.

Lead time in advance of flood events is required for Prado Dam operations in order to inform staffing needs for the USACE LAD Reservoir Operations Center (ROC), provide time to staff dams with dam operators, inform release decisions, and notify affected stakeholders in advance of anticipated flood events. LAD has developed a Corps Water Management System (CWMS) of the Santa Ana River watershed, which is an integrated system that links system observations to watershed models to help automate simulations and support reservoir operation decisions.

The Santa Ana River CWMS currently includes a Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS), HEC Reservoir System Simulation (HEC-ResSim), HEC River Analysis System, and an HEC Flood Impacts Analysis model. All These models can be used to support real -time operations, but the HEC-ResSim model is most frequently used. A key component of CWMS is the Control and Visualization Interface (CAVI), which supports quality assurance and quality control of recently collected monitoring data and forecast modeling to support water operations decision making.

USACE LAD utilizes gridded quantitative precipitation forecasts (QPFs) from two sources: Fox Weather and the National Weather Service's (NWS's) California Nevada River Forecast Center (CNRFC). LAD maintains a contract with Fox Weather for precipitation forecast services. Fox Weather provides hourly QPF with a three-day lead time and a frequency of up to twice per day. USACE LAD also uses six-hour QPF from the CNRFC, which has a six-day lead time and a frequency of two to four times per day depending on storm activity (once per day outside the flood season). QPFs are primarily used by LAD as situational awareness to help inform ROC staffing needs and stakeholder notifications. QPFs can be used as inputs to the HEC-HMS to generate inflow forecasts into Prado Dam; however, this is rarely done to support real -time operations.

USACE LAD uses deterministic inflow forecasts from the CNRFC to predict reservoir pool elevation. These hourly timestep forecasts are generated with a five-day lead time from two to four times per day using the CNRFC QPF (once per day outside of the flood season). LAD uses these deterministic forecasts with spreadsheet models and an HEC-ResSim model that is part of the Santa Ana River CWMS. The spreadsheet models are currently the main tool LAD uses to formulate forecast-based prereleases that include predicted storage levels behind Prado Dam. LAD will frequently use these spreadsheet models to evaluate multiple release schedule alternatives before making a final release decision.

In addition, LAD frequently monitors radar reflectivity data from local radar systems provided by DTN Weather, a service that LAD subscribes to that provides web-based, real-time radar imagery. These data are used for situational awareness to assess in real time whether a precipitation or inflow forecast might be off due to a shift in the position of a storm relative to the Santa Ana River watershed. Based on past experience, LAD has found these data to be very useful for potential adjustments in release schedules to minimize the over-release of stored water.

Figure 8-1 below provides A flowchart diagram of the primary tools used to support current operations. Although some of these tools are not currently integrated into the Santa Ana River watershed CWMS DSS (e.g., the weather models, CNRFC deterministic forecasts, the spreadsheet models), LAD uses information from all tools to support operations. Collectively, these tools represent a DSS to support LAD's operational needs.

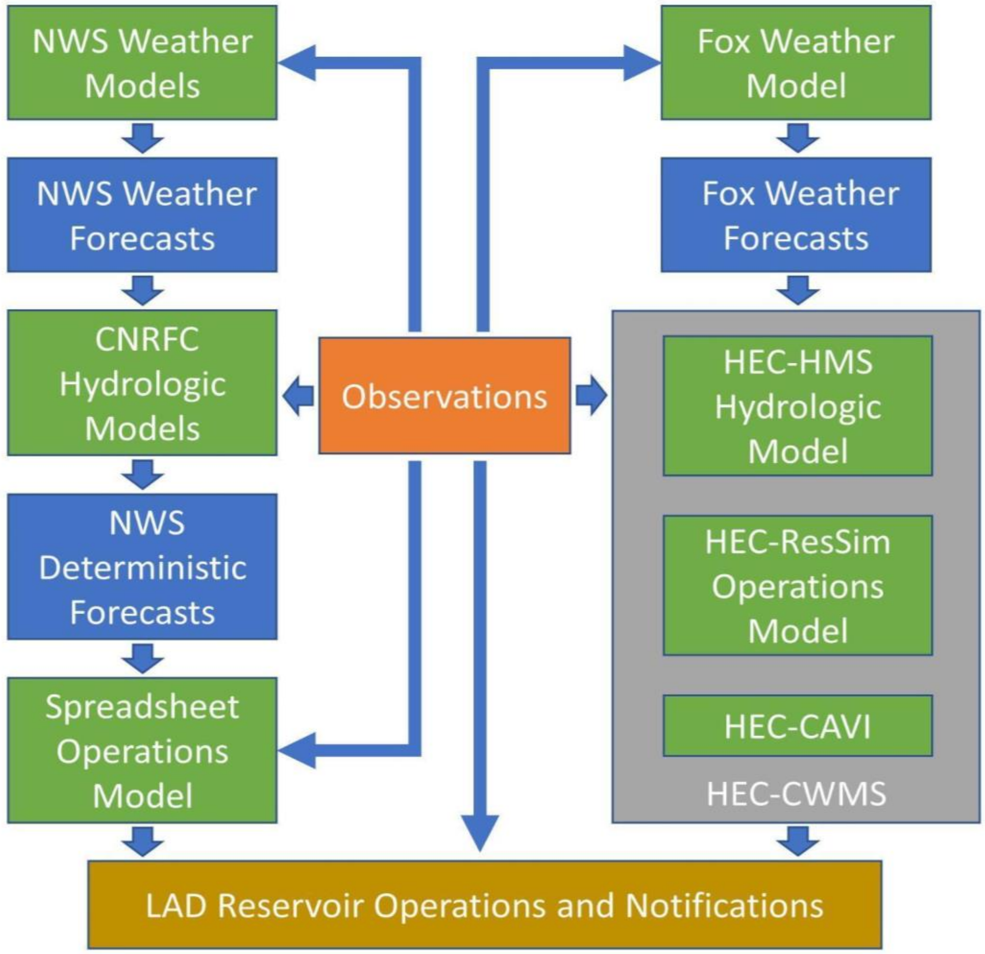

Figure 8-1. *Flowchart diagram showing the primary components of USACE LAD's existing DSS.*

Figure 8-2 below illustrates the relationship between types of operations at Prado Dam and the current tools used to support operations. This figure shows that all types of operations utilize all types of tools; however, the dotted line in the figure is used to show relationships where a given tool supports a specific type of operation, and the solid lines show relationships where a tool is the primary source of information to support operations. Note that, as indicated in the figure, the spreadsheet operations model is currently the primary tool to support LAD's reservoir release decisions.

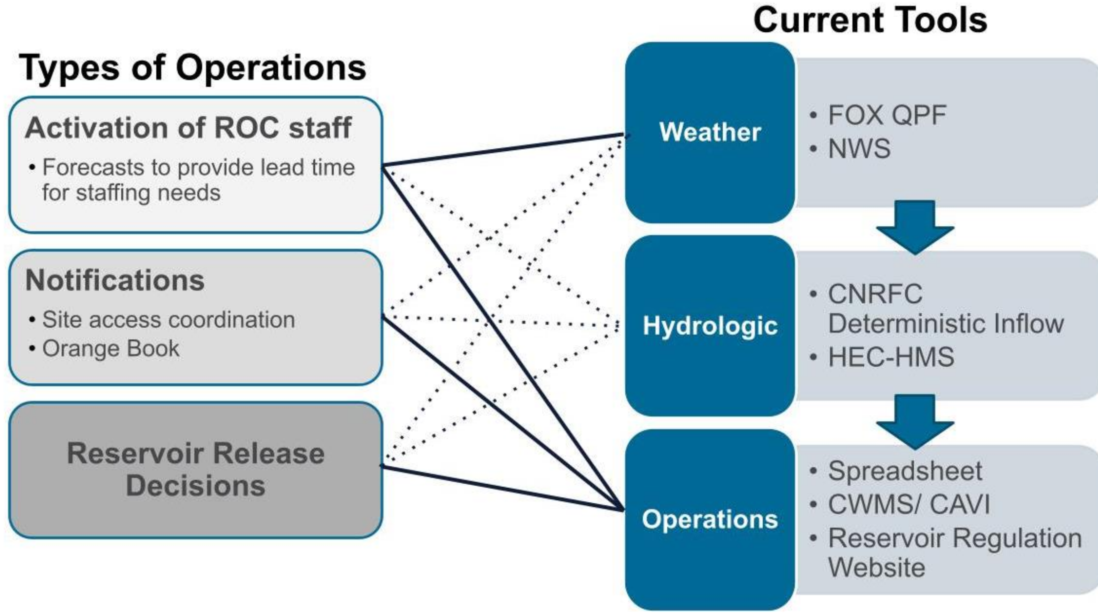

Figure 8-2. *Diagram showing the relationship of current types of operations to tools currently used by USACE LAD to support operations.*

8.3 Prado FIRO Virtual Operations

As part of the FVA, CW3E collaborated with OCWD to generate a real -time operations model for water year 2023 that could simulate and evaluate operations under current and forecasted conditions if FIRO were implemented at Prado Dam. FIRO was simulated using the Ensemble Forecast Operations (EFO) methodology (Section 4), which uses ensemble forecasts from the Hydrologic Ensemble Forecast System (HEFS) issued by the CNRFC (Section 4) to manage forecasted flood risk. This alternative (Virtual EFO) included an expanded buffer pool to 508 feet in elevation with flood control objectives of minimizing the encroachment of water in the flood pool above 514 feet (Corona Airport elevation) and minimizing overtopping the spillway crest at elevation 543 feet. The 508-foot buffer pool is proposed in the minor planned deviation expected to be implemented in fall 2023. The Virtual EFO can model the risk of encroaching over 514 and/or 543 feet, as described in Section 4 and Section 5. Virtual EFO release decisions were thus different from decisions made under the current WCP by human regulators.

Prado Reservoir storage and elevation results for the 2023 Virtual EFO alternative and observed conditions are shown in Figure 8-3 below. The Virtual EFO alternative deviated from observed operations in mid-January (at the beginning of the solid blue line) because the EFO model simulated a pre-release to minimize flood risk based on an AR forecasted to impact the Santa Ana River watershed. 2023 was a very active flood control season, with eight ARs that made landfall on the Santa Ana River watershed, which is evidenced by the rapid increases in observed and Virtual EFO storage. The Virtual EFO scenario simulated pre-releases in advance of large inflow events to manage water elevations well below 514 feet. Additionally, with the expanded buffer pool, the Virtual EFO scenario resulted in approximately 6,600 acre-feet of additional storage for water supply (and potential groundwater recharge) at the end of April relative to what actually took place. Results of these virtual experiments were updated with each CNRFC inflow forecast issuance (at least once per day) and posted to a password - protected webpage developed and maintained by CW3E.

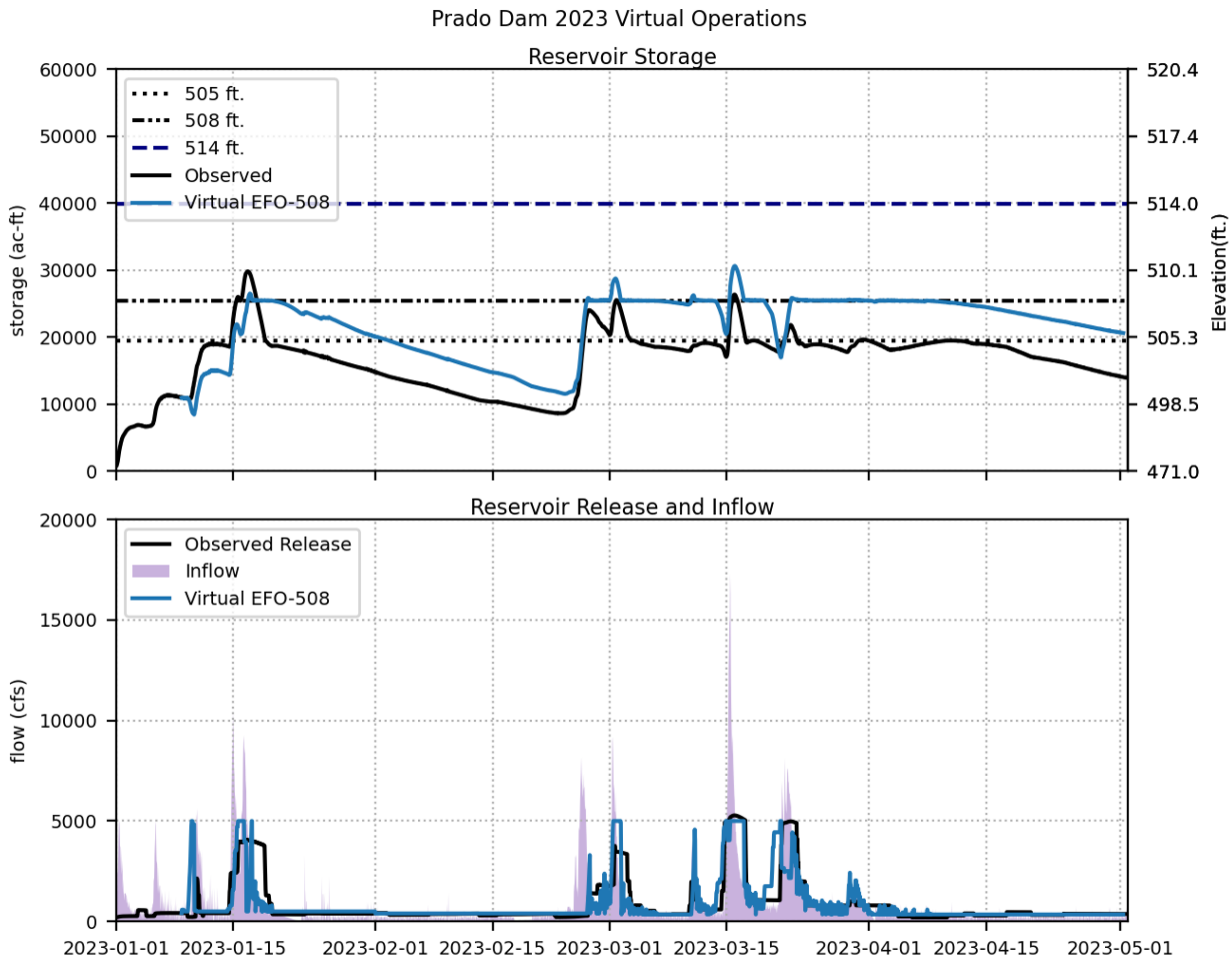

Figure 8-3. *Observed Prado Reservoir storage and simulation results of the Virtual EFO alternative for January–April 2023.*

8.4 Current Data Gaps for FIRO Implementation

The data gaps identified in this section are based on feedback provided during the workshops.

A FIRO WCP, which defines the different types of forecast information and how this information will be evaluated to inform release decisions, is essential for developing a FIRO DSS and implementing FIRO. A FIRO WCP has not been selected for Prado Dam, but multiple WCPs are being evaluated in the Water Resources Engineering (WRE) analysis of this assessment, as described in Section 4 and Section 5.

A central challenge in implementing FIRO that was emphasized during the workshops was accounting for uncertainty in forecasts. One common way to assess forecast uncertainty is through ensemble forecasts, which describe the forecast uncertainty through a moderately large set of equally likely outcomes. Sources of uncertainty in hydrologic forecasts include observations (precipitation, air temperature, and streamflow), model states (snowpack, soil moisture, and hydrologic routing), hydrologic model structure and parameters, and forecasted conditions (precipitation and air temperature). Individual members of an ensemble forecast are designed to be equally likely, and probability of different outcomes can be calculated across time to inform operations similar to the EFO alternative described in Section 4. NWS operates HEFS, and the CNRFC provides daily to sub-daily HEFS forecasts for numerous locations throughout California and Nevada, including inflow into Prado Dam and other locations within the Santa Ana River. The FIRO alternatives evaluated in this study utilize the quantified uncertainty of HEFS to inform release decisions. Differences between alternatives stem from the way this uncertainty is used.

Based on a review of historical events and the operational challenges posed by the events evaluated during the workshops, as previously discussed in Section 3, it would be useful to complete an assessment of QPF skill based on storm type, such as AR events versus non-AR events. The predictability of ARs may be greater than non-ARs for Southern California, and perhaps this relationship could be better understood and quantified. ARs are linked to the most significant flood events for the Santa Ana River, so improving confidence in predicting these events could provide useful situational awareness information for USACE LAD to support operations. Additionally, given the potential flood impacts from ARs, tools designed to predict ARs, such as those developed by CW3E that were reviewed during the workshops, may also provide additional lead time for flood events.

A common theme expressed at the workshops was "more information is not necessarily better." During ROC activation, Prado Dam is one of many facilities that LAD must manage, and the operational environment can be very dynamic as current conditions and forecasted weather can change very rapidly. Reservoir operators and decision makers may need to respond to these changes multiple times per day. Therefore, a DSS should provide the necessary information to fully inform the decision makers to confidently make decisions, but not overwhelm the decision makers with too much information that could cause confusion or potentially delay an important decision. Relevant information such as tools tailored for the Santa Ana River watershed could help simplify the decision making process.

8.5 Next Steps

A complete plan for FIRO DSS at Prado Dam cannot be developed before a WCP or set of WCPs is chosen for further evaluation during interim operations. However, scoping toward the development of a DSS can be accomplished at this time. The primary WCP alternatives include different variants of the EFO alternative evaluated in the Prado Dam Preliminary Viability Assessment and the Simpler Ensemble Forecast Operations (SFO) alternative developed by HEC for this study. Both the EFO and SFO alternatives were developed and simulated using the HEFS hindcasts developed by the CNRFC (Section 4). The initial DSS for FIRO implementation at Prado Dam will, therefore, need to incorporate HEFS forecasts to ensure comparable results to the WRE analysis completed for this FVA.

Once USACE LAD selects a preferred WCP or a preferred set of WCPs, LAD will need to integrate the plan into the existing DSS framework. Prior to this selection, DSS elements need to be in place to support the minor planned deviation (508-foot buffer pool). As previously discussed, LAD has developed Santa Ana River CWMS to support real -time operations and plans to continue to use this DST as the primary tool for decision making under FIRO. Therefore, LAD will also need to integrate the selected WCP alternatives into CWMS. HEC-ResSim is a central component of CWMS, and the SFO alternative has a more simplified evaluation of inflow ensembles and was developed to work with HEC-ResSim. Therefore, no special accommodation would be required to implement this alternative.

The EFO alternative, however, individually models each member of an ensemble and manages to the forecasted probabilities of exceeding critical storage thresholds, such as the Corona Airport at 514 feet of elevation or the 543-foot spillway crest. HEC-ResSim is not currently capable of simulating this alternative. Implementing the EFO alternative would require special accommodations to integrate this alternative into the CWMS framework. The EFO model has been loosely coupled to HEC-ResSim to support several studies, including the Lake Mendocino FVA, the Yuba-Feather Preliminary Viability Assessment, and the EFO model simulation for this study. A similar linking approach could be used to integrate the EFO model into CWMS. Additionally, the EFO model can also be integrated directly into the CWMS framework as an independent model so it can work with both HEC-ResSim and other modules within CWMS. Implementing FIRO at Prado Dam will likely follow a phased approach that will start through deviation requests from the Steering Committee to USACE LAD and result in fully implementing EFO with the revised WCM after the spillway raise is completed. Integrating EFO may also follow a phased approach, starting with a loose coupling to support deviations to the WCM, and moving to a full integration to support WCM update #2. Additionally, HEC-ResSim may be upgraded and modified to support simulation of ensemble forecast alternatives such as EFO.

USACE LAD frequently uses real-time observations and forecasted precipitation to support decision making. The AR landfall and AR scale tools can also provide additional lead time to inform management decisions. A website dedicated to the Santa Ana River could be developed to support real -time operations at Prado Dam. This website would provide observations, precipitation forecast products, and AR forecasting products focused on the Santa Ana River watershed. The addition of multiple models, including ensemble models, would provide situational awareness of potential hazardous events, the uncertainty within those events, and a probabilistic prediction of future impacts.

A FIRO DSS must be adaptive to future improvements in forecasting skill and future changes to Prado Dam, such as the spillway raise to 563 feet. The DSS that LAD uses to support FIRO at Prado Dam is expected to evolve and improve as water managers and FIRO practitioners gain experience. A collaborative framework of communication between water managers, forecasters, and developers should be established, including regular meetings and briefings, so forecasters and tool developers can receive ongoing feedback to support refining DSS. Additionally, regular lines of communication should be established between water managers and forecasters to support real -time collaboration as a flood event evolves.

The current DSS flowchart has been modified to show a configuration where additional tools may be integrated to develop a FIRO DSS (see Figure 8-4 below). The red boxes show additional tools that may be integrated, and the orange arrows show the new connections to support integrating these additional tools. All the added tools shown in the flowchart are described in previous sections of this FVA.

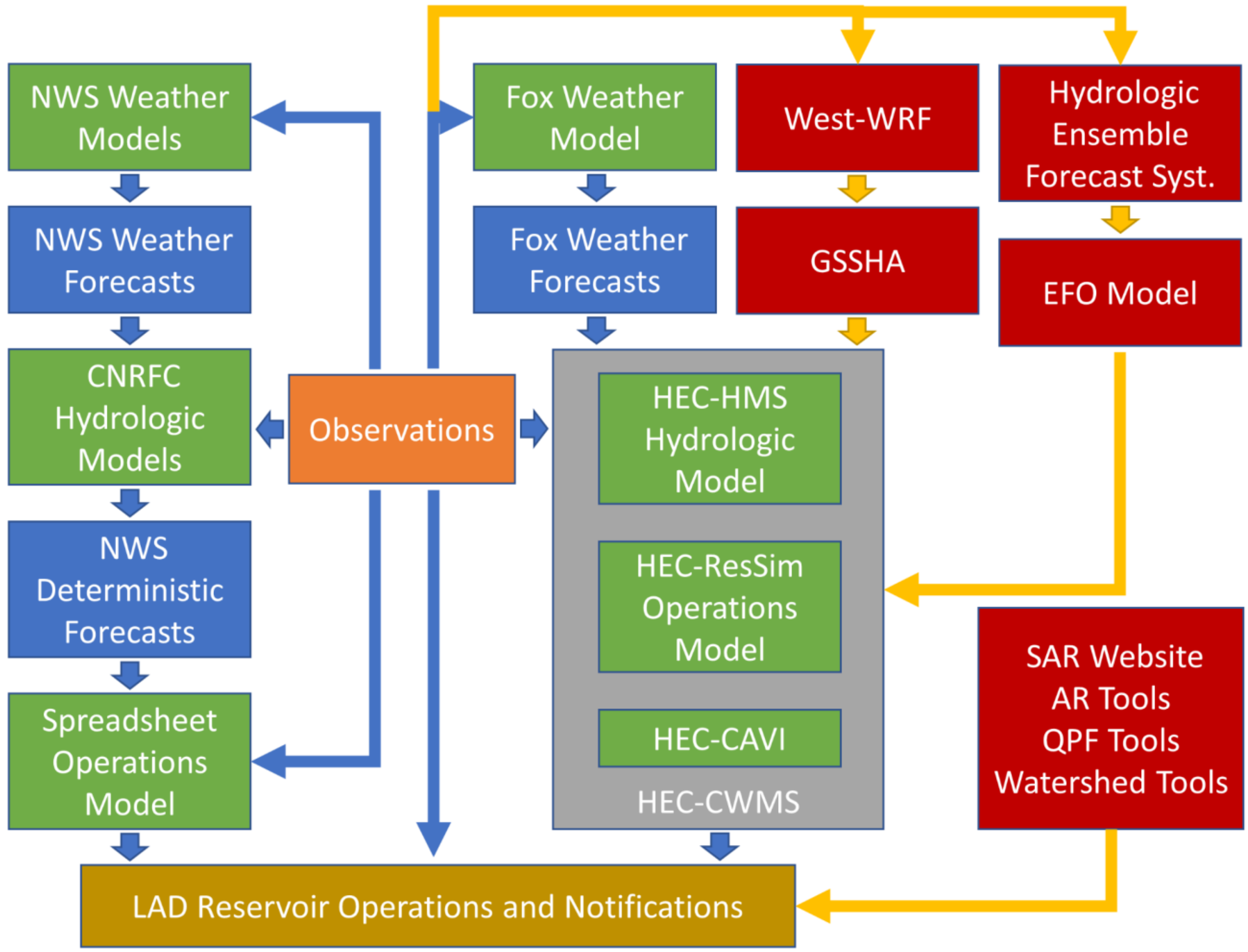

Figure 8-4. *Proposed framework for a FIRO DSS showing additional tools that may be included in the existing DSS framework.*

8.6 Roadmap to FIRO Implementation

The implementation will follow a phased approach, including interim implementation through temporary deviations to the WCM and full implementation through modifications to the WCM (as discussed in Section 1). In 2021, the FIRO Steering Committee requested a five-year minor planned deviation for Prado Dam that will increase the buffer pool elevation from 505 to 508 feet and manage flood risk using a FIRO WCP. This minor deviation request is currently under review but is anticipated to be approved in 2024. It will allow the real -time testing and refinement of DSTs and FIRO WCPs. USACE LAD is currently planning to raise the Prado Dam spillway to 563 feet, and construction is anticipated to begin in 2024 and completed by 2031. Full implementation will be pursued as part of the WCM changes that will be initiated in late 2024. Developing a FIRO DSS is recommended to begin in Fall 2023 and continue indefinitely as forecasts improve and DSTs are refined. Based on the phased approach for FIRO implementation, a roadmap for developing a FIRO DSS is outlined below. Additionally, Figure 1-3 has been modified to include the development of a FIRO DSS, as shown below in Figure 8-5.

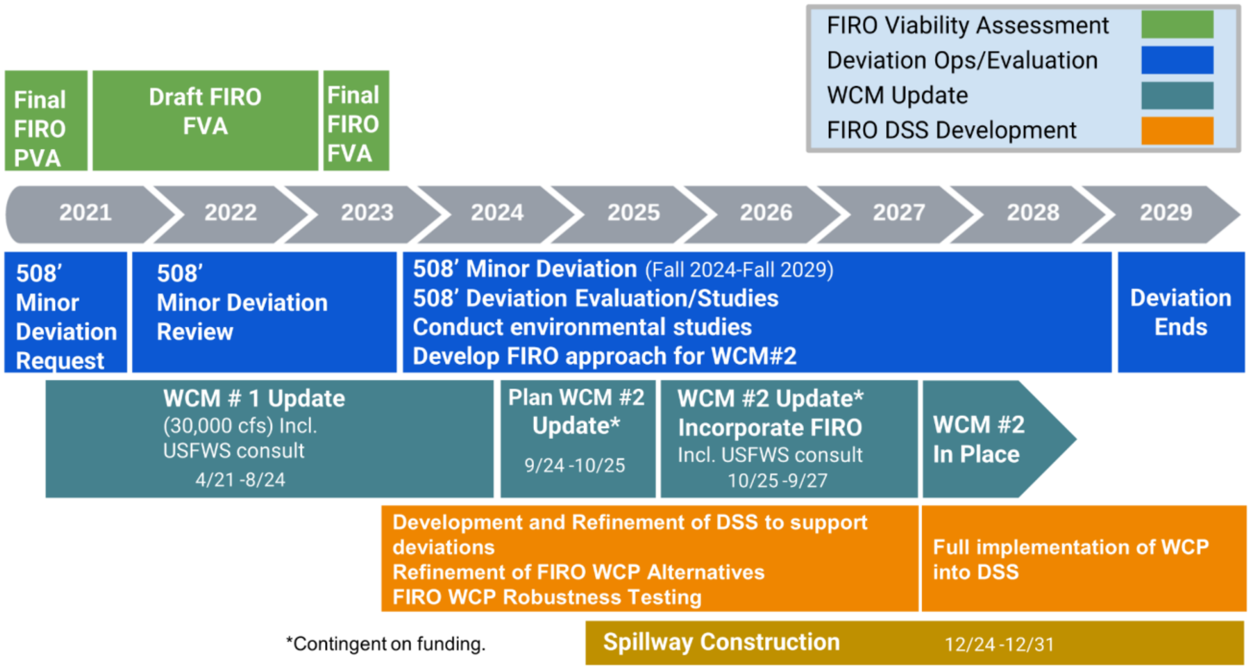

Figure 8-5. *FIRO implementation schedule with the inclusion of the development of a FIRO DSS as shown with the orange rectangles.*

Below is a FIRO implementation roadmap that includes information on developing and implementing a FIRO DSS, refining WCP alternatives, and integrating assessments from Seven Oaks Dam:

- **Develop FIRO DSS (2023–2027).**
  - Create FIRO Dashboard and dedicated website, including:
    - AR Tools such the AR Landfall Tool and AR Scale Tool.
    - QPF comparison tool to compare precipitation from different forecast models.
    - Watershed precipitation tools that summarize forecasted precipitation for the Santa Ana River watershed.
    - EFO dashboard that displays release decisions simulated to manage forecasted risk with respect to established risk tolerance levels.
  - Integrate select WCP alternatives into HEC-ResSim and CWMS to support real -time operations.
- **Develop and implement DSS collaboration framework (2023–2027).**
  - Develop a working group of USACE LAD ROC staff, water forecasters, and other subject matter experts.
  - Define regularly scheduled meetings with ROC staff and forecasters to discuss DST needs to support FIRO. Meetings should occur at least three times per year—one meeting in the fall before the flood control season, one in the middle of the winter season, and another in late spring or early summer at the end of the flood control season.

  - Develop communication requirements to support ROC staff for real -time operations during active forecast periods.

- **Refine WCP Alternatives (2023–2025).**
  - Refine WCP alternatives, as needed, after testing during minor deviations and feedback from ROC staff.
  - Complete robustness testing of WCM alternatives, which should include simulating extreme flood events through developing synthetic forecasts.

- **Integrate results from the Seven Oaks Reservoir viability assessments (2026).**
  - The FIRO viability assessment for Seven Oaks Dam, which is upstream of Prado Dam, is scheduled to begin in 2024. Reservoir operations modeling and analysis for Seven Oaks Dam should include the evaluation of potential impacts to Prado Dam operations. Prado Dam FIRO WCP alternatives may need refinement to account for potential changes in operations to Seven Oaks Dam under FIRO.

8.7 References

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