Title

Prado Dam Forecast Informed Reservoir Operations Preliminary Viability Assessment

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Preliminary Viability Assessment

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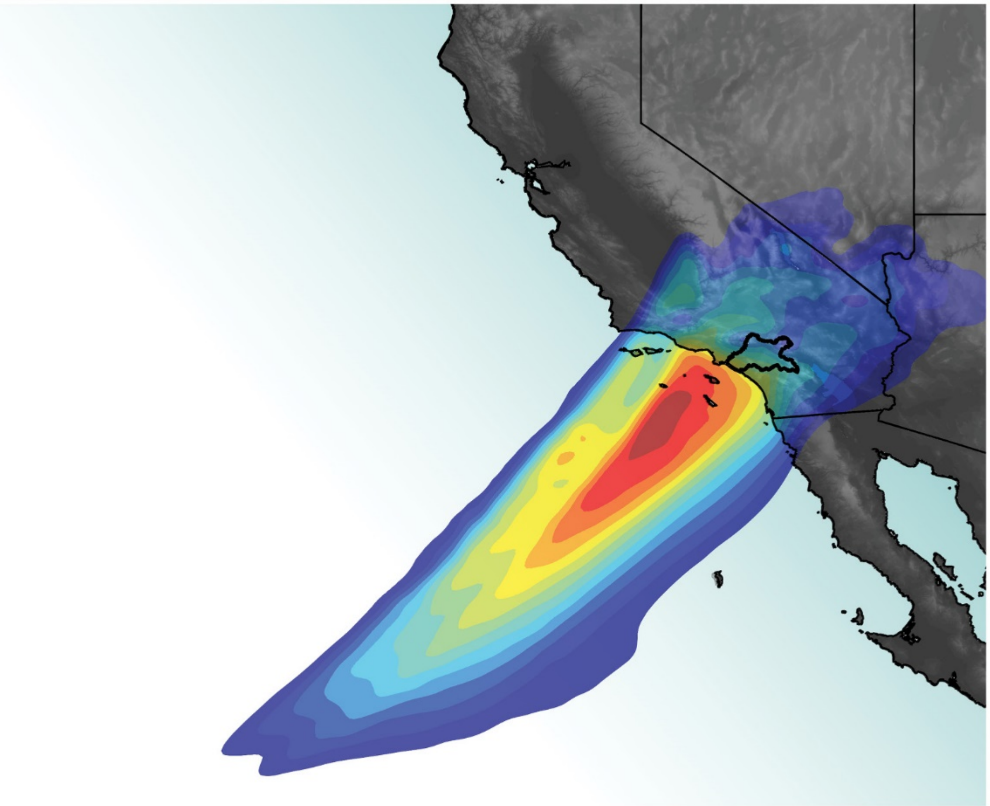

Prado Dam FIRO Steering Committee

- **F. Martin Ralph:** CW3E (Co-chair)
- **Greg Woodside:** Orange County Water District (Co-chair)
- **Jay Jasperse:** Sonoma Water
- **Michael Anderson:** California Department of Water Resources (DWR)
- **Cary Talbot:** USACE, Engineer Research and Development Center
- **Alan Haynes:** California Nevada River Forecast Center
- **Rene Vermeeren:** USACE Los Angeles District
- **Jon Sweeten:** USACE Los Angeles District
- **James Tyler:** Orange County Public Works
- **Karin Cleary Rose:** U.S. Fish and Wildlife Service, Palm Springs

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Appendices

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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
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
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
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

Abbreviation	Definition
OCWD	Orange County Water District
PVA	Preliminary Viability Assessment
QPE	quantitative precipitation estimation
QPF	qualitative precipitation forecast
RAOP	research and operations
RFM	Recharge Facilities Model
ROC	Reservoir Operation Center
SARM	Santa Ana River Mainstem
SCE	Shuffle Complex Evolution
STIV	Space-Time Image Velocimetry
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
WRF	Weather Research and Forecasting
WY	water year

Section 1 Executive Summary

This Preliminary Viability Assessment (PVA) was initiated by the Prado Dam Forecast Informed Reservoir Operations (FIRO) multi-agency Steering Committee in 2017 and follows the workplan completed in 2019. The PVA provides an initial evaluation of the viability of FIRO as a strategy for improving water supply reliability for Orange County Water District (OCWD), while not impairing and possibly enhancing environmental conditions and flood risk management. Constructed and operated by the U.S. Army Corps of Engineers (USACE), Prado Dam was primarily designed for flood risk management. Stormwater capture for downstream groundwater recharge into OCWD's water supply is a secondary purpose. The PVA demonstrated that FIRO is viable, and it lays the groundwork for a Final Viability Assessment (FVA) and recommendations for updating USACE's Water Control Manual (WCM), which governs operation of Prado Dam.

1.1 Project Overview

OCWD has been capturing and recharging stormwater in the Santa Ana River channel since 1936. Since USACE built Prado Dam in 1941, OCWD and USACE have worked together to maximize the capture of stormwater behind the dam. Figure 1-1 shows the elevations and volumes of the current conservation pool. USACE releases water temporarily captured at Prado Dam and OCWD recharges the water into the ground 10 miles downstream. The water conservation pool has been operated at elevations up to 505 feet based on a five-year major deviation approved by USACE in March 2018. The Prado Basin Ecosystem Restoration and Water Conservation Feasibility Study was approved in 2021 to make the 505-foot conservation pool a permanent feature within the Interim WCM.[1]

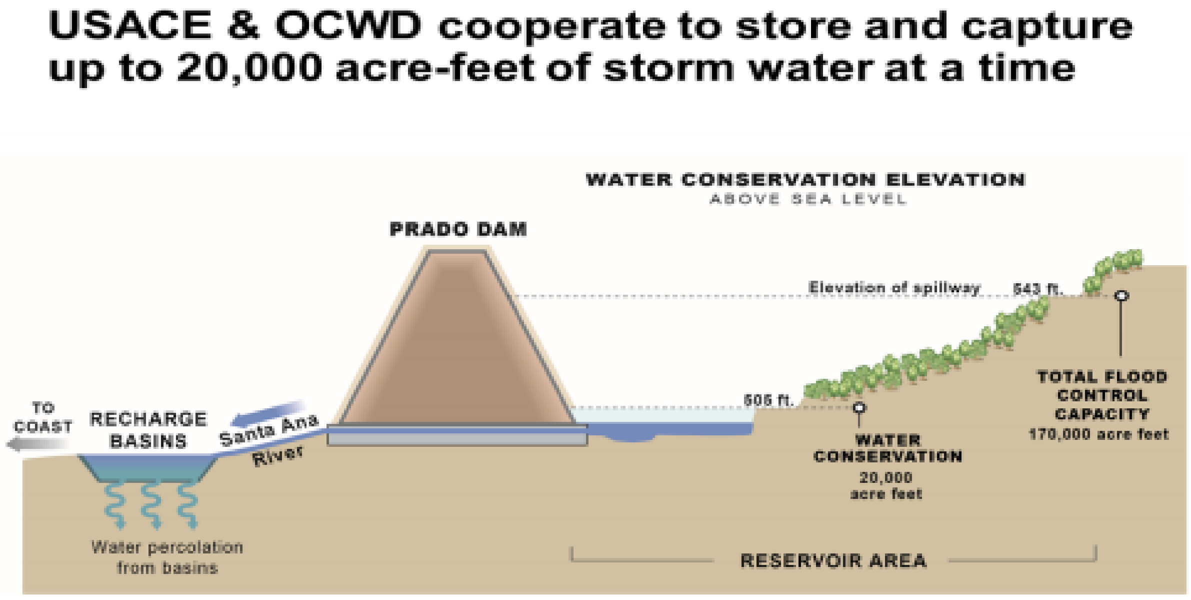

***Figure 1-1.** Schematic of Prado Dam water conservation elevation for stormwater storage and capture (credit: OCWD)..*

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[1] All cited elevations in this report are in feet, based on the datum of NGVD 1929.

Over the past 25 years, OCWD has recharged an average of 55,000 acre-feet (ac-ft) per year of stormwater with an annual maximum of 117,000 ac-ft in 1995. For planning purposes, OCWD assumes that 40,000 ac-ft of stormwater will be captured and recharged in an average year, which is enough water for 320,000 people annually. Local stormwater capture is important because it lessens demands on imported water supplies, which are more costly and increasingly unreliable due to the fragile Sacramento Delta, the oversubscribed Colorado River, and changes in weather patterns.

The Prado Dam WCM, which governs operational decision making, does not explicitly leverage weather and water forecasts. Nonetheless, USACE staff consider precipitation and streamflow forecasts in their decision process while adhering to WCM guidelines and procedures. This PVA assesses the potential application of FIRO at Prado Dam to capture larger volumes of stormwater in the future. This is an opportune time to consider FIRO. With improvements underway to raise the Prado Dam spillway crest and upgrade downstream infrastructure (Santa Ana River Mainstem Project), a very high level of flood risk management will be achieved.

1.2 Atmospheric Rivers and FIRO

Atmospheric rivers (ARs) are the major determinant of flooding and a lack of ARs leads to drought conditions in California. ARs are responsible for more than half of all beneficial precipitation and over 90 percent of flood damages. Long, narrow bands of concentrated moisture, ARs stretch thousands of miles across the Pacific Ocean, carrying up to 20 times as much water as the Mississippi River. When ARs make landfall, they can release a staggering amount of rain and snow (see the example of a landfalling AR in Figure 1-2). The absence of ARs can lead to drought. For this reason, studies of AR behavior and improved AR forecasts are essential to inform and implement FIRO.

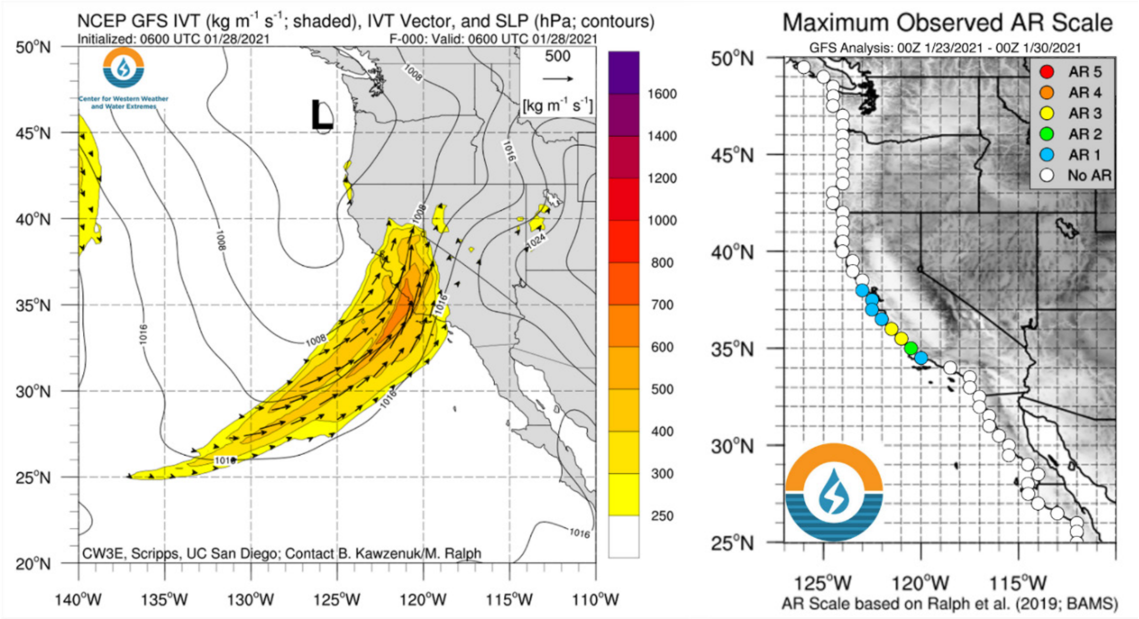

Figure 1-2. A landfalling AR generated 15–20 percent of Los Angeles Basin precipitation on January 29, 2021.

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.

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 in a manner that reflects 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 and precipitation variability unique to the U.S. West Coast. The ultimate goal of FIRO is to inform the update of USACE's WCM for Prado Dam to allow FIRO flexibility, as demonstrated by rigorous analyses and documented in the next step of this process—the FVA. Central to FIRO is an ongoing commitment to research that provides for continual improvement in operations as forecast skill allows.

To explore FIRO as a viable approach to increase the efficiency of stormwater capture at Prado Dam, OCWD co-chairs a Steering Committee with the Center for Western Weather and Water Extremes (CW3E) at UC San Diego's Scripps Institution of Oceanography. Steering Committee members include representatives from USACE, the U.S. Fish and Wildlife Service, the National Weather Service's California Nevada River Forecast Center, the California Department of Water Resources, and Orange County Public Works. Using the collaborative Steering Committee process, FIRO has proven viable on Lake Mendocino in Northern California and is currently being assessed in the Yuba and Feather River watersheds, at New Bullards Bar Reservoir, and at Lake Oroville.

Prado Dam FIRO Steering Committee

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Jay Jasperse, Sonoma Water
Michael Anderson, California Department of Water Resources
Cary Talbot, USACE Engineer Research and Development Center
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Rene Vermeeren, USACE Los Angeles District
Jon Sweeten, USACE Los Angeles District
James Tyler, Orange County Public Works
Karin Cleary-Rose, U.S. Fish and Wildlife Service

1.3 Results of the PVA

This Prado Dam PVA evaluated current forecasting technology and incorporated research to understand and therefore better predict precipitation processes in the Santa Ana River Watershed. The Ensemble Forecast Operations (EFO) model, which was used to assess FIRO at Lake Mendocino, was successfully generalized and applied to Prado Dam for the simulation of operations needed to assess strategies for implementation in the updated WCM. The EFO model operates without a traditional guide curve and uses the 15-day ensemble streamflow forecasts to identify required flood releases. The Steering Committee's preliminary assessment of FIRO was based on five operational strategies, described in Table 1-1 below.

Table 1-1. Alternative Water Control Plan strategies assessed for the Prado Dam FIRO PVA.

ID	Alternative Strategy	Description
1	Unrestricted: 505 feet (baseline)	Buffer pool* allowed to extend up to 505 feet without a seasonal restriction. Releases when pool is ≤ 505 feet at maximum recharge rate. Releases above 505 feet are at the maximum scheduled rate. No forecasts were used.
2	EFO-508 feet	Buffer pool allowed to extend up to 508 feet. Uses ensemble inflow forecast to determine release required to mitigate risk of exceeding spillway crest.**
3	EFO-512 feet	Buffer pool allowed to extend up to 512 feet. Uses ensemble inflow forecast to determine release required to mitigate risk of exceeding spillway crest.**
4	No Forecast-512 feet	Buffer pool allowed to extend up to 512 feet. Releases when pool is ≤ 512 feet at maximum recharge rate. Releases above 512 feet are at the maximum scheduled rate. No forecasts were used.
5	Perfect Forecast-512 feet	Buffer pool allowed to extend up to 512 feet. Uses observed inflows as forecasts (perfect forecasts) to determine releases that avoid exceeding spillway crest.**

* “Buffer pool” is a USACE Los Angeles District term used to describe an acceptable temporary encroachment into the flood pool for water conservation purposes.

** A spillway crest of 543 feet was evaluated for period of record simulations, and spillway crests of 543 and 563 feet were evaluated for 100-year and 200-year scaled hydrologic events.

The EFO model was successful in simulating the reservoir operations strategies listed in Table 1-1 over the hindcast period of record (1985–2011) and for three large events scaled to 100- and 200-year return frequency levels. Hindcast period of record simulations for all alternatives remained well below the spillway crest, and higher buffer pools led to greater groundwater recharge, averaging nearly 7,000 ac-ft per year. The scaled events, which generated spillway flow for all FIRO alternatives (ones that use forecasts), exhibited slightly lower spill rates than the baseline. The upper limit of the buffer pool is largely a function of community and environmental tolerance for more frequent flood pool inundation than operational constraints of the dam. Land and easement purchases coordinated by USACE and Orange County Public Works are required for the spillway raise and will be critical to easing impacts of more frequent inundation. At the highest pool elevation that was assessed (512 feet), the use of forecasts is needed to avoid increased flood risk.

The PVA also concluded that, while precipitation gages are adequate to support FIRO, improvements are needed at two stream gage locations to support operations and model calibration and development. In addition, the hydrologic engineering management plan (HEMP) initial assessment was found to provide a consistent framework within which Water Control Plan (WCP) alternatives can be simulated and compared. Identified refinements will improve the quality of the FVA.

High-level PVA findings that support FIRO viability include the following:

- Evaluation of FIRO WCP alternatives suggests that higher buffer pools can enhance groundwater recharge, averaging nearly 7,000 ac-ft per year, while not impacting and perhaps enhancing flood risk management outcomes.
- Much progress has been made to improve AR forecasts and AR tools. Evaluation of the AR landfall tool for Prado Dam showed full internal agreement at three-day lead times and a high degree of reliability at greater than five days' lead time, which is sufficient for dam operators to make timely releases.
- Studies of least Bell's vireo (a federally listed endangered species of bird that nests in the water conservation space behind the dam) indicate tolerance to inundation, but further studies are needed to assess prolonged inundation at higher elevations. An adaptive management approach with planned mitigation measures will be pursued.

1.4 Recommendations and Roadmap for the FVA

Based on these findings, the FIRO Steering Committee recommends continued research and monitoring to further improve potential FIRO outcomes, coordination with and support of the USACE WCM update process, development of operational decision support tools designed specifically for FIRO implementation, refinement of the HEMP for evaluating the WCP alternatives, and interim operational testing through USACE's deviation process. In particular, the Steering Committee recommends submitting a multi-year deviation beginning in water year 2023 (October 2022) to gain operational experience with a FIRO maximum buffer pool greater than 505 feet.

Figure 1-3 shows the timeline for the FVA and WCM update.

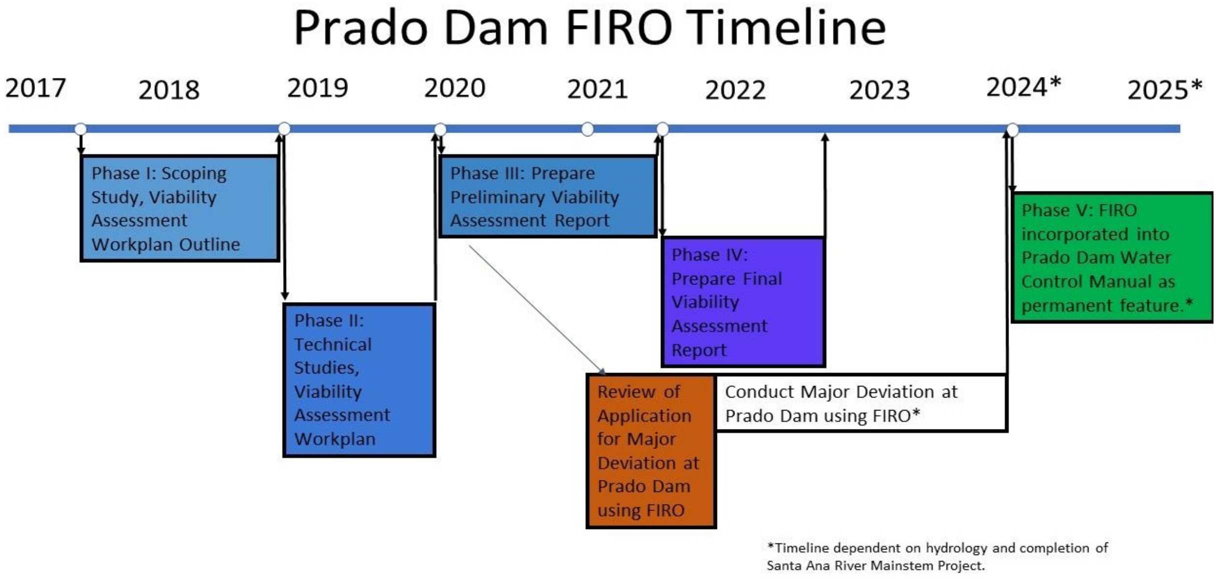

Figure 1-3. Prado Dam FIRO project and WCM update timeline.

Section 2 FIRO at Prado Dam

2.1 Background

The U.S. Army Corps of Engineers (USACE) constructed Prado Dam, located on the Santa Ana River, in 1941 for the primary purpose of flood risk management. It has a gross storage capacity of 173,000 acre-feet (ac-ft) at the spillway crest. Authorization for the original Prado Dam and Reservoir project is contained in the Flood Control Act of June 22, 1936 (PL 74-738), which authorized the construction of reservoirs and related flood control works for the protection of the metropolitan area of Orange County, California. The USACE Los Angeles District (LAD) owns and operates the dam.

Prado Dam is also operated to help Orange County Water District (OCWD) recharge the Orange County Groundwater Basin in northern Orange County. Stormwater capture is an important groundwater recharge source, as described below. OCWD was formed in 1933 by the California state legislature to manage the Orange County Groundwater Basin, conserve groundwater supplies, and protect its rights to the Santa Ana River. To fulfill its mandate, OCWD has developed a large managed aquifer recharge system in which various sources of water supply, including Santa Ana River baseflow, stormwater, imported water, and recycled water, are recharged to replenish the basin.

OCWD began capturing and recharging stormwater in 1936 in the Santa Ana River channel in Orange County. After completing Prado Dam in 1941, USACE began collaborating with OCWD on the capture and recharge of stormwater. This collaboration has evolved over time. Early efforts included closing ungated outlets in the dam that allowed high flows to be lost to the ocean. More recent efforts include allowing for the temporary storage of stormwater in the reservoir, released at rates that can be diverted and recharged by OCWD. The volume of water that can be temporarily stored behind the dam has increased over time. Currently, water can be temporarily stored up to an elevation of 505 feet above mean sea level,[2] which equates to approximately 20,000 ac-ft. Figure 2-1 shows the elevations and volumes of the current conservation pool.

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[2] All cited elevations in this report are in feet, based on the datum of NGVD 1929.

USACE & OCWD cooperate to store and capture up to 20,000 acre-feet of storm water at a time

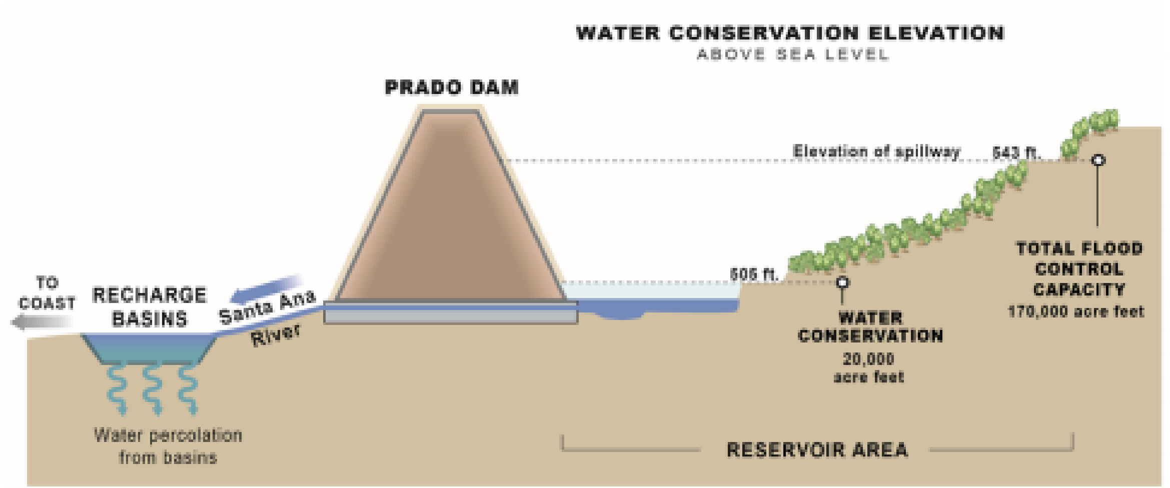


Figure 2-1. Schematic of Prado Dam water conservation elevation for stormwater storage and capture (credit: OCWD)..

The ability to temporarily store stormwater behind Prado Dam has proved invaluable. Over the past 25 years, OCWD has recharged an average of 55,000 ac-ft of stormwater per year with a maximum of 117,000 ac-ft in 1995. For planning purposes, OCWD assumes that 40,000 ac-ft of stormwater will be captured and recharged in an average year. That is enough water for 320,000 people annually. If this water were not available, it would cost approximately $40 million per year to purchase imported water to replace it. Imported water supplies are increasingly less reliable due to the fragile Bay-Delta, the oversubscribed Colorado River, and changes in weather patterns.

Further opportunities to maximize stormwater storage and recharge are now being explored through more sophisticated weather prediction, specifically improved prediction of atmospheric rivers (ARs). In recent years, scientists have increased their understanding of the importance of ARs as a major driver of precipitation in California and other parts of the West Coast. ARs originate in the Pacific Ocean and can make landfall along the California coastline. The absence of AR storms often leads to drought in California, whereas strong ARs cause more than 90 percent of flood damage in California. Figure 2-2 shows an AR that impacted Southern California in 2005.

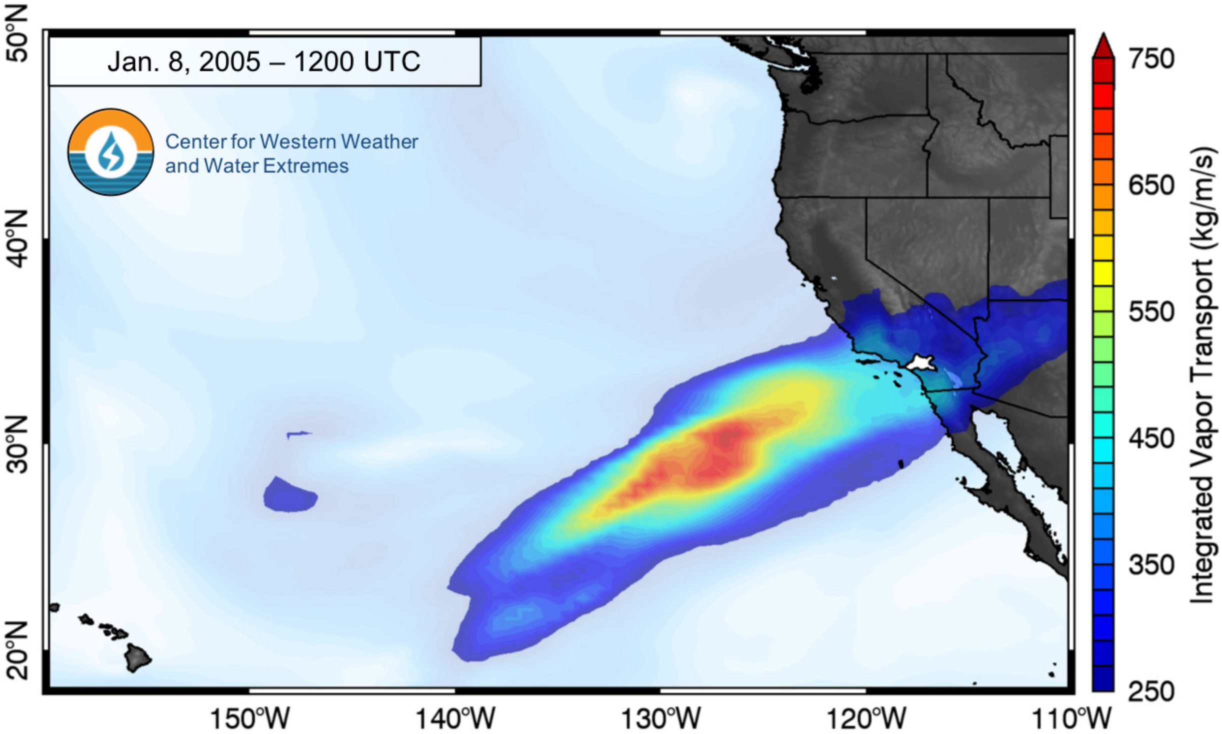


Figure 2-2. Landfalling AR that impacted the Santa Ana River watershed and Prado Dam in early January 2005.

Currently, most reservoirs, including Prado Dam, are operated according to Water Control Manuals (WCMs) that do not consider weather and streamflow forecasts in their release decision logic. Still, USACE reservoir operators, recognizing the improvements in forecast skill over the past few decades, commonly factor forecast information into their release decision making process. Forecast Informed Reservoir Operations (FIRO) represents a technical pathway for explicitly integrating weather and streamflow forecast information into WCMs and reservoir release decisions and, in doing so, make better use of existing multi-purpose reservoirs across the state and region.

FIRO is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts. FIRO represents an innovative use of emerging science and technology to optimize limited resources and adapt to changing climate conditions without costly reservoir infrastructure improvements.

FIRO was first initiated in 2014 at Lake Mendocino, in the Russian River watershed. A Preliminary Viability Assessment (PVA) determined that FIRO was a viable approach, and FIRO operations are currently being tested under a USACE major deviation while the Final Viability Assessment (FVA) is being completed. During water year 2020, FIRO resulted in approximately a 19 percent increase in end of flood season reservoir storage over existing WCM operations.

The Prado Dam FIRO PVA builds on past success and follows the process established by the Lake Mendocino project.

2.2 FIRO Project Objectives

Prado Dam is a prime candidate for FIRO exploration because:

- ARs significantly impact the Santa Ana watershed.
- Improved runoff volume forecasts can assist with flood risk management decisions.
- Stormwater capture for recharging OCWD's water supply is extremely valuable.
- Opportunities exist to increase the maximum buffer pool elevation for water conservation.
- Dam and system improvements for flood risk management are underway through the Santa Ana River Mainstem (SARM) project (see Section 2.7.1 and Appendix A).
- The WCM needs to be updated due to the upcoming completion of the SARM.
- Cooperative relationships exist among the USACE LAD and South Pacific Division, the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), the U.S. Fish and Wildlife Service (USFWS), the Orange County Department of Public Works (OCPW), and OCWD.

This PVA assesses the potential application of FIRO at Prado Dam on the Santa Ana River. The Lake Mendocino experience in the upper Russian River watershed informs the process, which builds on lessons learned about ARs as the source of significant West Coast precipitation events and runoff. As the owner and operator of Prado Dam, USACE has complete control over the dam's operation. If FIRO identifies potential modifications to the dam's operations, such modifications would be implemented through an updated Water Control Plan (WCP) and manual, only after USACE reviews and approves them. Additionally, this study may inform USACE in using weather forecasting technology at other USACE dams. The specific objectives of FIRO at Prado Dam are outlined below.

Water conservation objectives

- Maximize the use of available temporary storage space at Prado Dam for stormwater capture and downstream groundwater recharge.
- Minimize cases in which where water released from the buffer pool before a storm is not captured for downstream groundwater recharge due to an over-forecast of Prado inflow.
- Operate the dam with flexibility for small, short-term exceedance of buffer pool maximum elevation (five days or less) so that the water surface elevation can be adjusted after the peak inflow rate subsides to maximize downstream groundwater recharge.
- Provide analysis and framework for potentially higher temporary water conservation storage space in the future.

Flood risk management objectives

- Ensure that, at a minimum, any FIRO alternative does not reduce the flood risk management capacity of Prado Dam. Alternatives also must not impact dam safety. During this work, the flood risk management capacity of Prado Dam will increase due to the SARM. Evaluations will take this shift in capacity into account. In the process of developing and evaluating FIRO alternatives, it is entirely possible that the flood risk management capacity of Prado Dam can be improved through the application of FIRO.

Environmental objectives

- Explore habitat enhancement options that could offer environmental co-benefits.
- Avoid and, where avoidance is not possible, minimize and mitigate negative impacts on natural resources.

The overall purpose of this project is to answer the following question:

Can forecasts of landfalling ARs and associated precipitation and runoff be sufficiently leveraged in Prado Dam operations to enhance water conservation (e.g., stormwater capture and subsequent groundwater recharge) while not compromising, or even improving, flood risk management and environmental objectives?

2.3 FIRO Viability Assessment Process and Timeline

This Prado Dam PVA evaluated current forecasting technology and incorporated needs-based research. Figure 2-3 shows the general evaluation process used to conduct the Prado Dam PVA, which will then support the FVA and ultimately USACE’s WCM Update.

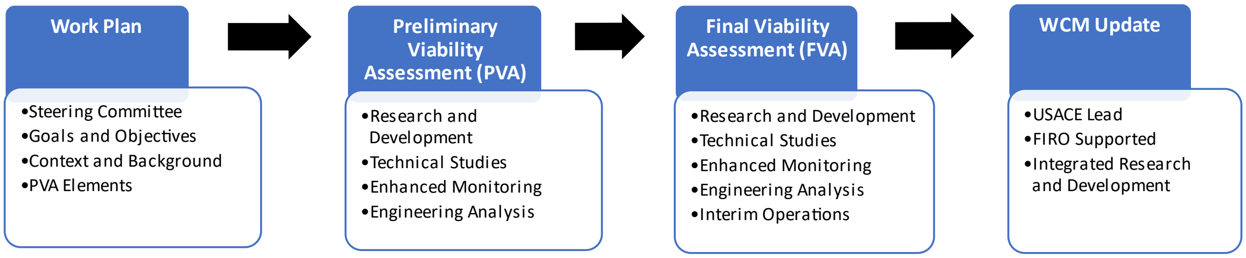


Figure 2-3. PVA process.

The timeline in Figure 2-4 shows the entire FIRO process for Prado Dam. The PVA builds on and follows the work plan, which was completed in 2019. Note that OCWD will apply for a multi-year major deviation to the WCP as part of the preliminary viability assessment process, and that the full implementation of FIRO will be progressive and depends on the modification of the existing spillway.

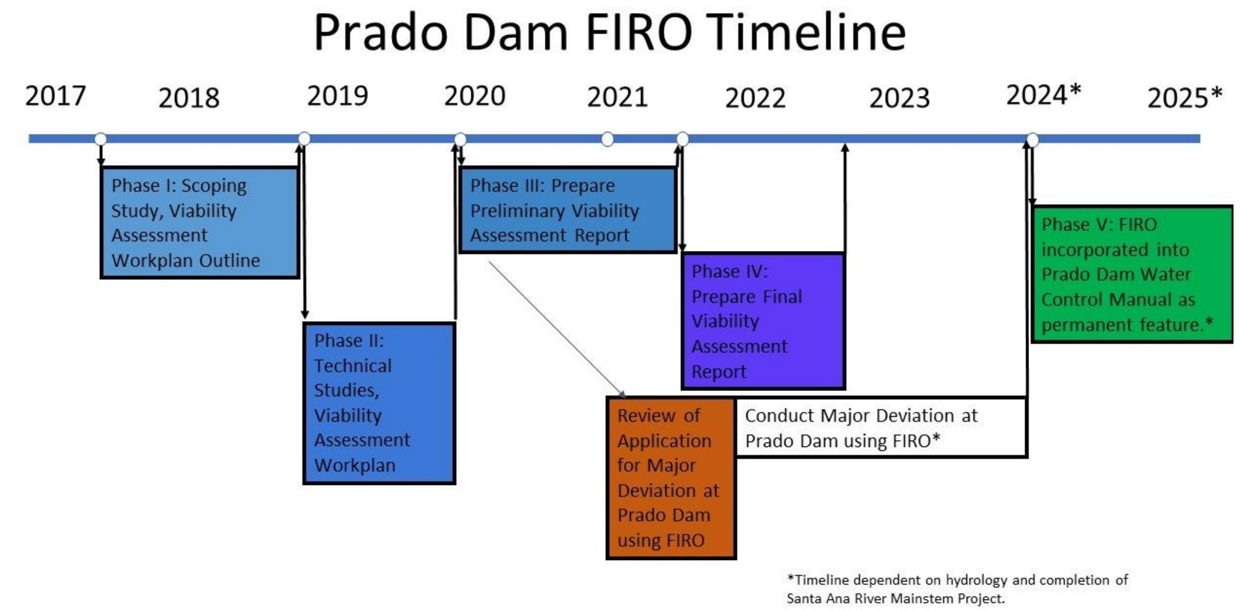


Figure 2-4. *Prado FIRO timeline.*

2.4 Prado Dam FIRO Steering Committee

The Prado Dam Steering Committee was formed in late 2017 and first met in March 2018. It is co-chaired by Dr. F. Martin Ralph, Director of the Center for Western Weather and Water Extremes (CW3E) at UC San Diego's Scripps Institution of Oceanography, and Greg Woodside, Executive Director of Planning and Natural Resources at OCWD. Committee members were carefully chosen to represent key organizations, and they bring together innovative leaders from those organizations that collaborate and contribute expertise and resources to accomplish common goals.

Co-chairs

- Greg Woodside: Executive Director of Planning and Natural Resources, OCWD
- F. Martin Ralph: Director, CW3E, Scripps Institution of Oceanography, UC San Diego

Members

- Jay Jasperse: Chief Engineer, Sonoma Water
- Michael Anderson: State Climatologist, California Department of Water Resources
- Cary Talbot: Chief, Flood and Storm Protection Division, USACE Engineer Research and Development Center
- Alan Haynes: NOAA NWS, Hydrologist-in-Charge, California Nevada River Forecast Center (CNRFC)
- Rene Vermeeren: Chief, Hydrology and Hydraulics Branch, Engineering Division, USACE LAD
- Jon Sweeten: Hydraulic Engineer, Reservoir Regulation Section, USACE LAD
- James Tyler: Manager, Real Estate/Finance and Engineering, OCPW

- Karin Cleary-Rose: Division Chief, USFWS, Palm Springs Office

Support staff

- Eliza Berry: Eastern Research Group, Inc.
- Chris Delaney: Sonoma Water
- Adam Hutchinson: OCWD
- Kim Gilbert: Chief, Reservoir Regulation Section, USACE LAD
- Joe Nguyen: OCPW
- Arleen O'Donnell: Eastern Research Group, Inc.
- Robert Hartman: Robert K. Hartman Consulting Services
- Dr. Forest Cannon: CW3E

Figure 2-5. *May 17, 2018, photo of Prado Dam Steering Committee members and support staff at Prado Dam. From 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, Arleen O'Donnell.*

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 that deliverables reflect interdisciplinary perspectives and interagency input.
- **Goal:** Develop clear pathways for assessing the viability of FIRO at Prado Dam.
- **Strategies:** Draft a PVA outlining tasks, roles, schedule, and requirements for assessing FIRO viability; conduct preliminary technical studies; and develop a PVA based on current forecast skill and an FVA based on potential improvements in forecast skill.

Process for achieving mission

- Hold quarterly Steering Committee meetings, at least two of which are in person each year.
- Develop meeting agendas and circulate meeting notes. Document and track action items.
- Conduct conference calls, site visits, small working group meetings, and other means of coordination.
- Hold an annual workshop to engage with, coordinate with, and learn from each other.
- Pursue communication and outreach opportunities.
- Develop a strategy for launching the viability assessment, including funding and implementation commitments.

2.5 Santa Ana River Watershed and Prado Dam

2.5.1 Meteorology and Climatology

The Santa Ana River watershed flows from the San Gabriel, San Bernardino, and San Jacinto Mountains, which form a barrier to moisture transport in winter storms, including from ARs. During these extreme events, moisture transported from the Pacific Ocean is forced upward over 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 inter-annual variability in total precipitation arising primarily to differences in AR activity. Thus, 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 the understanding and prediction of ARs and the physical mechanisms that generate precipitation in the watershed yield the potential to enhance water supply reliability and flood control capacity 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, as well as experience in developing the concept of FIRO at Lake Mendocino, a drought- and flood-prone reservoir in Northern California.

See Section 5.3 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 Prado Basin.

2.5.2 Geophysical Characteristics

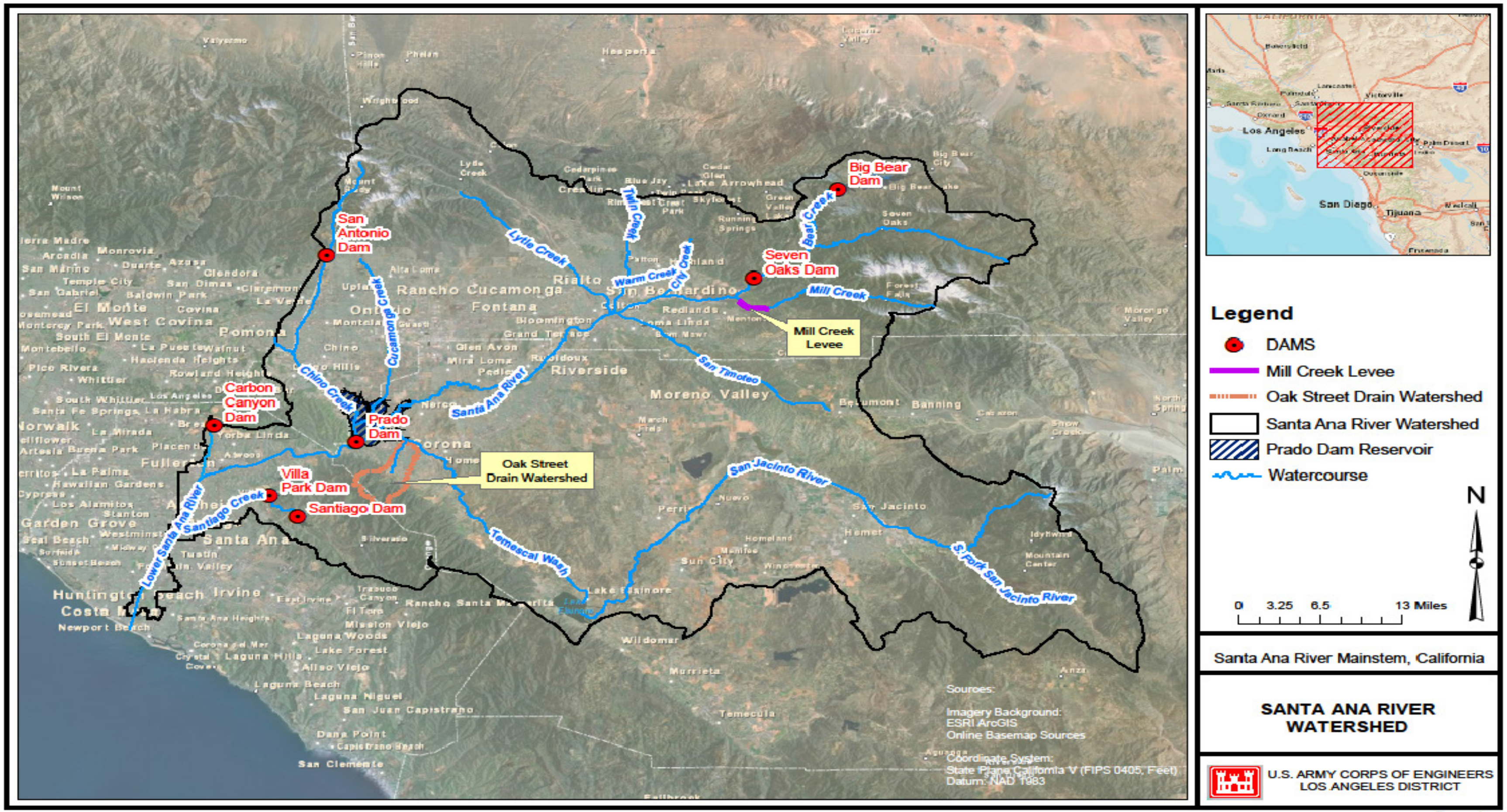
The Santa Ana River, more than 90 miles long, is the longest river entirely within Southern California. The effective contributing drainage of the entire river is approximately 2,450 square miles, of which 2,255 square miles (92 percent) are controlled by Prado Dam. Figure 2-6 shows the extent of the watershed. Santa Ana River tributaries originate in the San Bernardino Mountains and flow southwest through San Bernardino, Riverside, and Orange Counties before emptying in 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 (listed clockwise) include San Antonio/Chino Creek, Cucamonga Creek, Lytle Creek, Mill Creek, San Timoteo Creek, and the San Jacinto River, which flows into Temescal Creek. 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 in the mountains is 700 feet/mile 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). See Figure 2-6 for the locations of these dams.

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 regulation decisions at Prado Dam, flood risk management operations are also closely coordinated with the local sponsors.



Sources:
Imagery Background: ESRI ArcGIS Online Basemap Sources
Coordinate System: State Plane California V (FIPS 0405, Feet)
Datum: NAD 1983

Figure 2-6. Santa Ana River watershed.

2.5.3 Prado Dam Authorization and Current Operations

Authorization for the Prado Dam and Reservoir project is contained in the Flood Control Act of June 22, 1936 (PL 74-738), which authorized the construction of reservoirs and related flood control works to protect the metropolitan area of Orange County, California.

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. Paragraph 5 of the definite project report gives the following general description of the approved project:

> ***General:*** *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.*

Further, paragraph 9 reads:

> *…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. It is proposed to secure the conservation operation by omitting the gate on one of the 4 ft by 8 ft conduits.*

With the authorization found in the Flood Control Act of 1936 and in accordance with the definite project 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.* Construction was completed in April 1941 at a cost of about $9,450,000 (1941).

Further modifications to the original project authorization are contained in the Water Resources Development Act of 1986 (PL 99-662). The purpose of this modification was to provide additional capacity for the storage of floodwaters and sediment by enlarging the existing Prado Dam and Reservoir and 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 the 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 (EIR) for Prado Basin, Including Stabilization of the Bluff Toe at Norco Bluffs*, dated December 2001. The details of the SARM project are provided in Appendix A.

Table 2-1. Water storage volume at select elevations based on the 2015 topographic survey.

Water Surface Elevation (Feet, NGVD 29)	Volume (ac-ft)
498	9,369
505	19,469
508	25,374
510	29,823
514	39,900
516	45,675
520	58,735
530	99,608
543	172,758

2.5.4 Flood Risk Management and Water Conservation

Prado Dam and Reservoir are congressionally authorized to provide flood protection to the metropolitan area of Orange County. Protecting the downstream floodplain takes priority over protecting reservoir lands and leaseholders from inundation. The general WCP objectives, in addition to flood risk management, include (1) minimizing adverse environmental impacts, (2) minimizing impacts to endangered species, (3) minimizing maintenance costs to the dam and downstream channel, and (4) minimizing impacts to reservoir lands and activities (i.e., to leaseholders).

The currently approved WCP is the *Interim Water Control Plan (During Construction), Prado Dam and Reservoir, Santa Ana River, Orange County, California,* dated May 2003 (2003 IWCP), which will continue to be in force until all downstream channel improvements construction has been completed. The 2003 IWCP was developed to update only the WCP contained in the last approved WCM—the *Prado Dam Water Control Manual,* dated September 1994. Together with the 1994 WCM, the 2003 IWCP was implemented while the original outlet works were still operational and the new larger capacity outlet works were under construction. After the dam's embankment was raised to 594.4 feet and new, larger-discharge-capacity outlet works were installed, it became necessary to develop a water control document that describes existing project conditions while still implementing an IWCP during the ongoing construction at and downstream of Prado Dam. The 2003 IWCP is now just called the IWCP and is contained in the latest updated water control document, called the Prado Dam Interim Water Control Manual (IWCM). The IWCP also implemented the approved five-year planned major deviation to the 2003 IWCP. The planned major deviation allowed for a higher flood season buffer pool storage for water conservation by raising the maximum elevation from 498 feet up to 505 feet. The IWCM containing the IWCP replaced both the 2003 IWCP and the 1994 WCM documents.

The *Prado Basin Ecosystem Restoration and Water Conservation Feasibility Study* was approved in the spring of 2021. This study proposed to formally increase the maximum flood season buffer pool elevation for water conservation from 498 feet to 505 feet (year-round). This incorporates the same maximum buffer pool elevation as the approved major deviation. This change is now a permanent part of the IWCP. No additional updates to the IWCP/IWCM document are required. The 505-foot maximum buffer pool elevation is represented as the baseline operation described in Section 3 and assessed in Section 4.

Figure 2-7 depicts the IWCP, and the paragraphs following provide further operational details on it..

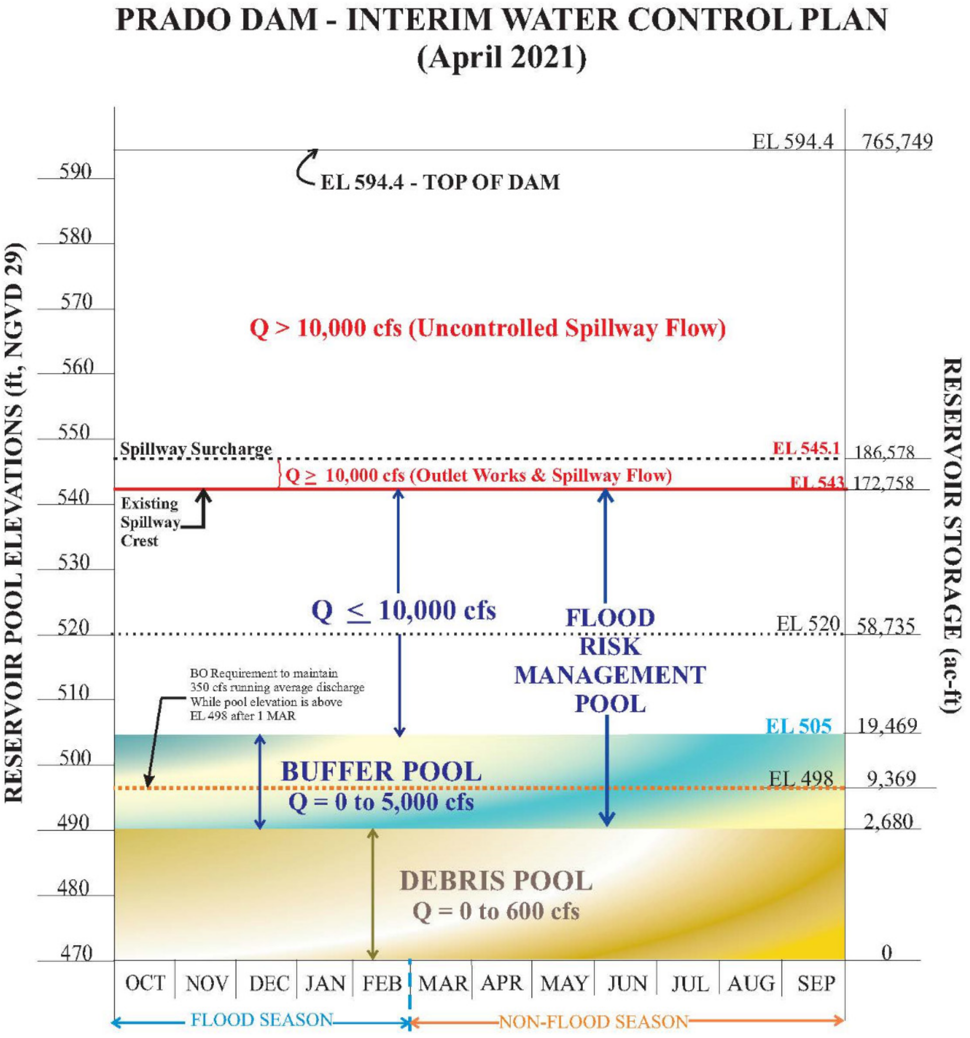


Figure 2-7. Prado Dam IWCP, July 2020.

The primary objective of the IWCP for Prado Dam is to limit the damaging flows that could result from large runoff events. Normal maximum flood risk management discharge is up to 5,000 cubic feet per second (cfs); however, it may also be increased up to 10,000 cfs if warranted by hydrometeorological conditions at the project, or if there are concerns for dam safety. Discharge anticipated to be greater than 5,000 cfs will be closely coordinated with all the downstream river bank construction contractors, the OCPW, Orange County Sanitation District, OCWD, and USFWS (when applicable). The maximum controlled discharge capacity of the new outlet works is 30,000 cfs. Discharge from the dam may also be curtailed or shut off completely to accommodate maintenance or inspections within the downstream channel, during an emergency situation and in cooperation with local authorities, or when there are impacts to safety at the Burlington North–Santa Fe railway bridge due to construction-related activities. Additional details on the IWCP and the other WCP alternatives evaluated in the PVA can be found in Section 3.

While it does not interfere with flood risk management, runoff into the reservoir can be stored in the buffer pool for water conservation. When storage exceeds or is anticipated to exceed the top of the buffer pool elevation, discharge from the dam may be increased up to 5,000 cfs. When the reservoir recedes below the top of the buffer pool elevation, and if there are no conflicts with flood risk management objectives, discharge from the dam will resume coordination with OCWD to benefit water conservation efforts.

The IWCP differs from the last approved 2003 IWCP only with respect to the flood season buffer pool regulation for water conservation. The recommended discharge plan for flood risk management operations, therefore, remains unchanged.

The responsibility to implement the IWCP lies solely with USACE LAD's Reservoir Operation Center (ROC). The dam tenders who physically operate the project make no independent regulation decisions or move any outlet gates without permission from the ROC. Dam tenders receive all gate operation instructions from the ROC.

The ROC's nominal discharge decisions consider, but are not limited to, the following information:

- Current pool elevation behind the dam.
- Maximum available downstream channel capacity.
- Currently calculated inflow into the dam's reservoir.
- Weather and streamflow forecast information from NWS and the CNRFC.[3]

The ROC uses a collection of locally and nationally developed tools to assist in their reservoir release decision making process. USACE policy calls for Districts to implement and use the Corps Water Management System (CWMS) in support of their operations. Appendix B discusses the status of the CWMS implementation for the Santa Ana watershed.

The following sections describe in detail the typical regulation for various pool elevation ranges.

2.5.4.a Debris Pool (Elevation 470 to 490 Feet)

The debris pool ranges from an elevation of 470 feet (project invert) up to 490 feet. During runoff events, discharge from the dam is kept at a minimum to create an impoundment so that excess debris and trash that wash into the reservoir can settle out and do not get pulled into the outlet works. The rate of discharge within the debris pool elevation can range from 0 to 600 cfs and it is often coordinated with OCWD so that they can divert the flow into their spreading

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[3] For hedging purposes within the constraints of the IWCM. Quantitative precipitation forecasts are not currently used as input for any kind of USACE runoff modeling for determining runoff volume.

grounds for groundwater recharge and water conservation. The proper operation of the dam and outlet works is improved when the pool is at or above 490 feet.

2.5.4.b Buffer Pool for Water Conservation (Elevation 490 to 505 Feet)[4]

The nominal release range for the buffer pool can range from 0 cfs to 5,000 cfs. Discharges from within the buffer pool elevations are also coordinated with OCWD to support their groundwater recharge operations for water conservation, or to coordinate preparation for the project's flood risk management regulation. As the pool elevation rises toward the top of the buffer pool elevation, the regulation/operation of Prado Dam transitions from water conservation to flood risk management.

While the water surface elevation is within the buffer pool, discharge from the dam is often gradually increased to adjust inflow and minimize any downstream channel erosion. Discharge can currently be up to 5,000 cfs and can be maintained with minimal or no concerns of damage within the downstream channel. Channel observers—as coordinated with Orange County and Riverside County Flood Control Districts and/or LAD's Hydraulics Section—will be necessary to ensure channel safety and no outbreak of channel flow into urban surroundings or impacts to Reach 9 construction activities.

The combination of a (1) relatively small buffer pool volume, (2) relatively large controlled outlet capacity, and (3) short transit time for flood releases to reach the Pacific Ocean effectively shortens the required lead time for skillful streamflow forecasts associated with a FIRO application. These factors are integrated into the reservoir modeling described in Section 3 and evaluated in Section 4.

2.5.4.c Flood Risk Management Pool (Elevation 505 to 543 Feet)

As the reservoir pool elevation approaches the top of buffer pool elevation, the regulation/operation of the dam will transition from water conservation to flood risk management. A flood risk management release is a gradual increase of discharge up to 5,000 cfs to match the calculated inflow to the reservoir. The discharge may also exceed 5,000 cfs to prevent spillway flow above 543 feet in elevation.

OCPW received a certification letter in 1999 stating that a 100-year level of protection on the lower Santa Ana River from Weir Canyon Road to the Pacific Ocean will be maintained during all construction activities. This certification was contingent upon (1) the operation of Seven Oaks Dam, (2) completion of the lower Santa Ana River channel improvements from Reaches 1–7 and the existing OCPW channels being fully entrenched and capable of safely conveying the 100-year flood, and (3) Prado Dam's ability to release up to 9,200 cfs from the outlet works during large runoff events.

The decision to implement this "100-year level of protection" regulation/operation will consider the following information and factors:

- Current water surface elevation within the reservoir.
- Latest quantitative precipitation forecast information.
- Quantity of observed rainfall.

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[4] LAD has completed operational discretionary authority of this impoundment, so it can be drained completely at any time, as needed, for the purposes of flood risk management, environmental concerns, or for concerns relating to dam safety.

- CNRFC inflow forecast.
- Status of Reach 9 construction activities and available channel capacity.

The total amount of Prado Dam's additional storage volume that may be used for temporary stormwater capture is 15 percent of the total storage below the spillway crest or 50,000 ac-ft, whichever is less. USACE policy provides that the volume may be less than 15 percent based on various factors (USACE Engineering Regulation 1105-2-100, April 2000). For the current spillway elevation of 543 feet, 15 percent of the available volume is 26,000 ac-ft, with a water surface elevation of 508 feet. For the future spillway, upon completion of improvement projects discussed below, 15 percent of the available volume would be 50,100 ac-ft (the cap of 50,000 ac-ft would apply). A storage volume of 50,000 ac-ft corresponds to a water surface elevation of 517 feet. A potential increase in the maximum elevation of temporary stormwater capture will need to consider USACE Engineering Regulation 1105-2-100, other USACE policies, land uses within the Prado Basin, potential environmental impacts, and potential infrastructure impacts.

Therefore, if it is determined that the pool elevation behind Prado Dam could rise up to 520 feet in elevation due to the level of storage already behind the dam or due to the estimated size of the forecasted event, proactive measures may be taken to drain the reservoir down as low as elevation 490. At 520 feet, approximately half of the storage capacity below the spillway crest (543 feet) is filled. Additionally, if the CNRFC inflow forecast is significant enough to indicate potential storage up to spillway crest, discharge may be increased up to 10,000 cfs.

All flood risk management releases are made as safely as possible following a rate of release change schedule. Channel observers are dispatched to monitor downstream conditions, especially if releases are 5,000 cfs or greater. Constant coordination between the channel observers and the LAD's Reservoir Operations Center ensures that releases from Prado Dam are kept within the downstream channel limits. When the opportunity exists during flood risk management operations, a performance test may be implemented on Prado Dam's new release outlets and low-flow gates to ensure that each gate can pass the design maximum of 5,000 cfs and 30,000 cfs, respectively.

2.5.4.d Spillway Flow (Elevation 543 Feet and Higher)

The current maximum flood risk management releases through the outlet works will be maintained as the reservoir pool rises above the spillway crest. This decision to maximize discharge (potentially up to 30,000 cfs) was determined as necessary, following a USACE dam safety assessment in October 2019. Prior to this assessment, deficiencies with the existing spillway structure were identified that resulted in changing Prado Dam's Dam Safety Action Classification rating from 3 down to 2. The maximum controlled discharge from the dam would be maintained to avoid or limit the magnitude and duration of spillway discharge.

2.6 Operational Constraints

The IWCP considers impacts to developments within the reservoir, as well as downstream impacts due to high releases. Prior notifications and coordination with the local government, the general public, and private constituents are made as a courtesy to inform them of the potential impacts due to either the rising pool impoundment or a higher discharge condition from the dam.

2.6.1 Existing Spillway at Elevation 543 Feet

The updated design storm analysis showed increased runoff resulting from urbanization of the watershed, which led to the modification of the Prado Dam and Reservoir project's existing features, including raising the spillway crest elevation. Before modifications, the project could handle an approximately 70-year runoff event, although it was originally designed for a 190-year event. With an operational Seven Oaks Dam and a controlled discharge from Prado Dam of 9,200 cfs, the developments around the lower Santa Ana River in Orange County now have at least a 100-year level of protection. Still, an updated independent analysis of the existing conditions at Prado Dam and Reservoir (i.e., raised embankment, new outlet works, unraised spillway) must be completed to assess the level of protection this project can provide at present. In addition, the existing spillway has structural deficiencies that were identified during the dam safety assessment in October 2019. Discharge from the dam, as the reservoir elevation rises toward the existing spillway crest, may be maximized up to 30,000 cfs to prevent spillway flow, or to limit its magnitude and duration. Currently, USACE is working to have an interim risk reduction measure in place to address the existing spillway deficiencies.

2.6.2 Inundation Within the Reservoir

In addition to developments within Prado Reservoir, there are construction activities that include new Prado dikes (Alcoa and River Road), modification to existing dikes (Housing Tract and Sewage Treatment Plant), Norco Bluffs, and a variety of utilities that will need to either be protected in place or relocated. Because flood risk management is the primary authorized purpose of the dam, developments and upstream construction sites within the reservoir boundary, up to the top of dam elevation, are subject to inundation during operations. During runoff events, the ROC will remain aware of highwater impoundment impacts to these developments and upstream construction sites; however, consideration to avoid inundating these sites will not be given over flood risk management needs. The following are a few notable developments within the reservoir:

- **Least Bell's vireo nesting habitat.** The least Bell's vireo (see Figure 2-8) is the endangered species that is relevant to Prado Dam and Reservoir operations. It is a federally endangered bird with critical habitat in the Prado flood control space. Much progress has been made in restoring this population (see Figure 2-9), and continued success depends, in part, on how water levels are managed. If water levels behind the dam are too high, nests can be flooded and the vegetation needed for nesting and foraging habitat can be negatively impacted, resulting in fewer productive nests and fledglings. Studies are underway to better understand the relationship between water levels and least Bell's vireo habitat to accommodate this species' requirements during flooding events. See Appendix C for more information, including the Biological Opinion and Memorandum of Agreement. Also note that, while there are several other threatened or endangered species within the Santa Ana River watershed, they do not currently pose operational constraints to Prado Dam and Reservoir operations.

Figure 2-8. Photo of least Bell's vireo with chicks (Courtesy of B. Peterson, USFWS).

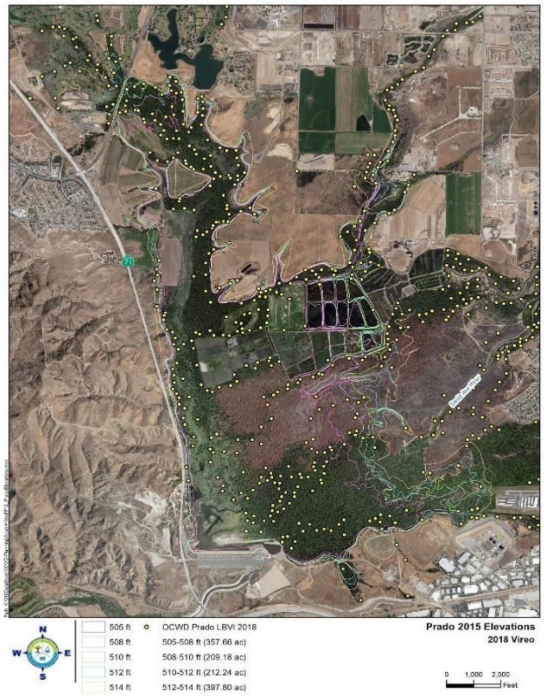


Figure 2-9. Least Bell's vireo nesting sites indicated by yellow dots.

- **Corona Municipal Airport.** This is a recreational airport managed by the city of Corona and used primarily for small private planes. The airport is located between 514 feet and 536 feet in elevation. The ROC provides a courtesy rising water surface notification to the city of Corona if privately owned aircraft and other movable airport facilities could be inundated.
- **Euclid Avenue (Route 83).** This route runs north–south just east of Highway 71 and inundates when pool impoundment behind Prado Dam is above 515 feet. Currently, the ROC notifies CalTrans (San Bernardino Office) if the pool elevation behind the dam starts to encroach 510 feet so coordination can be made to close access of the road, if necessary.

2.7 Opportunities for Improvement

2.7.1 Santa Ana River Mainstem Project

The SARM project consists of seven major features, including constructing a 550-foot earth and rockfill 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, creating a water-holding reservoir on Santiago Creek, and 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 construction, originally part of the Santa Ana River improvements project, will also take place when Orange County has acquired all lands within the new taking line (566 feet) in fee/easement. The spillway modification work is currently in the design phase.

While the spillway structure remains at elevation 543 feet, a major flood runoff event that exceeds the current reservoir capacity could cause catastrophic damages in an area downstream inhabited by about 2 million people. A design 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.

Implementation of FIRO will likely be phased to correspond with the completion of various SARM features. In other words, as SARM features are completed, the ability of Prado Dam to temporarily store more water will also increase. See Appendix A for a full description of SARM features.

2.7.2 Enhanced Recharge

The primary tools OCWD uses to divert and capture stormwater in the Santa Ana River downstream of Prado Dam are two inflatable dams and off-river recharge basin storage. At the beginning of the storm season, when most of the system storage is available and the recharge basins are clean, OCWD can divert up to 800 cfs from the Santa Ana River for a short period as recharge facilities are filled. When recharge facilities are filled, the diversion rate from the river declines to about 500 cfs for several weeks. Once all system storage is filled, the rate of diversion from the river will decline over time to approximately 350 to 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. To this end, OCWD has, for the past 20 years, been convening an internal, multi-disciplinary group called the Recharge Enhancement Working Group. The goal is to develop concepts and projects designed to improve OCWD’s recharge system. A couple of notable projects that are relevant to this document include:

- **Recharge Facilities Model.** This model, based on GoldSim software, simulates the operation of OCWD’s 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 3 and Section 4.
- **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.

2.7.3 Environmental Considerations

The Santa Ana watershed has two endangered species and three threatened species, listed in Table 2-2. All but one, the Santa Ana sucker (threatened), are birds. Of these, the least Bell’s vireo is the only species known to be affected by Prado Dam operations. In addition, the pond turtle is being considered for listing in this watershed.

Table 2-2. Threatened and endangered species in the Santa Ana River watershed.

Species	Endangered Species Act Listing
Least Bell's vireo	Endangered
Southwestern willow flycatcher	Endangered
Santa Ana sucker	Threatened
Western yellow-billed cuckoo	Threatened
Coastal California gnatcatcher	Threatened

The Prado Basin supports a major population of the least Bell's vireo, *Vireo belli pusillus* (see Figure 2-8). The least Bell's vireo is listed as an endangered species by the state of California and USFWS. The vireo population in the Prado Basin has been monitored since 1986. Vireo can be found in southern Baja Mexico in the winter and migrate to Southern California in late winter, typically arriving in the Prado Basin in March.

As mentioned in Section 2.6, the least Bell's vireo is relevant to FIRO because its nesting habitat is sensitive to and affected by Prado Dam operations. Important considerations in determining the impact of FIRO operations include the extent to which the nesting habitat can tolerate higher water levels, and over what duration, to avoid damage to vegetation or the nests themselves. Finally, locating mitigation sites so that this species can maintain and possibly expand its habitat may be a benefit of this project.

OCWD and USFWS are cooperating on studies to better understand the habitat requirements for the vireo with respect to higher water elevations behind the dam. Section 3.2 of the PVA discusses in more detail what is known about vireo habitat requirements, recent studies underway, and how the vireo habitat can be further monitored to identify opportunities to continue to build on the enormous progress made to date in re-establishing this bird.

Section 3 How FIRO Viability Was Assessed

The Prado Dam Forecast Informed Reservoir Operations (FIRO) Steering Committee collaboratively developed and finalized a multi-year workplan to assess the viability of FIRO for Prado Dam operations in 2019. Specifically, the plan called for assessing the potential of existing weather and water forecasts to improve Orange County Water District's (OCWD's) ability to recharge groundwater while not compromising—or, indeed, while improving—flood risk management outcomes for the U.S. Army Corps of Engineers (USACE).

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 USACE WCPs, 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 the Simulation Plan (Section 3.3). 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 OCWD's recharge facilities. This work is described in the Modeling Plan (Section 3.2).

3.1 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 full plan can be found in Appendix D; 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.

Tasks in this process, as applied in technical analyses to support the Prado Dam FIRO Preliminary Viability Assessment (PVA), include:

- A set of feasibility criteria and performance metrics is developed for assessing and comparing FIRO alternatives.
- The project development team nominates a set of alternative FIRO strategies. The strategies are screened to ensure they meet specified requirements, described below.
- Performance of the river-reservoir system with each FIRO strategy is simulated using a common set of meteorological and hydrological conditions.
- Simulation results are used 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-foot maximum buffer pool).
- The project development team uses the technical analysis results to (1) describe the general viability of FIRO for the Steering Committee and (2) to identify refinements in the process or additional studies needed for the Final Viability Assessment (FVA). The results of the analysis are provided in Section 4.

3.1.1 Boundary Conditions

Both hard constraints and operational considerations were defined for the analysis. Table 3-1 provides the hard constraints that must be explicitly followed by each of the alternative WCPs.

Table 3-1. 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, movement of construction equipment, and bank erosion and stability. Limits were provided by USACE Los Angeles District (LAD) staff for flows up to 30,000 cubic feet per second (cfs).
2	Must minimize exceeding targets associated with railroad bridge and channel/bank construction	Two total release limits were evaluated: • 10,000 cfs before the completion of the BNSF railway bridge and Reach 9. • 30,000 cfs following the completion of the BNSF railway bridge and Reach 9.
3	Must accommodate maximum release schedule	The maximum release schedule is defined in the Interim Water Control Manual. Chart provided by LAD staff for spillway at 543 feet. Schedule associated with future 563-foot spillway also provided by LAD staff.
4	Must meet instream minimum flow requirements	Minimum release set at 50 cfs.

Operational considerations are provided in Table 3-2. These considerations establish the basis for the metrics described below.

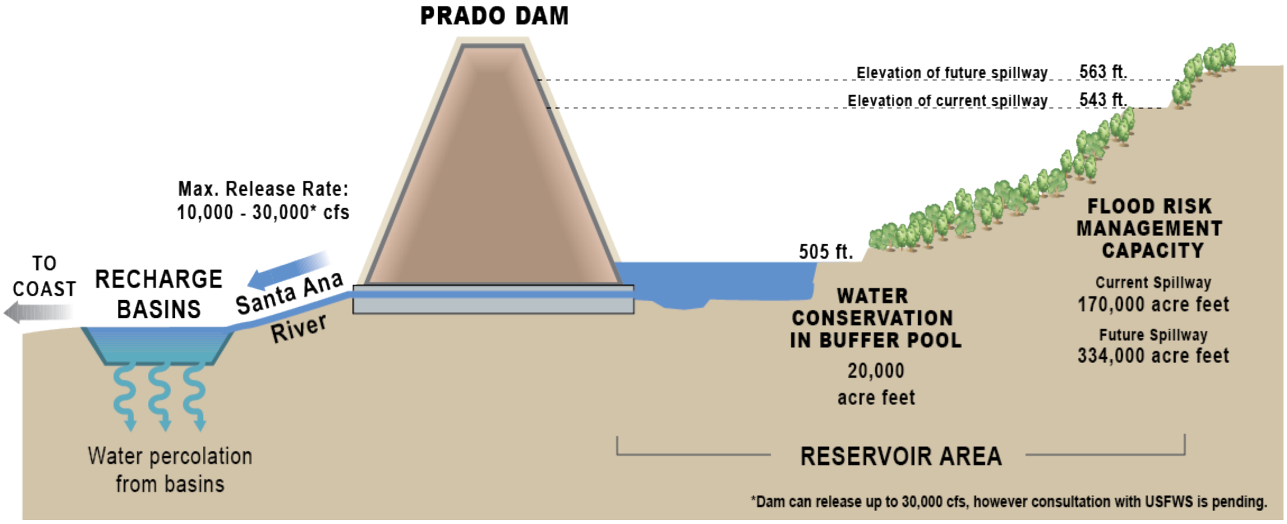
Table 3-2. Operational considerations evaluated in the hydrologic engineering study.

ID	Operational Consideration	Description
1	Corona Airport	Flooding/closure of Corona Airport at 515 feet.
2	Euclid Avenue	Euclid Avenue closed at 520 feet (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 may flood vireo nests.
4	Potential harm to riparian habitat above 505 feet	Prolonged inundation of riparian vegetation can harm the vireo habitat.
5	Spillway flow	Spillway flow greater than the downstream channel capacity has serious flood impacts. Any spillway flow has negative implications for the Corps.

With the phased deployment of the Santa Ana River Mainstem (SARM) project over the next several years, it was necessary to evaluate the effectiveness of FIRO strategies under three physical conditions: (1) the current state, where the spillway is at 543 feet and Reach 9 is incomplete; (2) spillway at 543 feet and Reach 9 complete; and (3) spillway at 563 feet and Reach 9 complete (the SARM project's end state), as shown in Table 3-3 and Figure 3-1.

Table 3-3. Spillway elevation and maximum scheduled release conditions associated with phased completion of the SARM project.

Condition	Spillway Elevation	Maximum Scheduled Release (cfs)
1	543 feet	10,000
2	543 feet	30,000
3	563 feet	30,000



*Dam can release up to 30,000 cfs, however consultation with USFWS is pending.

Figure 3-1. Phased SARM implementation (credit: OCWD).

3.1.2 Metrics

The metrics to be evaluated for each WCP alternative are shown in Table 3-4. The metrics cover flood risk management, environmental, groundwater recharge, and approved activities within the maximum flood pool.

Table 3-4. Metrics for the evaluation of FIRO alternatives (listed in Table 3-5).

ID	Metric Description	Category	Likely Method of Computation
M1	Annual maximum discharge frequency from Prado Dam	Flood risk management	Frequency curve. Simulate 27-year hindcast and extend with scaled events of 100- and 200-year frequency.
M2	Annual maximum pool elevation frequency function of Prado Dam	Flood risk management and environmental	Frequency curve. Simulate 27-year hindcast and extend with events of 100- and 200-year frequency.
M3	Vireo nest inundation between 3/21 and 5/1	Environmental	Simulate 27-year hindcast period. Frequency of daily inundation from March 21 to May 1.
M4	Average annual number of days of pool above 505 feet	Environmental	Frequency curve. Simulate 27-year hindcast.
M5	Average annual number of days of pool above 508 feet	Environmental	Frequency curve. Simulate 27-year hindcast.
M6	Average annual number of days of pool above 510 feet	Environmental	Frequency curve. Simulate 27-year hindcast.
M7	Average annual number of days of pool above 512 feet	Environmental	Frequency curve. Simulate 27-year hindcast.
M8	Average annual number of days of pool above 514 feet	Environmental, Corona Airport	Frequency curve. Simulate 27-year hindcast.
M9	Average annual number of days of pool above 515 feet	Environmental, Corona Airport	Frequency curve. Simulate 27-year hindcast.
M10	Average annual number of days of pool above 520 feet	Environmental, Euclid Avenue closure	Frequency curve. Simulate 27-year hindcast.
M11	Average annual total recharge below Prado Dam	Water supply	Frequency curve. Simulate 27-year hindcast.
M12	Average annual release above recharge capacity (volume)	Water supply	Frequency curve. Simulate 27-year hindcast.

3.1.3 FIRO WCP Alternatives

The original plan in the HEMP called for six alternatives with buffer pools that ranged up to 515 feet. As the study developed, the number of elevations evaluated was reduced and perfect forecast (PFO-512) and no forecast (NF-512) alternatives was added for elevation 512 feet, as shown in Table 3-5.

Table 3-5. Candidate WCP alternative strategies from the Prado FIRO HEMP.

ID	Alternative Strategy	Description
1	Unrestricted: 505 feet (baseline)	Buffer pool allowed to extend up to 505 feet without a seasonal restriction. Releases when pool is ≤ 505 feet at maximum recharge rate. Releases above 505 feet are at the maximum scheduled rate. No forecasts were used, consistent with current (baseline) operations.
2	EFO-508	Buffer pool allowed to extend up to 508 feet. Uses ensemble inflow forecast to determine release required to mitigate risk of exceeding spillway crest.*
3	EFO-512	Buffer pool allowed to extend up to 512 feet. Uses ensemble inflow forecast to determine release required to mitigate risk of exceeding spillway crest.*
4	NF-512	Buffer pool allowed to extend up to 512 feet without a seasonal restriction. Releases when pool is ≤ 512 feet at maximum recharge rate. Releases above 512 feet are at the maximum scheduled rate. No forecasts were used.
5	PFO-512	Buffer pool allowed to extend up to 512 feet. Uses observed inflows as forecasts (perfect forecasts) to determine releases that avoid exceeding spillway crest.*

* A spillway crest of 543 feet was evaluated for period of record simulations, and spillway crests of 543 and 563 feet were evaluated for 100-year and 200-year scaled hydrologic events.

Each of these alternatives was simulated under three physical conditions associated with phased completion of the SARM project, as shown in Table 3-3. The five alternatives combined with three physical conditions result in 15 scenarios.

Reservoir operations for each WCP were simulated using the Prado Ensemble Forecast Operations (EFO) model, a generalized version of the EFO model code originally developed for Lake Mendocino (Delaney et al. 2020). The effort to generalize the EFO and parameterize it for Prado Dam is described in Section 3.2.

For alternatives 2 and 3, the EFO model uses ensemble streamflow forecasts to assess the risk of exceeding a critical threshold of storage or water surface elevation (i.e., the spillway crest). When the risk becomes excessive by virtue of the current storage and forecast inflow, a release is identified that brings the risk down to an acceptable tolerance level. The two EFO alternatives (EFO-508 and EFO-512) only differ in the maximum elevation of the buffer pool but use the same risk tolerance levels that were developed using an optimization process described in Section 3.2.

Alternative 4 (NF-512) is a simple raising of the maximum buffer pool to 512 without the benefit of forecast flows. This alternative was added to assess whether the buffer pool could be raised to benefit water supply and not increase flood risk without using FIRO. The reservoir release logic was the same as alternative 1 but with a higher buffer pool.

Alternative 5 (PFO-512) incorporates the same buffer pool elevation of 512 feet as alternative 3 (EFO-512), but incorporates the EFO methodology with perfect forecast skill by using observed flows in place of hindcasted flows. The perfect forecasts used for alternative 5 consist of only one ensemble member and, therefore, assume a zero percent risk tolerance for all forecast lead times. The critical elevation/storage threshold used for alternatives 3, 4, and 5 (to manage the risk of exceeding this threshold) varied according to the spillway crest being simulated (543 and 563 feet). Pre-releases were simulated for alternatives 2, 3, and 5 when the forecasts indicated that the risk of exceeding the critical threshold was greater than that defined in the risk tolerance curve.

When simulated pool levels were at or below the maximum buffer elevation, the release was governed by the capacity of OCWD's recharge facilities. The capacity of the recharge facilities to accept water was modeled as described in Section 3.2. When the pool was above that level, releases were made at the maximum permissible rate to return the pool to the maximum elevation.

3.2 System 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 table. Practically, there are times when flood control releases in excess of the recharge capacity are needed. This section describes the development of the EFO model for Prado Dam and the additional integrated modeling that guides releases associated with groundwater recharge.

3.2.1 EFO Model for Prado Dam

Computer code was developed for the Prado EFO model based on a model developed for Lake Mendocino in Northern California that incorporates the EFO approach for reservoir flood control operations (Delaney et al. 2020). The original code was developed in the Matlab programming language specifically for Lake Mendocino operations. The Lake Mendocino code logic was brought into an object-oriented framework using the Python programming language. The resulting EFO model software provides the basic building blocks common to most reservoir systems, along with a framework of object classes that can be sub-classed to develop logic for custom system features if needed. The primary object classes of the EFO model are summarized below.

- **Junctions.** Define locations in a reservoir system where inflows and water balance calculations are performed to compute an outflow. Junction types include reservoirs and flow junctions. Rules can be added to junctions to provide logic for reservoir releases and diversions.
- **Inflows.** Data inputs for junctions, which can include natural inflows, reach losses (i.e., negative inflows) and routed flows from an upstream junction.
- **Reach.** Defines links to route flows from an upstream model junction to a downstream junction.
- **Rules.** Define logic for setting releases and diversions from model junctions.

Each of the primary class types has an abstract base class (with the keyword "Base" at the end of the class name) and multiple subclasses that inherit and expand from the properties and methods of the base class. Figure 3-2 shows a unified modeling language diagram of the EFO model class structure.

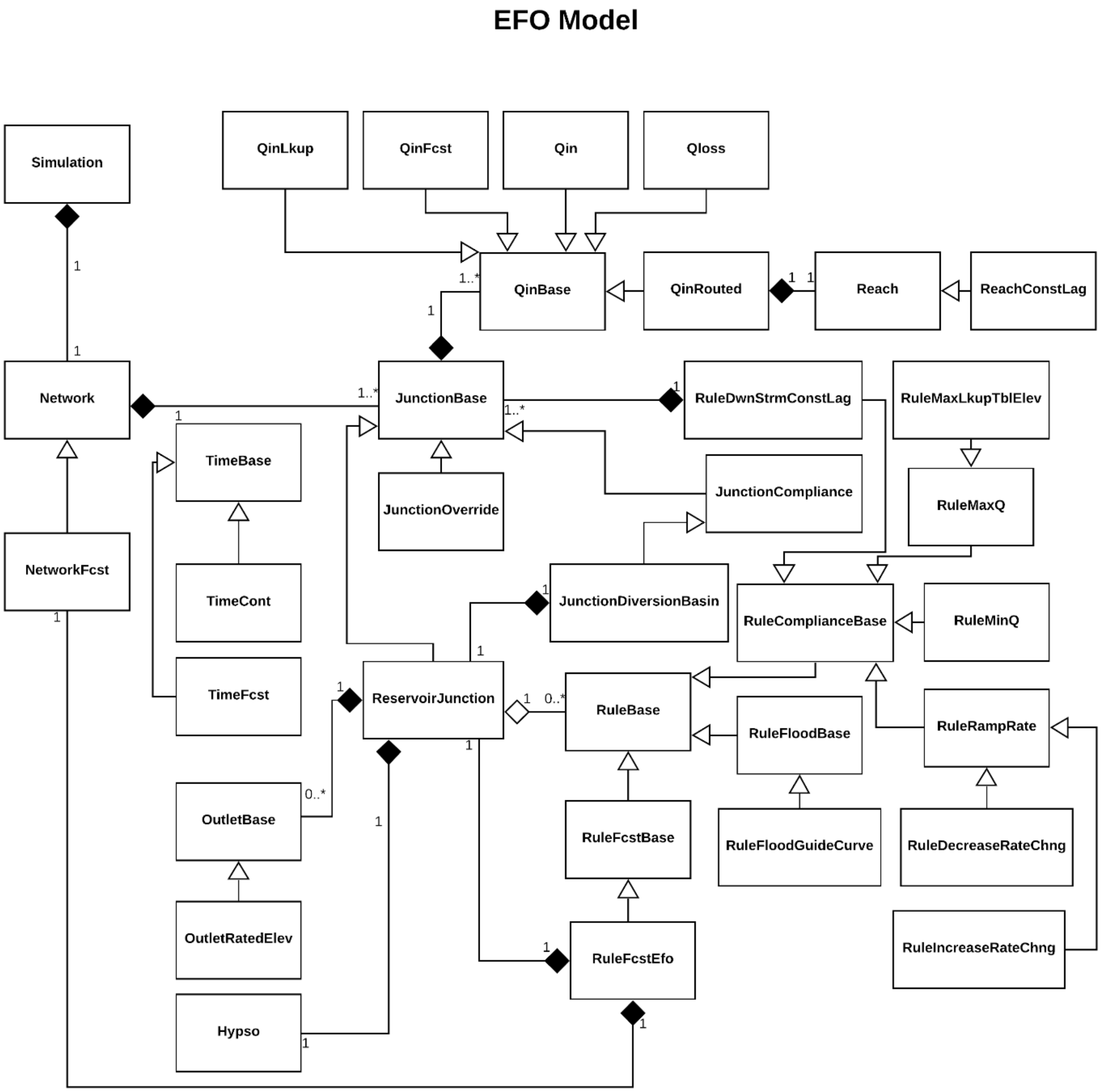


Figure 3-2. Unified modeling language diagram of the EFO model.

Using the object classes of the EFO model code, a model was developed for Prado Dam (called the Prado EFO model) to simulate the five reservoir management alternatives identified in Table 3-5. The Prado EFO model simulates Prado Reservoir operations and hydrologic conditions in the Santa Ana River at the OCWD diversion facilities at an hourly or daily time step. Figure 3-3 provides a flowchart showing the order of simulation for the primary components (objects) of the Prado EFO model.

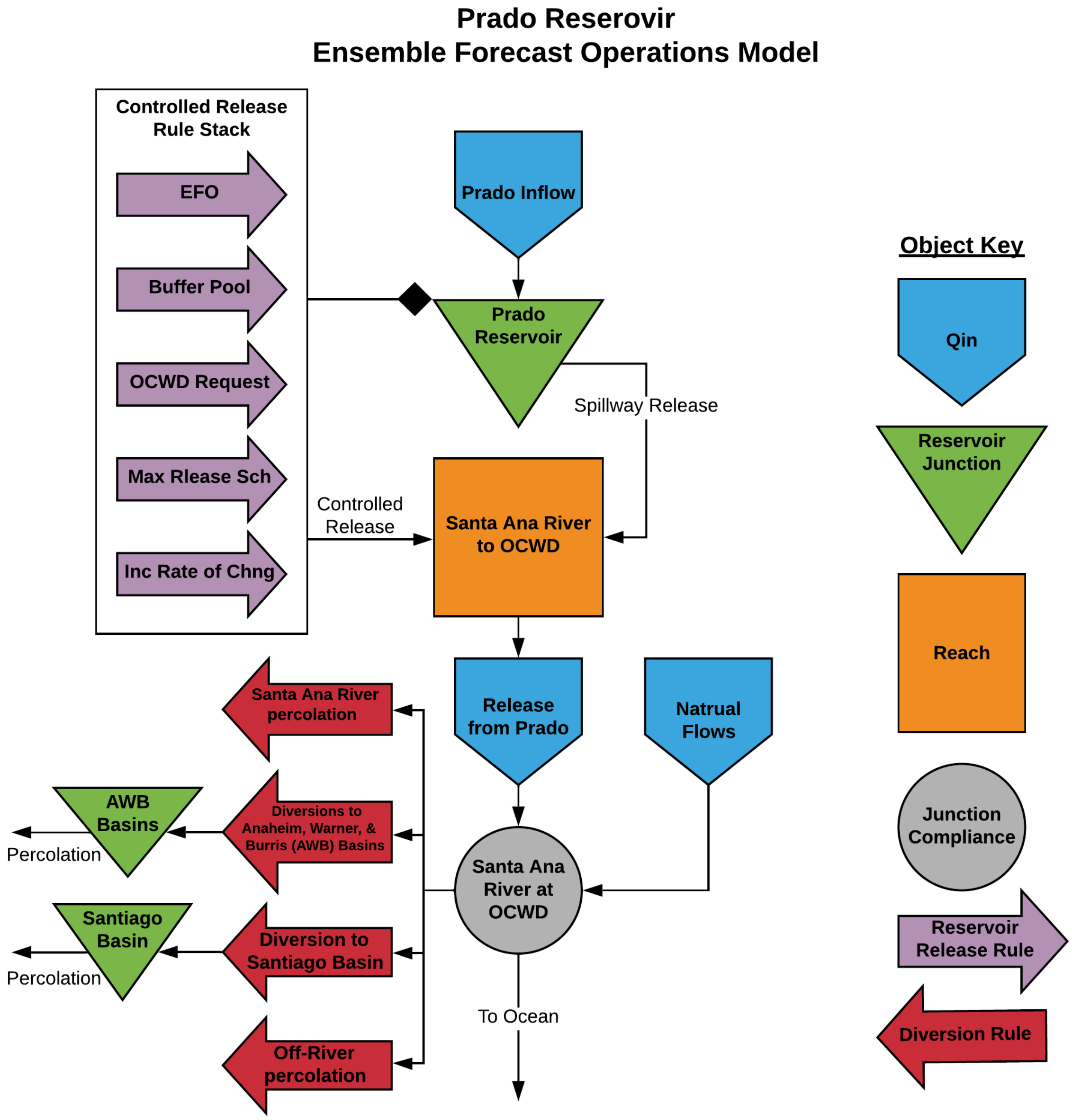


Figure 3-3. Flowchart of the simulation process for the primary model objects of the Prado EFO model.

The model applies reservoir operation rules of Prado Reservoir and water balance calculations to simulate reservoir releases and storage levels. It simulates releases through the controlled outlet by evaluating a series of rules (called the rule stack) in a succession defined in the rule stack.

Prado Reservoir consists of two outlet structures: a controlled release outlet and an uncontrolled spillway. The controlled gated outlet release rating curve applied in the Prado EFO model was provided from a HEC-ResSim model of Prado Reservoir developed by USACE in 2015, as shown in Figure 3-4.

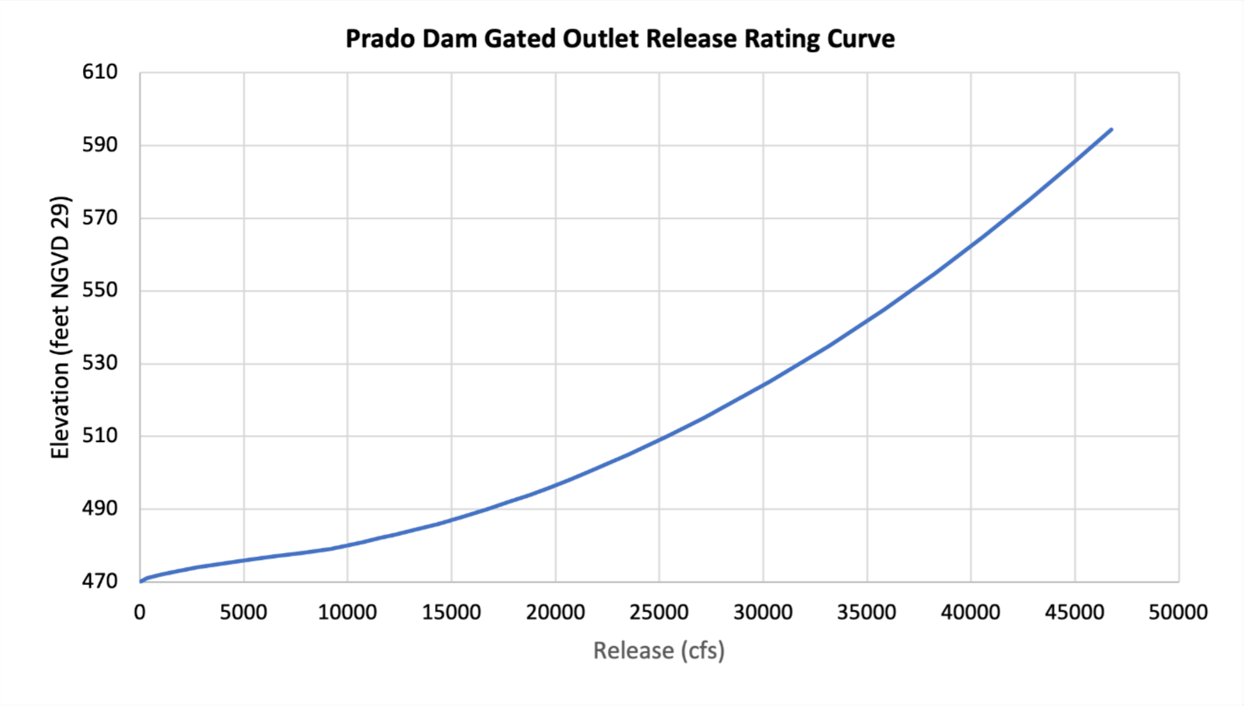


Figure 3-4. Prado Dam Prado Dam gated outlet release rating curve.

The existing uncontrolled spillway has a crest elevation of 543 feet. The rating curve for the uncontrolled spillway used for the Prado EFO model was also provided from the HEC-ResSim model, as shown in Figure 3-5. Additionally, configurations are included in the HEMP that evaluate a raised spillway crest elevation of 563 feet (NGVD 29), which is included in the Santa Ana River *Phase II General Design Memorandum* (USACE 1988).

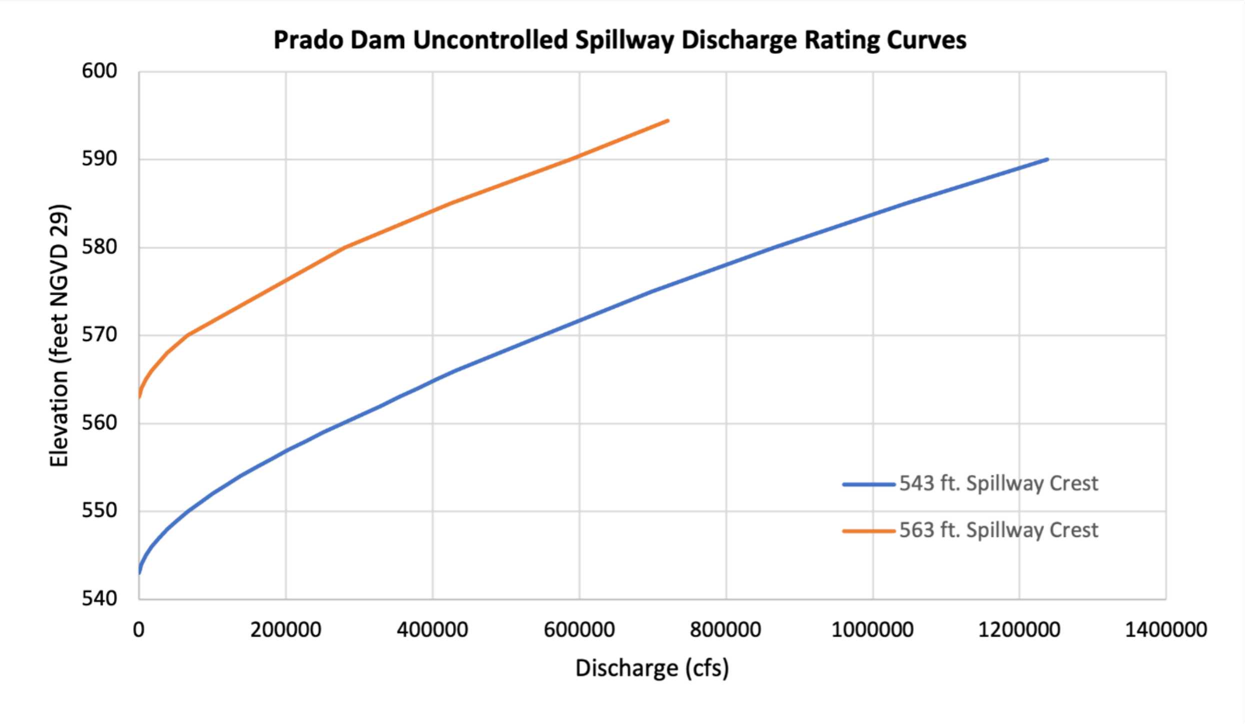


Figure 3-5. *Prado Dam uncontrolled spillway discharge rating curves for the existing spillway with a crest elevation of 543 feet and an alternative spillway with a crest elevation of 563 feet.*

Operations at Prado Reservoir are guided by the Interim WCP, which defines operational constraints for different reservoir pools (Figure 3-6).

The WCP defines maximum release constraints for the reservoir pools as summarized in Table 3-3. For the period of record analysis, the maximum release schedule defined in the interim water control diagram was used, as provided in the column labeled “Current” in Table 3-6. For the simulation of scaled flood events (discussed in Section 3.3), an alternative maximum release schedule was also simulated, as provided in the column labeled “Alternative” in Table 3-6.

Maximum release schedules at Prado Reservoir are a function of total release. Therefore, to account for the combined controlled outlet and spillway flow in the Prado EFO model, during periods of uncontrolled spillway releases, controlled outlet releases are reduced such that the sum of the uncontrolled spillway release and the controlled outlet release is less than or equal to the operating maximum release constraint.

When simulated storage levels are within the buffer or debris pool as shown in Figure 3-6, controlled outlet releases are made to meet the operations of the OCWD aquifer recharge system. Section 2 summarizes these operations. These releases are constrained by the maximum release schedule provided in Table 3-6. The buffer pool elevation (505 feet) shown in Figure 3-6 was used to simulate the baseline (current operations).

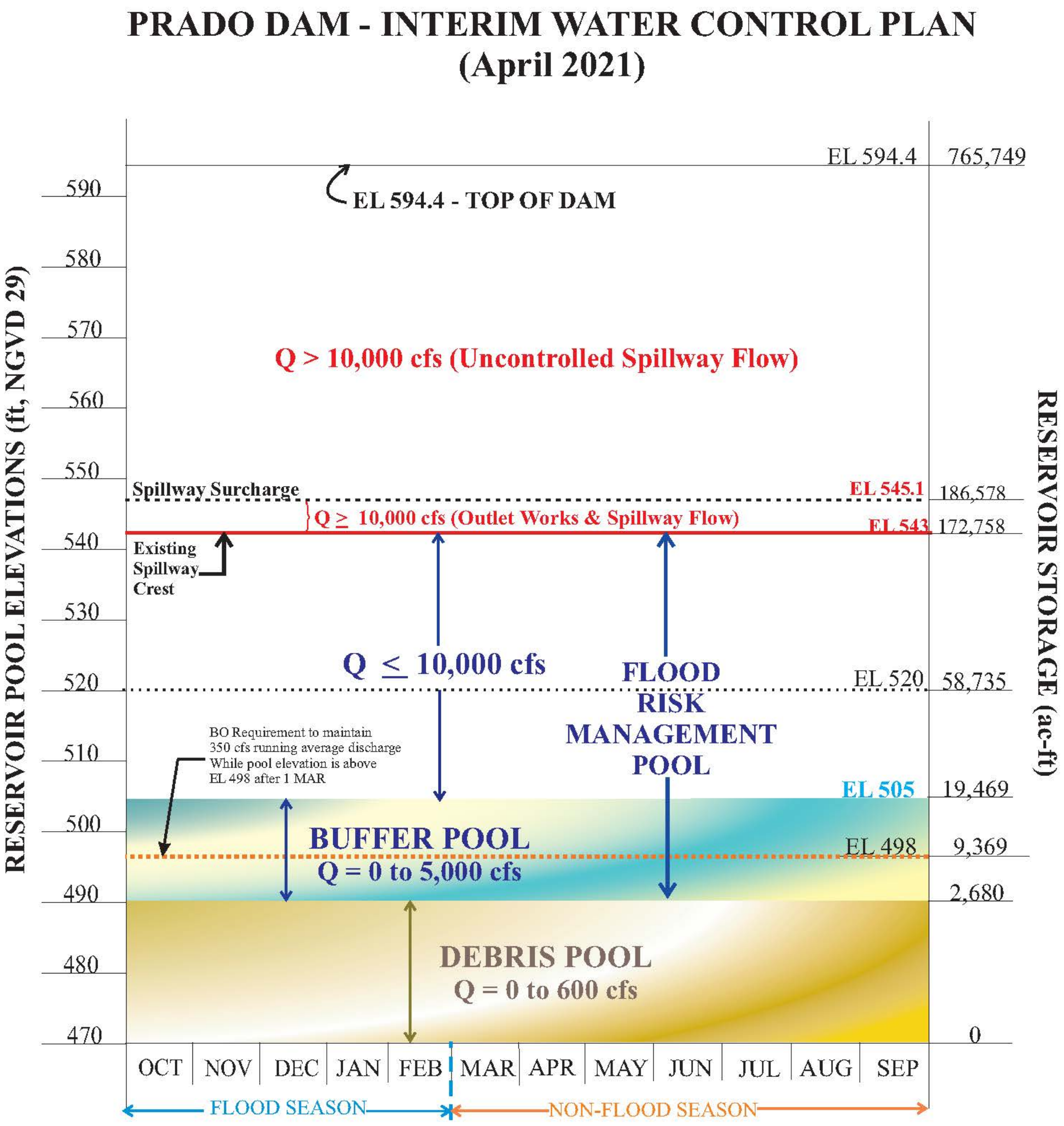


Figure 3-6. Prado Reservoir current operations Interim WCP.

Table 3-6. Prado Reservoir maximum release schedule for current and alternative operations.

Elevation (Feet, NGVD 29)	Maximum Release (cfs)	
	Current	Alternative
> 470 and ≤ 490	600	600
> 490 and ≤ 505	5,000	5,000
> 505 and ≤ 540	10,000	10,000
> 540 and ≤ 594.4	10,000	30,000

The Prado Reservoir water control manual sets constraints on the rate that controlled outlet releases increase per hour, as shown in Table 3-7. Release rate of change is governed by the potential impacts on downstream evacuation of the channel, movement of construction equipment, and bank erosion and stability. These constraints were applied in the Prado EFO model for daily average releases for daily time step simulations, and hourly average releases for hourly time step simulations.

Table 3-7. Prado Reservoir increasing rate of change constraints.

Release (cfs)	Increasing Rate of Change (cfs/Hour)
0	100
300	250
1,000	400
2,500	625
5,000	1,000

The Prado EFO model uses stage and storage relationships to convert simulated storage levels to elevations as needed for certain operational rules. The stage versus storage curves used for this study were provided by USACE LAD staff and were estimated from a 2015 bathymetric survey of Prado Reservoir.

3.2.1.a Calibration of the EFO Risk Curve

A central component of the EFO approach is the risk tolerance curve. The risk tolerance curve is used to formulate flood release schedules based on current reservoir storage and projected inflows. As applied in the EFO model, the curve defines the percentage of future storage ensembles (current storage + ensemble inflow forecast) that are permitted to exceed a defined threshold without mitigative action. The process for calibrating the risk curve is covered in Appendix F. The risk curve identified and used for the PVA assessment of the EFO alternatives is shown in Figure 3-7.

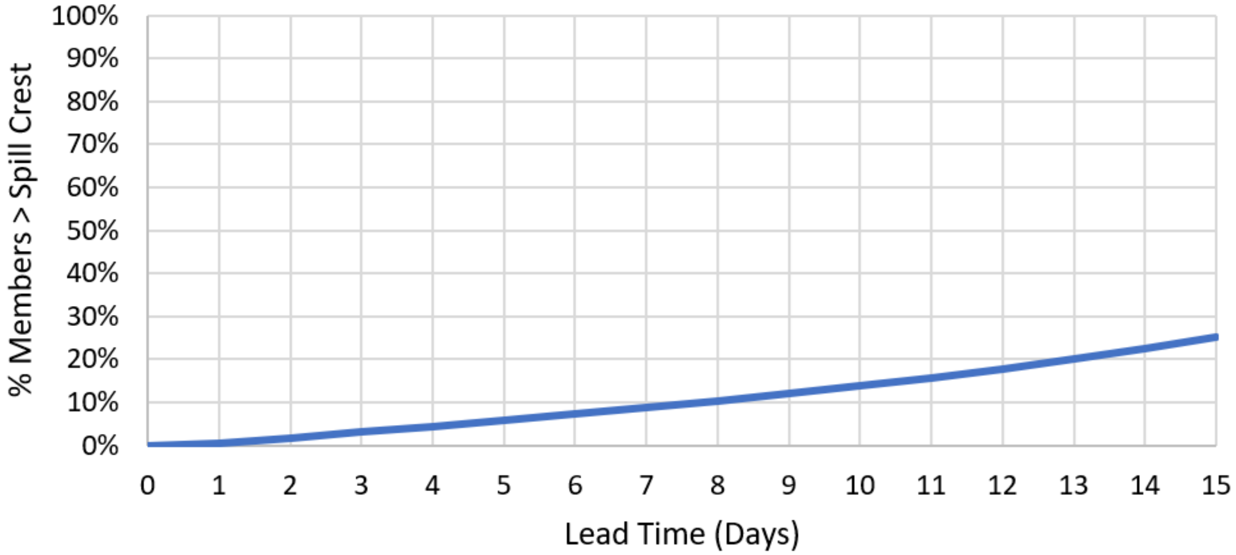


Figure 3-7. Calibrated EFO model risk curve for Prado Dam used in the PVA analysis.

3.2.2 Simulation of OCWD Diversions and Groundwater Recharge

The Prado EFO model simulates water supply operations of the OCWD recharge facilities to inform Prado Reservoir releases when storage is within the buffer pool or debris pool. These facilities enable OCWD to divert surface water from the Santa Ana River into spreading basins that percolate and recharge the groundwater supply of the Orange County Groundwater Basin. Simulating these operations accurately is an important part of determining the impacts of FIRO on OCWD's groundwater recharge program—and thus an important part of the PVA.

The main part of the OCWD recharge facilities is the 1,200 acres of spreading basins owned and operated by OCWD that are located about 9 miles downstream of Prado Dam along the Santa Ana River. Releases from Prado Reservoir are managed by USACE, with collaboration from OCWD, to maximize the amount of Santa Ana River flows that can be diverted by check dams into the spreading basins, where the water percolates to recharge the aquifer in the Orange County Groundwater Basin. The Santa Ana River flows also percolate within the stream channel and an off-river channel used for conveying a portion of diverted water to the spreading basins. The system can percolate up to approximately 500 cfs at any one time and 250,000 acre-feet (ac-ft) per year. Along with Prado Reservoir releases, inflows into the recharge facilities can come from local runoff, recycled water from the groundwater replenishment system, and transfers from the Metropolitan Water District. Figure 3-8 shows an overview the OCWD recharge facilities.

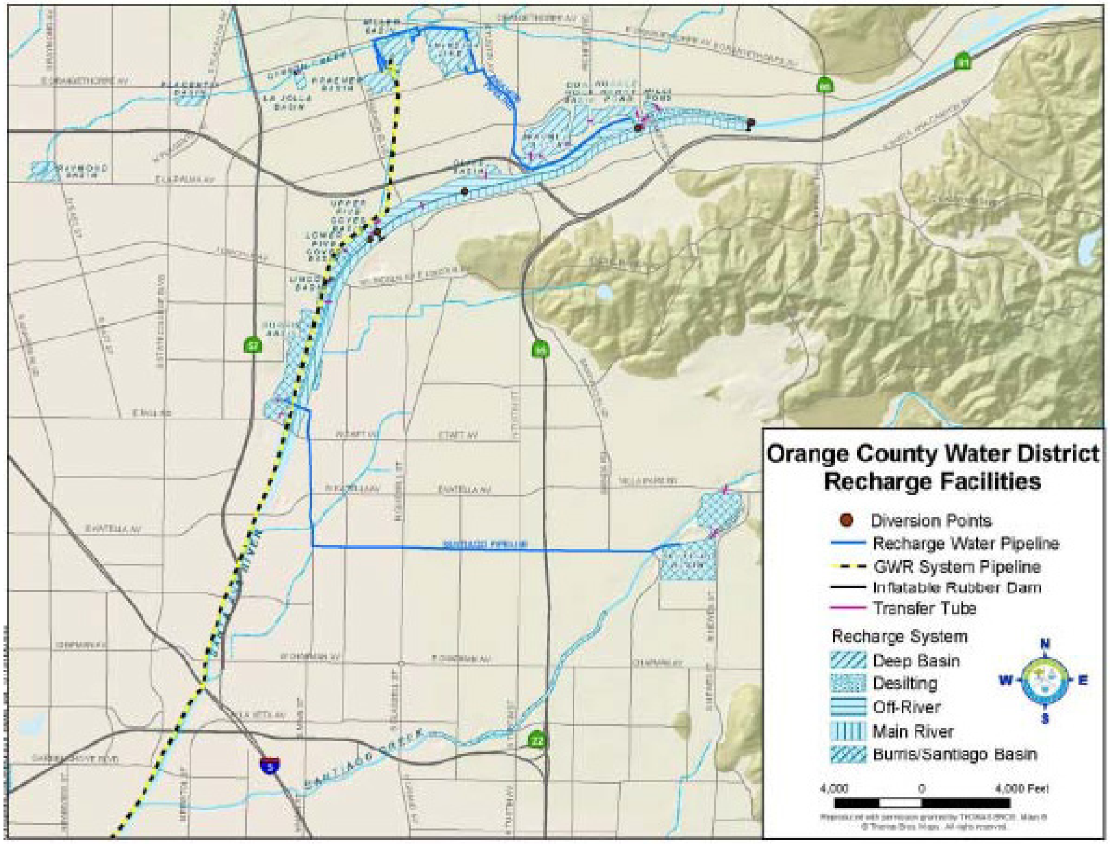


Figure 3-8. OCWD recharge facilities (Reginato and Foreman 2009).

To develop the logic for percolation processes in the Prado EFO model, the OCWD Recharge Facilities Model (RFM) was run and results were analyzed. This model uses calibrated GoldSim software developed by Jacobs Engineering Group in 2009 and updated in 2015.

OCWD uses the RFM to simulate its recharge facilities for water supply planning. The model can handle complex operations with multiple rules and physical constraints to accurately simulate recharge operations on a daily time step. The OCWD RFM also simulates Prado Reservoir flood control and buffer pool operations based on current USACE operational practices.

The OCWD RFM's complexities and simulation runtimes make it difficult to couple with the Prado EFO model. Additionally, due to time constraints, the operations of the OCWD Recharge System could not be directly coded into the Prado EFO model at the same level of detail as the OCWD RFM. Therefore, the OCWD RFM simulation results were analyzed to develop simplified constraints that could be applied to the Prado EFO to closely approximate OCWD RFM simulations. Based on analysis of the OCWD RFM and input from OCWD staff, simulation of the recharge facilities operations in the Prado EFO model (shown as the red arrow diversion rules in Figure 3-3) were consolidated into four components: (1) Santa Ana River percolation (2); the Anaheim, Warner, and Burris (AWB) spreading basins; (3) the Santiago spreading basin; and (4) off-river systems.

The objective of the Prado EFO model's simulation of the OCWD Recharge Facilities is to closely match annual percolation volumes for each of the four systems in the OCWD RFM using simplified logic and correlations. The OCWD RFM version used in this analysis is OCWD_OPT_v1.54_v12 and the operations are based on the baseline (Scenario 2A High Flow) model parameters. All four components of the aquifer recharge system are represented in diagrams in Appendix E.

3.2.2.a Santa Ana River

The Prado EFO model simulates percolation in the Santa Ana River channel upstream of the OCWD diversion facilities. The Santa Ana River percolation rates are incorporated in the Prado EFO model as a monthly varying pattern, which was estimated through a calibration process to the OCWD RFM simulation results (Figure 3-9).

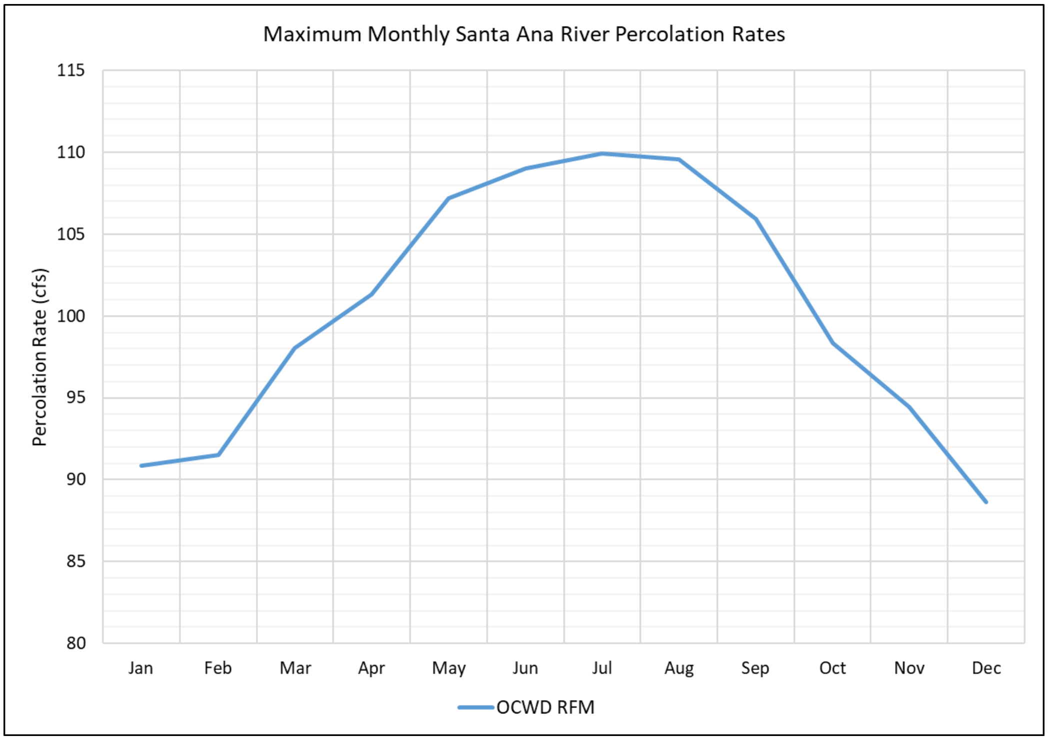


Figure 3-9. Maximum monthly Santa Ana River percolation rate.

3.2.2.b AWB Basins

The Prado EFO model groups the spreading basins into two systems: the Santiago Basin and the AWB basins. The spreading basins all function similarly: water is diverted from the Santa Ana River into all the spreading basins and percolates into the ground at a rate that is a function of the hydraulic head. In the case of the AWB basins, the Santa Ana River also contains sediment that can clog the basins and reduce the percolation rate throughout the year. OCWD cleans the basins when percolation drops to a certain threshold to renew the percolation capacity, which means that the percolation rate is a function not only of hydraulic head, but also the amount of sediment that has entered the basin since it was last cleaned.

The Prado EFO model simulates percolation rate in the AWB basins using regression equations applied to the total system. The output from the OCWD RFM baseline model run—January 1, 1966, through December 31, 1990—was used to fit a regression equation to the basin storage as a proxy for the water surface elevation versus percolation relationship. To account for the reduced percolation rate due to clogging, the data were stratified to regions of cumulative water year (WY) percolation and a separate regression equation was estimated for each stratification. After testing different stratification levels and regression models, six levels of stratification and a third-degree polynomial model provided the best estimation of percolation rates. Figure 3-10 shows the regression models and stratifications. Based on the results of a calibration process to best approximate results of the OCWD RFM, a maximum diversion rate to the AWB basins of 675 cfs was used for the Prado EFO model.

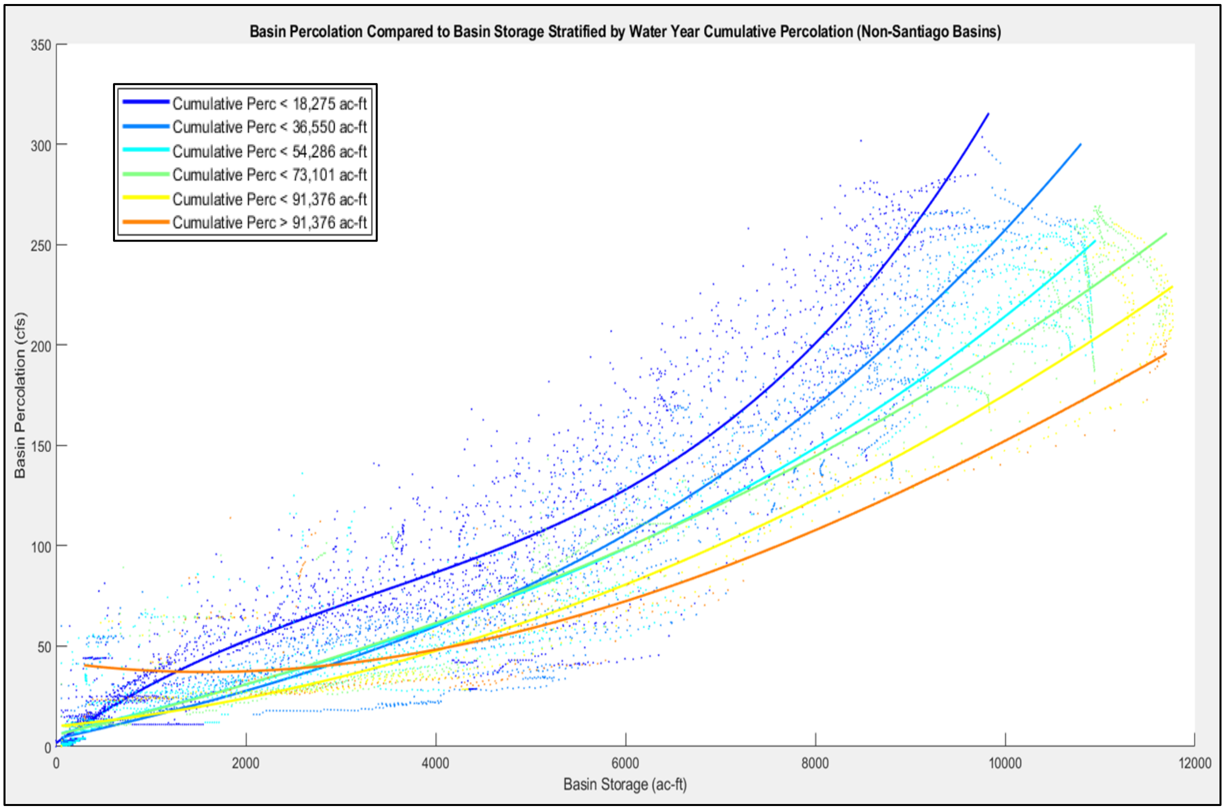


Figure 3-10. OCWD basin percolation versus OCWD basin storage stratified by WY cumulative percolation (dots) with third-degree polynomial models (lines).

3.2.2.c Santiago Basin

Unlike the AWB basins, the Santiago Basin can percolate water without clogging because it consists of a gravel pit with coarse sediments, and therefore the percolation rate is strictly a function of the hydraulic head in the basin. The OCWD RFM simulates the percolation of this basin using a simplified empirical equation that uses surface water elevation.

The Prado EFO model uses a second-degree polynomial model to approximate percolation of the Santiago Basin as a function of total storage. This regression was developed through a correlation of the OCWD RFM model basin storage to OCWD RFM model basin percolation (Figure 3-11). Since there is no clogging, there is no stratification of regression equations based on cumulative WY percolation and, therefore, only one equation was needed. Based on the results of a calibration process, a maximum diversion rate of 125 cfs to the Santiago Basin was used for the Prado EFO model.

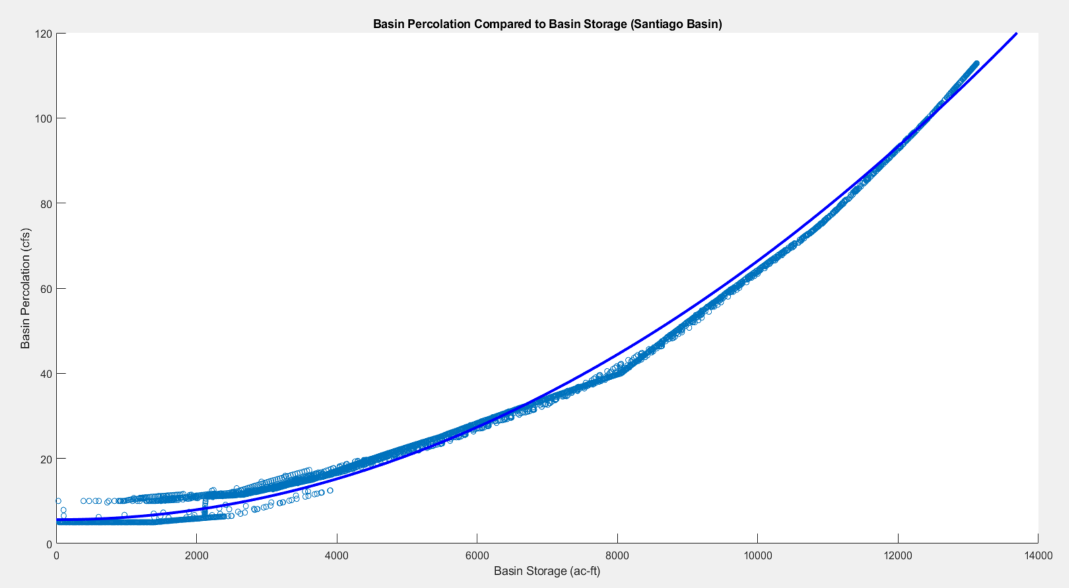


***Figure 3-11.** Santiago Basin percolation versus Santiago Basin storage (dots) with second-degree polynomial model (lines).*

3.2.2.d Off-River System

The OCWD diverts additional water into a channel system parallel to the Santa Ana River, which is called the Off-River system. The Off-River percolation is simulated in the Prado EFO model by diverting water available in the Santa Ana River, after diversions into the AWB and Santiago basins have been calculated, into the Off-River system at maximum diversion rate of 18.6 cfs.

3.2.2.e Validation

Parameters that define the components of percolation in the OCWD Recharge System in the Prado EFO model were calibrated to the OCWD RFM simulation results to approximate total period of record and WY total percolation volumes. It is important to match the WY totals to accurately reflect the drawdown of Prado Reservoir during the dry period every year. For validation, total percolation of all recharge system components (Santiago Basin + AWB basins + Santa Ana River percolation + Off-River) was evaluated against OCWD RFM results.

Figure 3-12 shows a time series of cumulative WY percolation for both the Prado EFO model and the OCWD RFM. The models display close alignment of the cumulative percolation pattern. In addition, Figure 3-13 shows WY total volumes of the Prado EFO model versus the OCWD RFM model. A least squares linear regression shows a coefficient of determination (R^2) of 0.99 and a slope of nearly 1.0. This indicates that the Prado EFO model is capturing the annual OCWD RFM percolation operations very well. Based on these results, the Prado EFO model simulation should accurately capture the function of the OCWD Facilities.

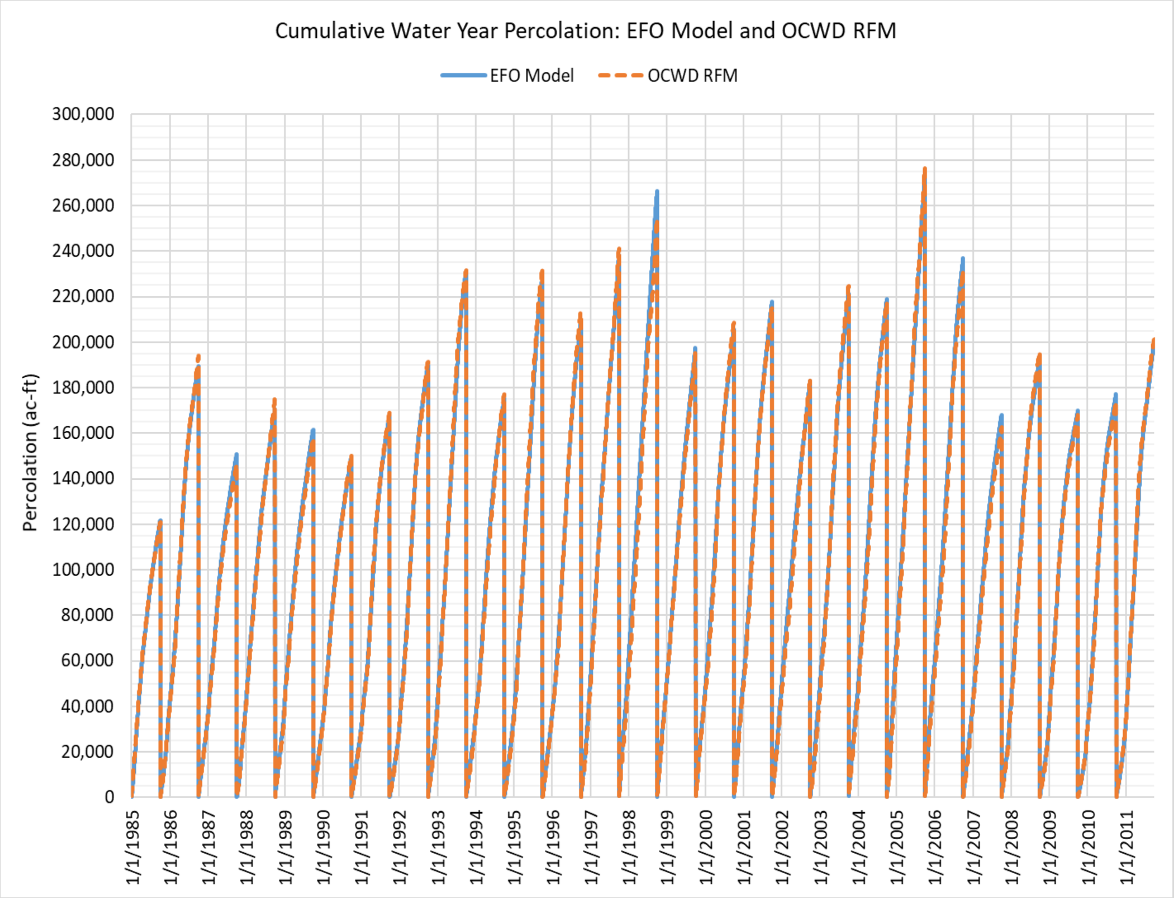


Figure 3-12. Cumulative WY percolation for Prado EFO model and OCWD RFM.

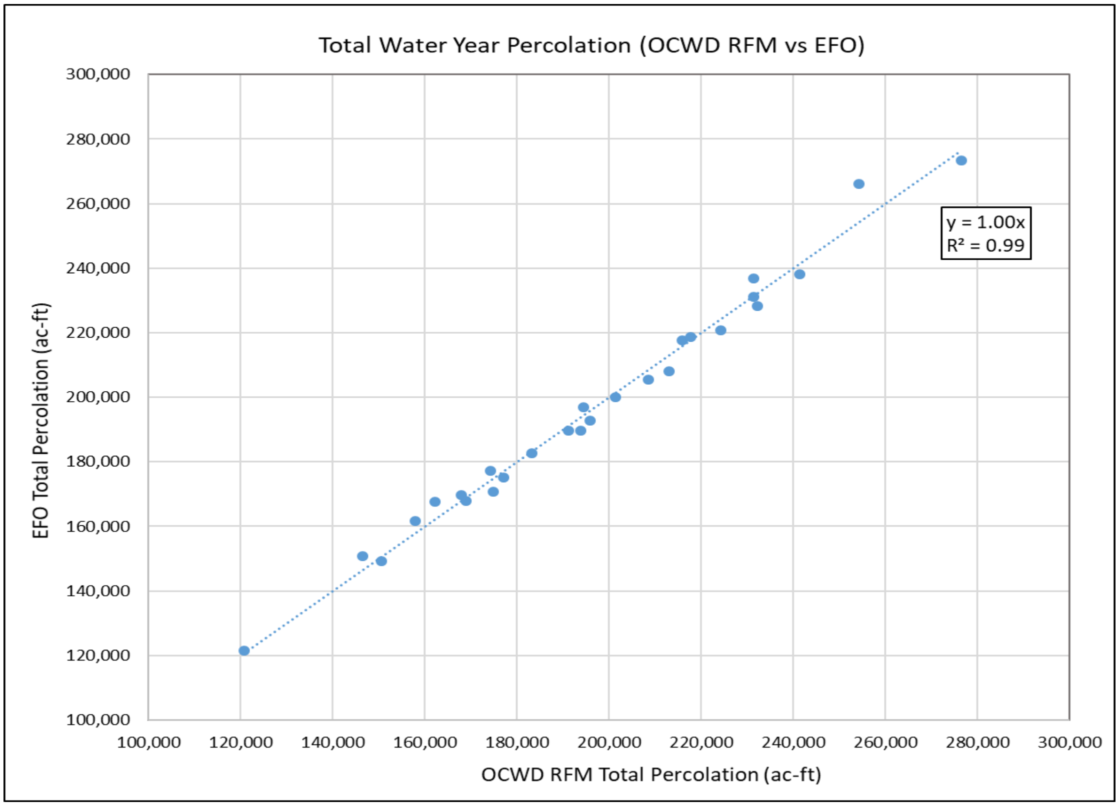


Figure 3-13. *Scatter plot of Prado EFO model versus OCWD RFM total WY percolation.*

3.3 Simulation Plan

The simulation plan defines and provides the observations and forecasts needed to simulate reservoir operations for each WCP identified in Table 3-5. The use of forecasts complicates the plan because, unlike observations, forecasts (1) can be generated using any number of models and model sophistication and (2) may or may not be available for the desired period of evaluation. This subsection describes the source of the forecasts used to evaluation the FIRO WCPs as well as the need to evaluate extreme events not adequately represented in the evaluation period of record.

3.3.1 Streamflow Observations

A primary input for the Prado EFO model is the observed inflows into the reservoir. These data were provided by USACE for 1985 to 2011. Natural flows downstream of Prado Dam to the OCWD diversion site on the Santa Ana 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 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.

3.3.2 Streamflow Forecasts

For reasons of expediency and operational application, streamflow forecasts from the California Nevada River Forecast Center (CNRFC) were selected for use in the PVA evaluations. CNRFC streamflow forecasts are operationally available for the Santa Ana River Basin as both five-day deterministic values as well as 15-day ensembles. Both are generated using the NWS Community Hydrologic Prediction System (CHPS) with common model parameters and states.

CHPS is an object-oriented modeling framework based on the Deltares Flood Early Warning System (FEWS). The NWS completed its transition from the National Weather Service River Forecast System (NWSRFS) in 2013. CHPS is a combination of integrated and adapted models that describe hydrologic/hydraulic processes as well as a vast array of data and information handling, storage, display, and analysis tools. In the transition to CHPS, common FEWS features were adopted and a collection of NWSRFS-specific models and tools were adapted into the framework.

The specific models deployed by the CNRFC are quite consistent across their area of responsibility (Figure 3-14), but the models for each location are individually configured and calibrated to approximate observed streamflow when presented with observations of precipitation, air temperature, and freezing level elevation. CNRFC models are classified as empirical or "process simulation." They are not rigorous physically based models that attempt to capture the full physics of watershed behavior. CNRFC model applications are "semi-lumped" as opposed to an interconnected grid network. Watersheds with large elevation ranges are typically modeled in two to three elevation bands to better represent elevation-dependent processes, features, and conditions. CNRFC watershed models are run with a six-hour time step and riverine models are run with an hourly time step.

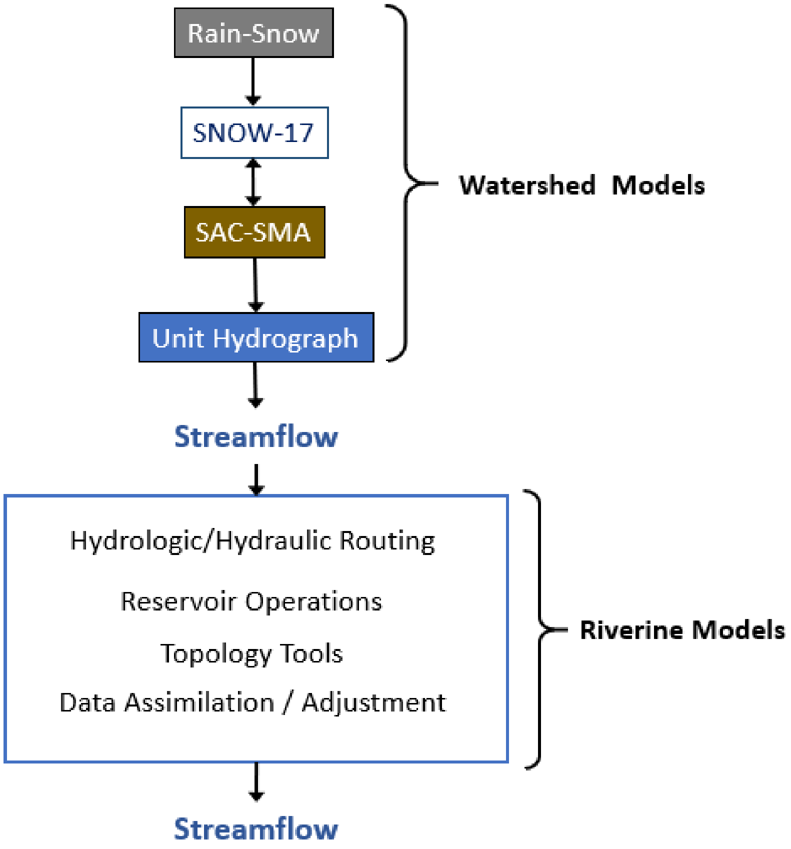


Figure 3-14. *Watershed and riverine models deployed by the CNRFC within the CHPS framework.*

The generalized process used to generate the 5-day deterministic forecasts is shown in Figure 3-15. Here, the CHPS hydrologic models are presented with new observations and updated meteorological forecasts with each forecast cycle. There is at least one forecast cycle per day (365 days/year), with two on weekdays in the winter and up to four during flood events. As well as needing the latest weather forecast, reliable streamflow forecasts depend on quality control of observations and the monitoring and tuning of model states. In conducting forecasting duties, hydrologists work their way through the model topology for each river basin, making the necessary adjustments to the observational data and model states to achieve (1) a good fit of the simulated streamflow to the observations during the last several days and (2) confidence in the streamflow forecast given the forecast meteorology. When complete, the forecasts are packaged into graphics and text products used to generate public watches and warnings and to help with resource management decisions (e.g., reservoir releases). Current and archived river forecasts can be found on the CNRFC website (www.cnrfc.noaa.gov).

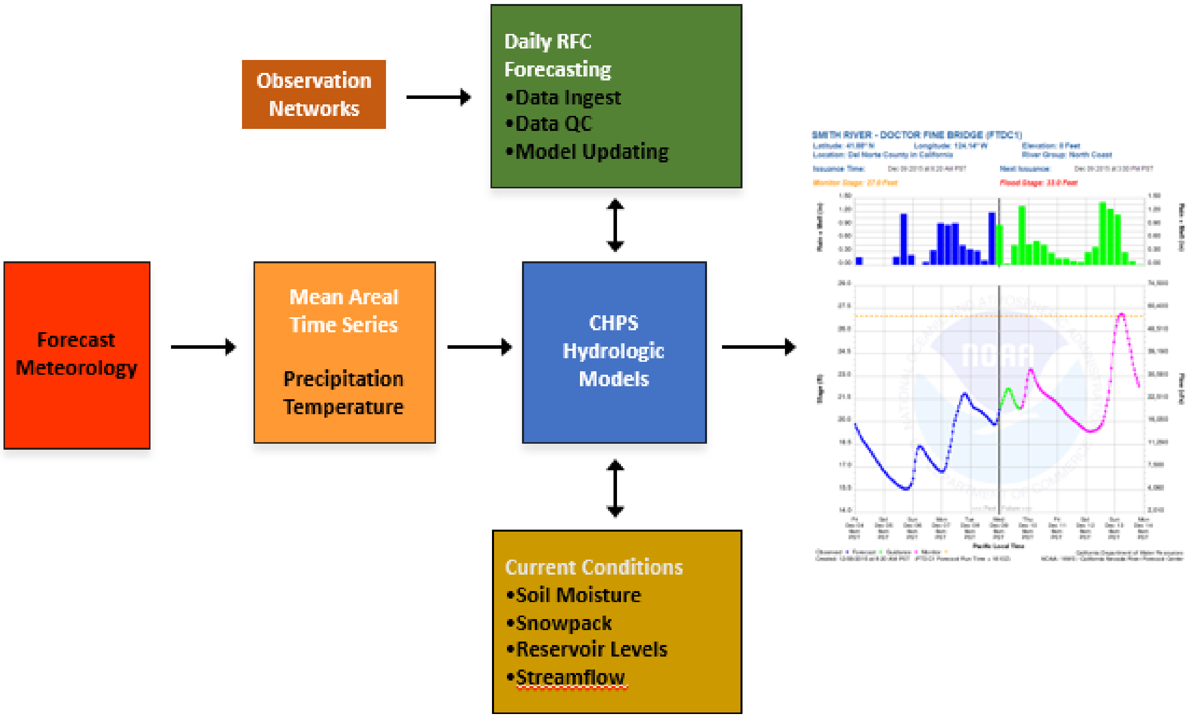


Figure 3-15. Generalized forecast process used by the CNRFC to generate five-day deterministic streamflow forecasts.

The CNRFC model topology for simulating and forecasting the Santa Ana River watershed is shown in Figure 3-16. Seven Oaks Dam operations are not explicitly modeled and directly contribute to flow at Mentone. Potential contributions from the Lake Elsinore portion of the watershed were considered "non-contributing." Both are reasonable assumptions for the purposes of this study.

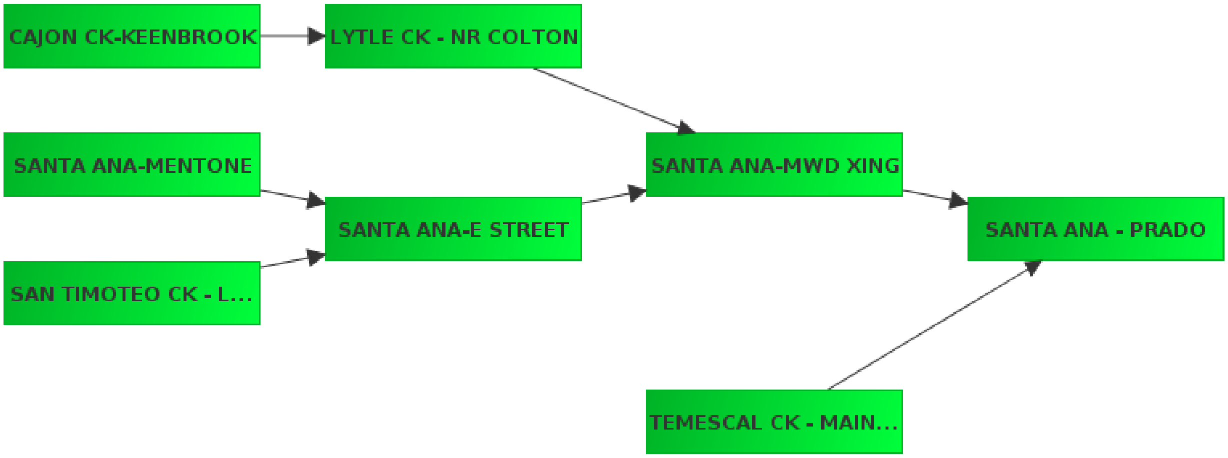


Figure 3-16. CNRFC CHPS model topology for the Santa Ana River.

The same models and model states are used in the CHPS modeling framework to create ensemble streamflow forecasts. Ensembles provide a way to describe the uncertainty in the streamflow forecast. Instead of just one deterministic forecast, there are many equally likely forecasts or forecast scenarios. Ensembles are useful for describing the uncertainty and for extending the lead time past where a deterministic forecast would have value. To generate ensemble streamflow forecasts, the CNRFC uses a system called the Hydrologic Ensemble Forecast System (HEFS) (Hartman 2016). Figure 3-17 shows the HEFS process deployed by the CNRFC.

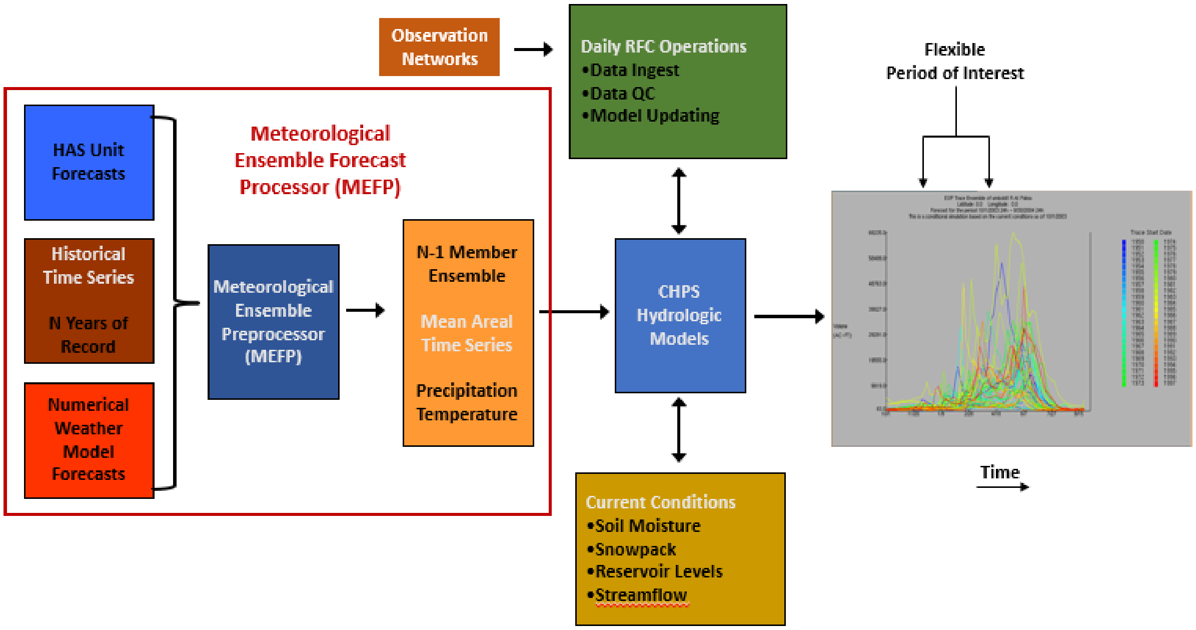


Figure 3-17. CNRFC ensemble streamflow generation process (HEFS).

Note that the only real difference is in the meteorological weather forecast. Instead of a single deterministic forecast of precipitation and air temperature, a set of ensemble precipitation and air temperatures are generated and passed through the hydrologic models. This results in a set of ensemble streamflow forecasts that can be used to generate graphical or tabular information or used directly in a decision support model.

The engine of HEFS is the Meteorological Ensemble Forecast Processor (MEFP). The MEFP generates a set of meteorological (precipitation and air temperature) ensemble forecasts given (1) a raw single-value forecast and (2) the calibrated relationship between the raw single-value forecast and the observation for the specific watershed. The MEFP science is described in Demargne et al. (2014). The MEFP can use any source of weather forecasts with an adequate archived history to perform the calibration (about 10 years). Calibrations are specific to each watershed or sub-watershed modeled and parameters are stored for use in operations and hindcasting. The MEFP accounts for the bias in the raw single-value forecast and the spread of the ensembles reflects the skill at each lead time. MEFP-calibrated parameters are allowed to vary throughout the year.

The historical time series of watershed observations (Figure 3-17, dark brown box) plays a key role in retaining the spatial and temporal relationship between adjacent watersheds and sub-watersheds. They also influence the value of the individual ensemble members at each time step. As the skill diminishes, the generated ensembles become more like the historical time series (climatology). When the raw single-value forecast has "no skill" (based on the calibration) the MEFP returns climatology or "resampled" climatology if that option is selected. The duration of the historical time series also determines the number of ensemble members. From Table 3-8, MEFP Calibration 1 produces 62 members (1949–2011 inclusive, less one).

HEFS has additional features not shown in Figure 3-17. These include ensemble post-processing (Ens-Post), product generating (GraphGen), and ensemble verification (EVS).

The CNRFC has calibrated the MEFP using archived HAS (Hydrometeorological Analysis and Support) QPF (quantitative precipitation forecasts) and GEFS hindcasts (Hamill et al. 2013) as shown in Table 3-8. In operations, the CNRFC uses three days of HAS QPF followed by 12 days of GEFS (total of 15 days) and began using MEFP Calibration 2 in February 2021. Operational HEFS forecasts extend 30 days (three days HAS, 12 days GEFSv12, 15 days climatology) and have 39 members (1980–2019 inclusive, less one).

Table 3-8. Use of HAS and GEFS in CNRFC MEFP calibrations.

MEFP Calibration	Historical Climatology	HAS Period	GEFS Version	GEFS Period	Operational Forecast Source	Hindcast Source	Hindcast Period of Record	Number of Members
1	1949–2011	2000–2011	10	1985–2011	3 days HAS 12 days GEFS	15 days GEFS	1985–2011	62
2	1980–2019	2005–2019	12	1990–2019	3 days HAS 12 days GEFS	15 days GEFS	1990–2019	39

3.3.2.a Streamflow Hindcasts

Hindcasts are forecasts generated for dates in the past using a specific set of models and data; they are useful for assessing the performance of current forecasting technologies over a longer period than is otherwise possible. The hindcasts generated using MEFP Calibration 1 (Table 3-8) were used in the PVA evaluations (described in Section 4). These hindcasts only use GEFS because the period of available forecasts is longer, covering a broader range of watershed conditions. Hindcasts generated through MEFP Calibration 2 will be used in the Prado Dam FVA.

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 in Figure 3-17). In the hindcast process the hydrology models are run without the benefit of review and tuning. Second, the operational HEFS ensembles use the HAS (weather forecaster) QPF, 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 therefore the results should be 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.

3.3.2.b 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 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 hydrology was developed to match the 100-year and 200-year peak daily inflows estimated by USACE, which are 60,000 and 80,000 cfs respectively (USACE 2020).

Six scaled events were developed from the 1998, 2005, and 2010 flood events within the hindcast record. Scaling factors were calculated from the ratio of design frequency peak flow (100-year and 200-year) to the observed peak flow. Each of the scaled events was 22 days long with the peak flow occurring on day 15. Table 3-9 summarizes the scaled events. The events were simulated at an hourly time step to capture the dynamic complexity of the spillway releases during the high flow conditions created by these events. To create the scaled event hydrology, observed hourly inflows and hindcasted hourly inflows were scaled by the factors provided in the table. The resultant scaled hydrographs are shown in Figure 3-18, Figure 3-19, and Figure 3-20.

Table 3-9. Scaling factors developed for the 100- and 200-year scaled flood events.

Date	Observed Peak Flow	Scale Factor		Event Start	Event End
		100-Year	200-Year		
2/24/1998	16,370	3.67	4.89	2/9/1998	3/3/1998
1/10/2005	24,539	2.45	3.26	12/26/2004	1/17/2005
12/22/2010	25,352	2.37	3.16	12/7/2010	12/29/2010

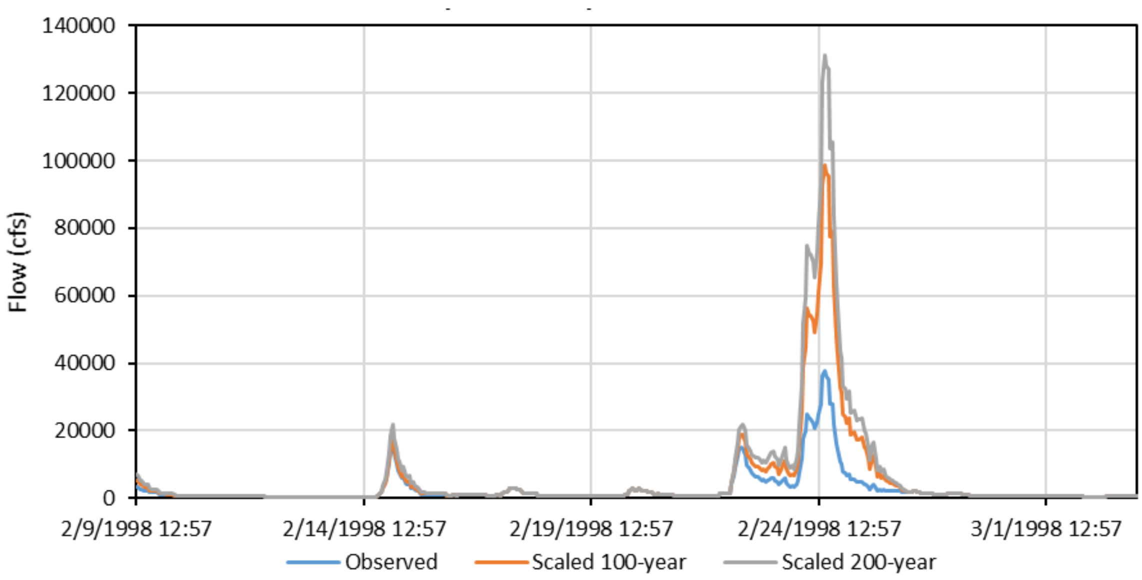


Figure 3-18. *Scaled Prado Dam inflows for the 1998 100-year and 200-year events. Observed inflows are also included for reference.*

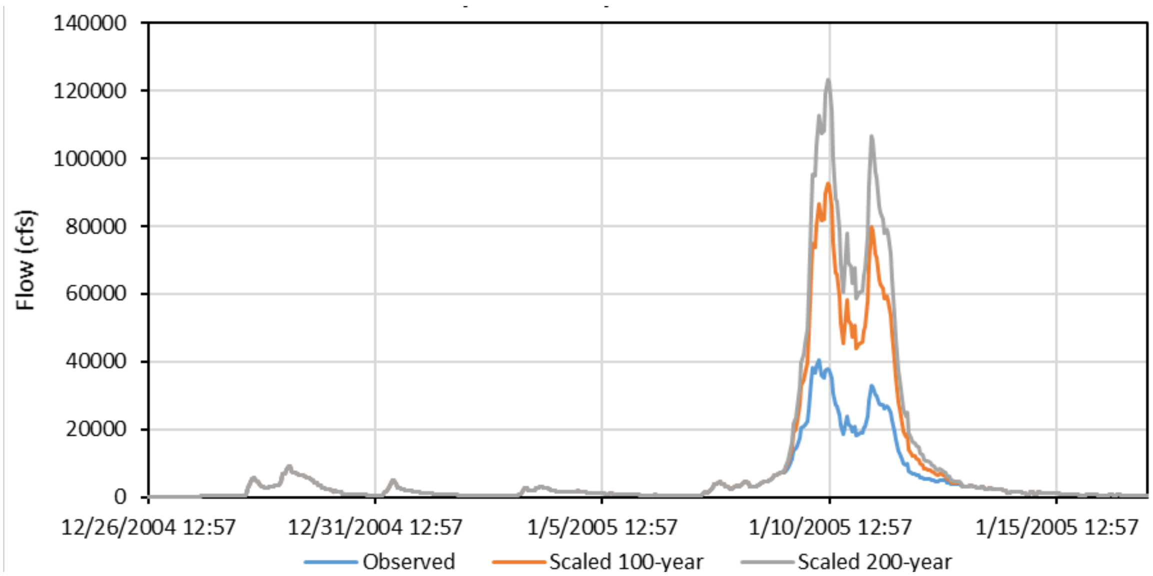


Figure 3-19. *Scaled Prado Dam inflows for the 2005 100-year and 200-year events. Observed inflows are also included for reference.*

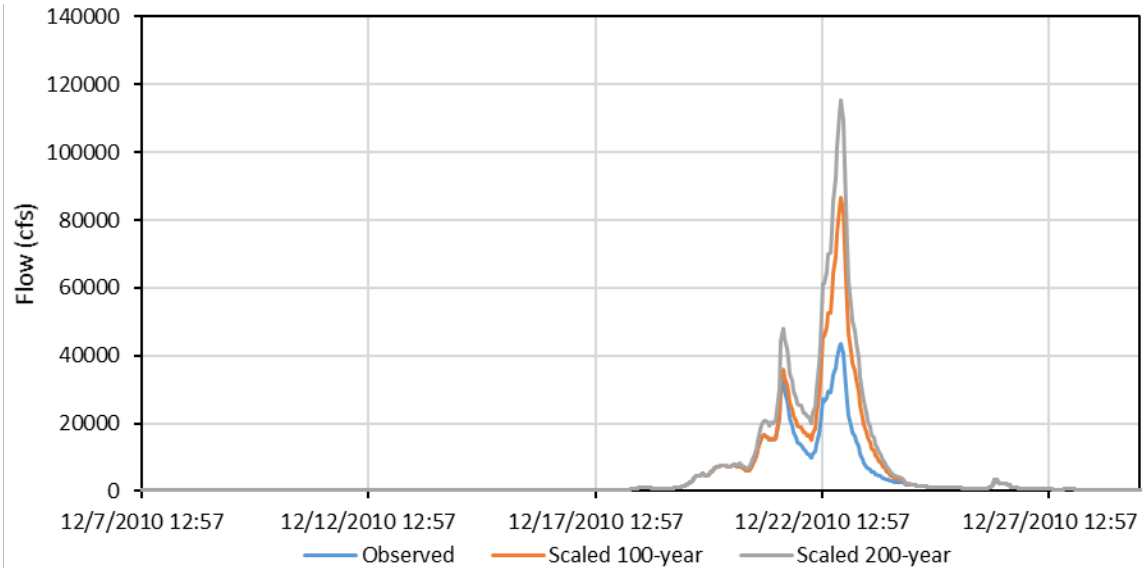


Figure 3-20. *Scaled Prado Dam inflows for the 2010 100-year and 200-year events. Observed inflows are also included for reference.*

Key refinements for the FVA:

- Improve representation of current baseflow conditions above Prado Dam.
- Improve generated scaled extreme events.
- Use GEFSv12 in streamflow hindcasts.
- Include scaled extreme events in risk tolerance curve calibration.

3.4 Refinements for the FVA

In conducting this work, several issues arose that will need to be addressed as a part of the FVA. Additional detail is provided on each of these suggested refinements below:

1. In the last 20 years, the baseflow in the Santa Ana River above Prado Dam has fallen off considerably due to greater recapture of wastewater and aquifer recharge above the dam. Baseflow has gone from about 150,000 to about 70,000 ac-ft annually. There are no direct measurements that can be used to adjust inflow observations. To ensure that the FVA assessment reflects the anticipated future state, (1) the historical observations associated with the 1985–2011 hindcast period need to be adjusted to reflect current baseflow conditions and (2) the CNRFC simulation and forecasting of Prado Dam inflow needs to be calibrated to the current baseflow conditions.
2. The CNRFC could not generate the scaled hindcast events in time for the first draft of the PVA. Instead, a simple scaling of the events was performed as an approximation to preliminarily estimate the flood risk management performance associated with extreme events. These scalings were based on the 100-year and 200-year one-day volume inflows as provided by the USACE LAD. For the process of developing and evaluating the scaled

events, the three-day volumes may be more appropriate and should be considered for the FVA. When available, the frequency distributions for maximum annual reservoir elevation, spillway activation, and maximum annual release should be updated using the CNRFC scaled hindcast events generated with a validated volume duration.

3. The FVA should use HEFS hindcasts and scaled events generated with GEFSv12.
4. The calibration of the EFO model's risk tolerance curve, as described in Appendix F, only incorporated the period of record hindcasts to identify a curve that meets the project objectives to improve water supply reliability while not increasing flood risk and is adequate for proof-of-concept demonstration of FIRO for Prado Dam. As previously mentioned, the hindcast period of record does not include extreme flood events that fully challenge the flood control operations of the reservoir. Future efforts to calibrate the risk tolerance curve should incorporate more extreme hydrology such as the scaled 100- and 200-year events, producing a more robust curve to minimize future flood risk.

3.5 References

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[USACE] U.S. Army Corps of Engineers. 1988. Santa Ana River *Phase II General Design Memorandum on the Santa Ana River Mainstem including Santiago Creek: Design Memoral1dum No.1.* Los Angeles District.

[USACE] U.S. Army Corps of Engineers. 2020. *Prado Dam flood hazard assessment, inflow volume based approach to estimating stage-frequency.*

Section 4 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. These alternatives are listed in Table 4-1.

Table 4-1. Candidate WCP alternative strategies.

ID	Alternative Strategy	Description
1	Unrestricted 505 feet (baseline)	Buffer pool allowed to extend up to 505 feet without a seasonal restriction. Releases when pool is ≤ 505 feet at maximum recharge rate. Releases above 505 feet are at the maximum scheduled rate. No forecasts were used.
2	EFO-508	Buffer pool allowed to extend up to 508 feet. Uses ensemble inflow forecast to determine release required to mitigate risk of exceeding spillway crest.*
3	EFO-512	Buffer pool allowed to extend up to 512 feet. Uses ensemble inflow forecast to determine release required to mitigate risk of exceeding spillway crest.*
4	NF-512	Buffer pool allowed to extend up to 512 feet without a seasonal restriction. Releases when pool is ≤ 512 feet at maximum recharge rate. Releases above 512′ are at the maximum scheduled rate. No forecasts were used.
5	PFO-512	Buffer pool allowed to extend up to 512 feet. Uses observed inflows as forecasts (perfect forecasts) to determine releases that avoid exceeding spillway crest.*

* A spillway crest of 543 feet was evaluated for period of record simulations, and spillway crests of 543 and 563 feet were evaluated for 100-year and 200-year scaled hydrologic events.

The alternatives include the baseline (#1), two strategies that use ensemble streamflow forecasts (#2 and #3), a strategy that does not use forecasts but allows for a higher buffer pool (#4), and a strategy that assumes perfect forecast skill (#5). Perfect forecasts were emulated by substituting the actual observations. The simulation plan described in Section 3.3 called for:

- Simulation of the period of record of the ensemble streamflow hindcasts (1985–2011).
- Simulation of scaled 100-year and 200-year events for February 1998, January 2005, and December 2010.

In addition, the simulations of each WCP run were configured for each of three Santa Ana River Mainstem (SARM) states:

- Spillway elevation 543 feet, maximum release 10,000 cubic feet per second (cfs), below called "543/10."
- Spillway elevation 543 feet, maximum release 30,000 cfs ("543/30").
- Spillway elevation 563 feet, maximum release 30,000 cfs ("563/30").

Because 543/30 did not approach the spillway crest for the hindcast period of record simulation, 563/30 was not simulated for the hindcast period of record. This required a total of 100 separate simulation runs. A complete graphical summary of the results is provided in Appendix G.

The goals of this assessment were to:

- Refine the process through which Forecast Informed Reservoir Operations (FIRO) and non-FIRO WCP strategies could be simulated and evaluated for the Final Viability Assessment (FVA).
- Gain insight on the viability of FIRO for Prado Dam.
- Gain insight on the type of WCPs that should be evaluated for the FVA.

As such, the analysis and results shown are not intended to yield a recommendation on a specific FIRO WCP for Prado Dam. Instead, they provide information for a follow-on study that includes an implementation recommendation.

4.1 Key Findings

1. The models and processes described in Section 3.2 were successful in simulating Prado Dam operations for the hindcast period of record and for scaled extreme events.
2. The hindcast period of record simulations (1985–2011) with 543/10 and 543/30 did not reach the spillway crest for any of the alternatives and therefore did not provide any change in flood risk management outcomes. Scaled events (100-year and 200-year) were needed to discriminate between alternatives.
3. For the hindcast period of record simulations, the alternatives with a higher buffer pool provided for greater groundwater recharge. There was almost no groundwater recharge difference between the 512-foot alternatives that used no forecasts, ensemble forecasts, and perfect forecasts.
4. Scaled event simulations for EFO-508 and EFO-512 provided better flood risk management outcomes than baseline. NF-512 provided slightly worse flood risk management outcomes. This suggests that buffer pools above 505 feet are viable, but only if forecasts are used to inform release decisions.
5. The completion of the SARM will dramatically increase the level of flood protection below Prado Dam. The increased maximum release of 30,000 cfs provides for a total evacuation of the buffer pool (tested to 512 feet but likely much higher) with more than adequate forecast lead time.
6. The upper limit of the buffer pool elevation is a function of community/environmental tolerance for more frequent flood pool inundation in the winter.

Key findings of the evaluation:

- The models and processes described in Section 3.2 were successful in simulating Prado Dam operations for the hindcast period of record and for scaled extreme events.
- The hindcast period of record simulations (1985–2011) with 543/10 and 543/30 did not reach the spillway crest for any of the alternatives and therefore did not provide any differences in flood risk management outcomes. Scaled events (100-year and 200-year) were needed to discriminate between alternatives.
- For the hindcast period of record simulations, the alternatives with a higher buffer pool provided for greater groundwater recharge. There was almost no groundwater recharge difference between the 512-foot alternatives that used no forecasts, ensemble forecasts, and perfect forecasts.
- Scaled event simulations for EFO-508 and EFO-512 provided better flood risk management outcomes than baseline. NF-512 provided slightly worse flood risk management outcomes. This suggests that buffer pools above 505 feet are viable, but only if forecasts are used to inform release decisions.
- The completion of the SARM will dramatically increase the level of flood protection below Prado Dam. The increased maximum release of 30,000 cfs provides for a total evacuation of the buffer pool with more than adequate forecast lead time.
- The upper limit of the buffer pool elevation is a function of community/environmental tolerance for more frequent flood pool inundation in the winter.

4.2 Groundwater Recharge Metrics

The evaluation described here was based on the 1985–2011 hindcast period of record simulations for each alternative for the 543/10 configuration. Figure 4-1 shows the cumulative groundwater recharge for each of the alternatives considered. Notice that in the early years of the simulation (marked by drought), there is essentially no difference between the alternatives. This suggests that FIRO strategies are opportunistic and cannot generate benefits every year.

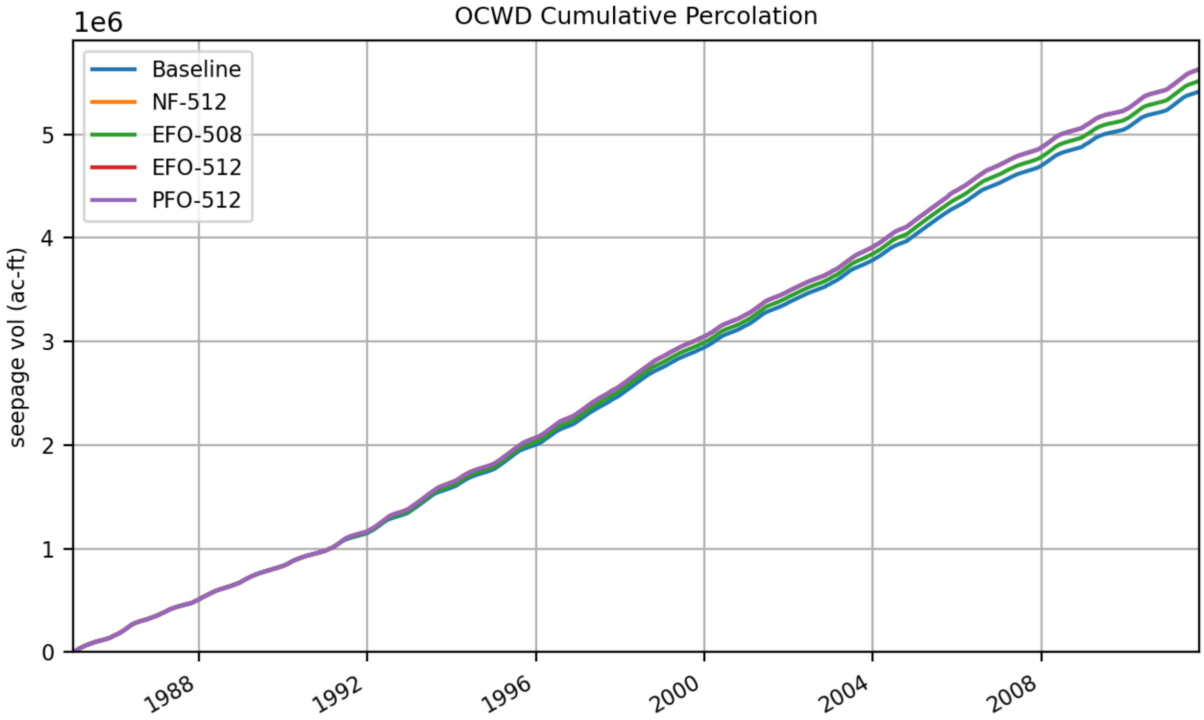


Figure 4-1. Cumulative groundwater recharge for each WCP alternative. Note that all the 512 alternatives have nearly identical results and plot on top of each other. Note also that recharge for all alternatives was the same through 1992 due to drought conditions.

Figure 4-2 shows the frequency of annual groundwater recharge per alternative for the 543/10 configuration. NF-512, EFO-512, and PFO-512 show very consistent results with gains (increases from baseline) ranging from 3,700 to 24,700 acre-feet (ac-ft) for the 3.7 to 70 percent exceedance range, and little to no gain in the 75 to 96 percent exceedance range (drought years). These alternatives show about a 6.5 percent increase in median water year percolation volumes relative to baseline and a 3.4 percent increase in average. EFO-508 shows a similar trend, but due to the smaller buffer pool, the gains are not as extensive—a 3.4 percent increase in median and a 1.7 percent increase in mean water year percolation volume relative to baseline.

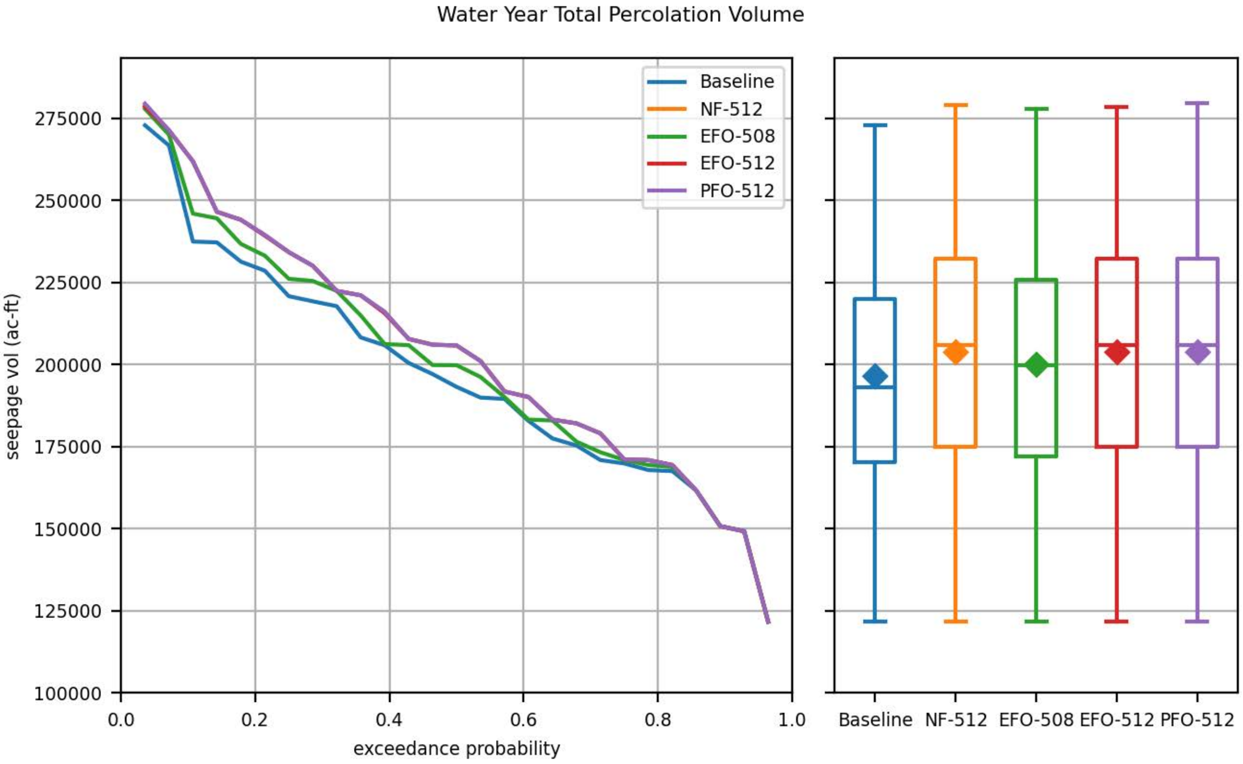
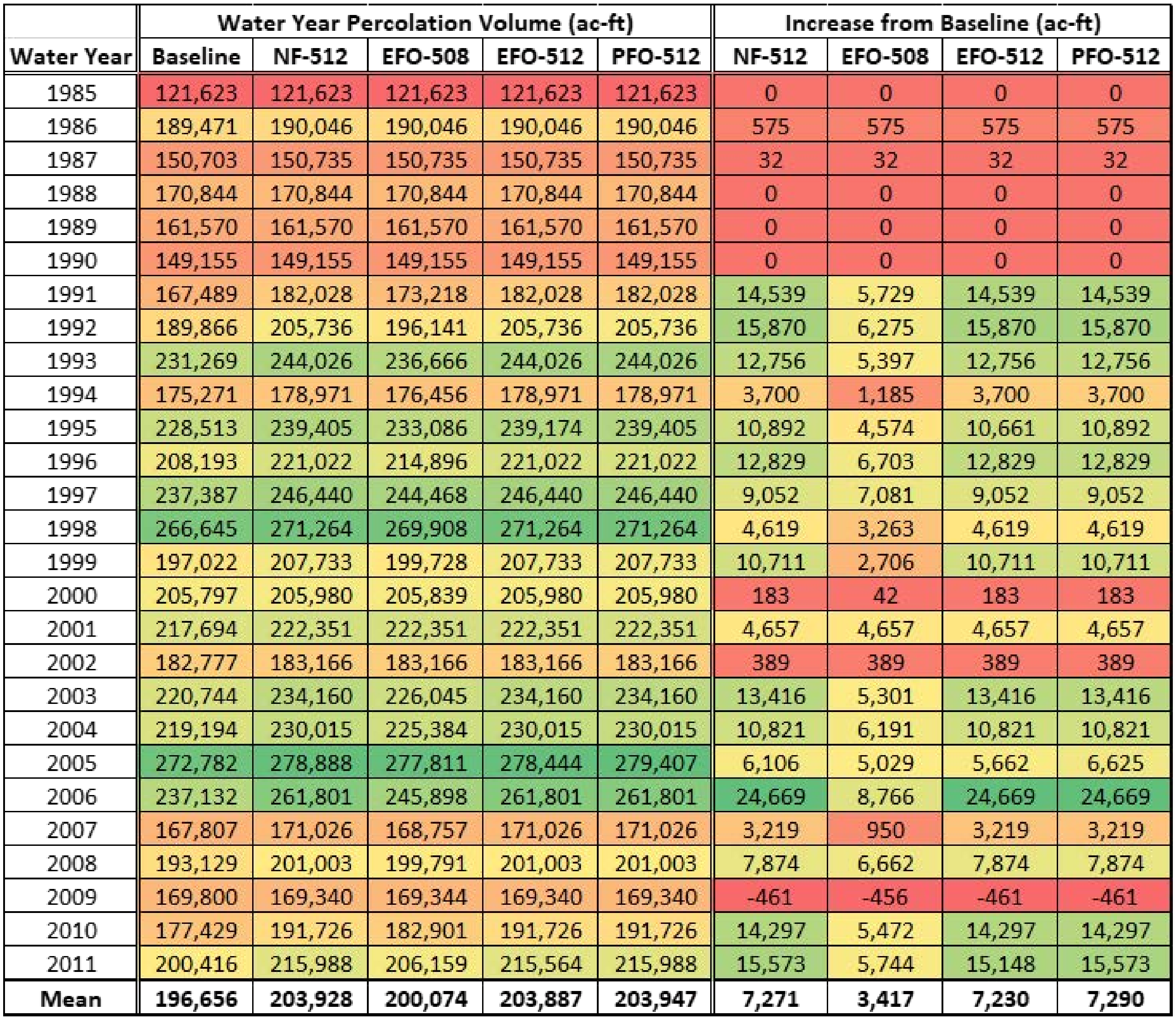


Figure 4-2. *Water year percolation volumes plotted as probability exceedance (left panel) and box and whisker plots (right panel). The upper and lower whiskers are the range of results, boxes are the interquartile range, and diamond markers are the mean.*

Table 4-2 provides the year by-year total groundwater recharge as well as the difference in recharge from the baseline WCP. Note that in drought years (e.g., 1985–1990) there was essentially no difference because so little runoff was available for storage. The increased buffer pool size of NF-512, EFO-508, EFO-512, and PFO-512 allows additional water to be detained in the reservoir after a large storm, which can later be released at a rate to accommodate Orange County Water District (OCWD) groundwater recharge operations.

While the differences appear small, the gains offset expensive alternative sources. Wet years, particularly those with several events that result in storage above 505 feet, result in significant recharge differences.

Table 4-2. Annual percolation volumes by water year and water year increases from baseline (gains). Mean water year percolation volumes and mean increases from baseline provided in bottom row.

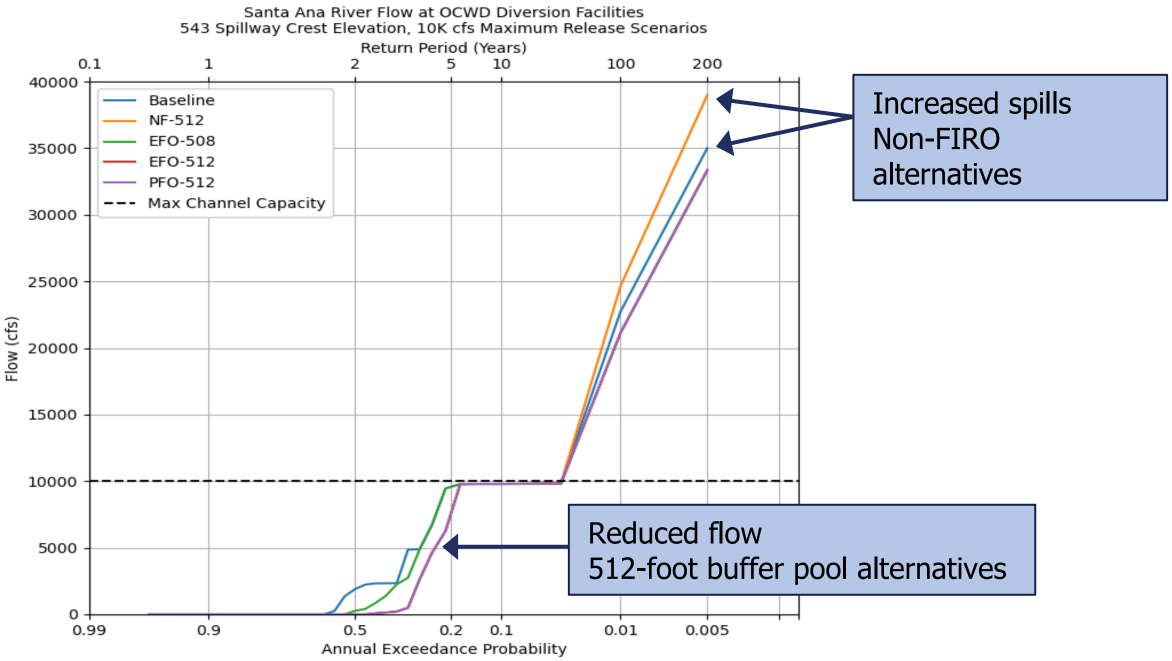


	Water Year Percolation Volume (ac-ft)					Increase from Baseline (ac-ft)			
Water Year	**Baseline**	**NF-512**	**EFO-508**	**EFO-512**	**PFO-512**	**NF-512**	**EFO-508**	**EFO-512**	**PFO-512**
1985	121,623	121,623	121,623	121,623	121,623	0	0	0	0
1986	189,471	190,046	190,046	190,046	190,046	575	575	575	575
1987	150,703	150,735	150,735	150,735	150,735	32	32	32	32
1988	170,844	170,844	170,844	170,844	170,844	0	0	0	0
1989	161,570	161,570	161,570	161,570	161,570	0	0	0	0
1990	149,155	149,155	149,155	149,155	149,155	0	0	0	0
1991	167,489	182,028	173,218	182,028	182,028	14,539	5,729	14,539	14,539
1992	189,866	205,736	196,141	205,736	205,736	15,870	6,275	15,870	15,870
1993	231,269	244,026	236,666	244,026	244,026	12,756	5,397	12,756	12,756
1994	175,271	178,971	176,456	178,971	178,971	3,700	1,185	3,700	3,700
1995	228,513	239,405	233,086	239,174	239,405	10,892	4,574	10,661	10,892
1996	208,193	221,022	214,896	221,022	221,022	12,829	6,703	12,829	12,829
1997	237,387	246,440	244,468	246,440	246,440	9,052	7,081	9,052	9,052
1998	266,645	271,264	269,908	271,264	271,264	4,619	3,263	4,619	4,619
1999	197,022	207,733	199,728	207,733	207,733	10,711	2,706	10,711	10,711
2000	205,797	205,980	205,839	205,980	205,980	183	42	183	183
2001	217,694	222,351	222,351	222,351	222,351	4,657	4,657	4,657	4,657
2002	182,777	183,166	183,166	183,166	183,166	389	389	389	389
2003	220,744	234,160	226,045	234,160	234,160	13,416	5,301	13,416	13,416
2004	219,194	230,015	225,384	230,015	230,015	10,821	6,191	10,821	10,821
2005	272,782	278,888	277,811	278,444	279,407	6,106	5,029	5,662	6,625
2006	237,132	261,801	245,898	261,801	261,801	24,669	8,766	24,669	24,669
2007	167,807	171,026	168,757	171,026	171,026	3,219	950	3,219	3,219
2008	193,129	201,003	199,791	201,003	201,003	7,874	6,662	7,874	7,874
2009	169,800	169,340	169,344	169,340	169,340	-461	-456	-461	-461
2010	177,429	191,726	182,901	191,726	191,726	14,297	5,472	14,297	14,297
2011	200,416	215,988	206,159	215,564	215,988	15,573	5,744	15,148	15,573
Mean	**196,656**	**203,928**	**200,074**	**203,887**	**203,947**	**7,271**	**3,417**	**7,230**	**7,290**

4.3 Flood Risk Management

As described in Section 3.3, 100-year and 200-year scalings were simulated for three events within the hindcast period of record. These analyses were combined to create frequency plots that extended to the 200-year level. The key flood risk management metrics identified in the hydraulic engineering management plan were the frequency of the annual maximum discharge and the frequency of annual maximum water surface elevation behind Prado Dam. To account for local flows between Prado Dam and the OCWD recharge facilities, the annual maximum flow at the OCWD recharge facilities was substituted for the annual maximum flow immediately below Prado Dam.

Figure 4-3 shows the frequency of annual maximum flows at the OCWD diversion for the 543/10 configuration. Baseline and EFO-508 show highest flows from the ~58 to 18 percent annual exceedance probability (AEP) range, while NF-512, EFO-512, and PFO-512 show reduced flows for the same range due to the increase size of the buffer pool relative to baseline and EFO-508. All alternatives show maximum annual discharge at channel capacity between the 18 and 4 percent AEP range. NF-512, which does not use forecasts, shows the highest flows for 1 and 0.5 percent AEP (100 and 200-year return periods) due to an increase in spillway releases from Prado Dam for the scaled 100-year and 200-year event simulations.

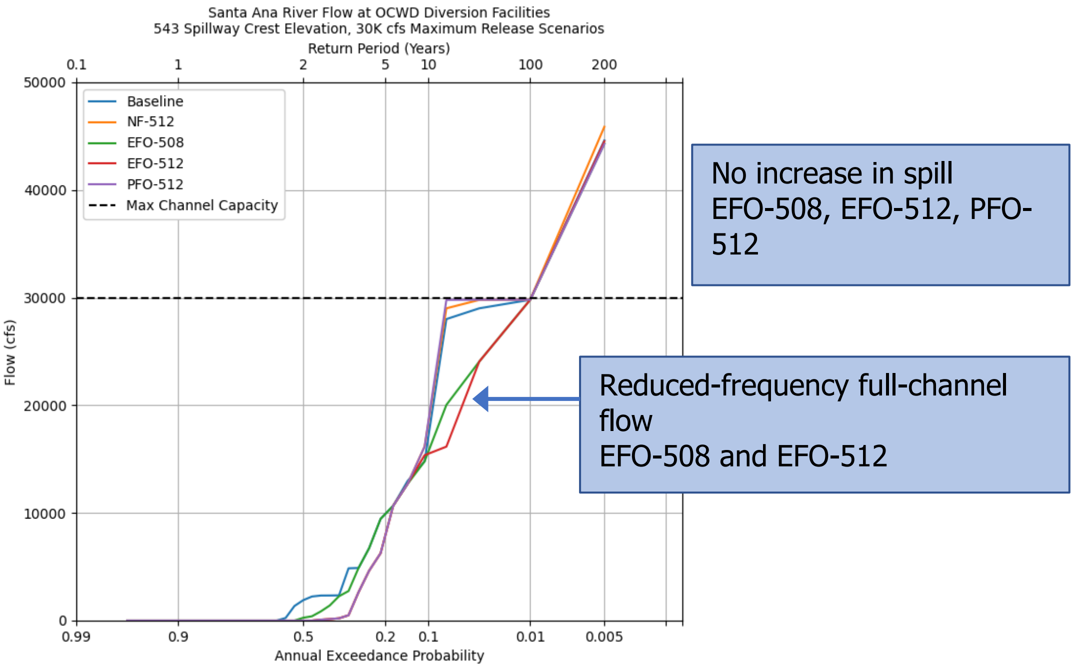


Increased spills
Non-FIRO
alternatives

Reduced flow
512-foot buffer pool alternatives

Figure 4-3. Annual maximum discharge (cfs) on the Santa Ana River at the OCWD diversion facilities plotted as annual exceedance probability, assuming 543/10 configuration.

Figure 4-4 provides the same information but for the 543/30,000 configuration. Note that there is little difference in the 100-year and 200-year flows, but the alternatives that use forecasts (EFO-508 and EFO-512) have lower flows in the 10- to 100-year range. This is considered a significant benefit: while the SARM-complete channel capacity will be 30,000 cfs, there are still significant impacts at these higher flow rates.

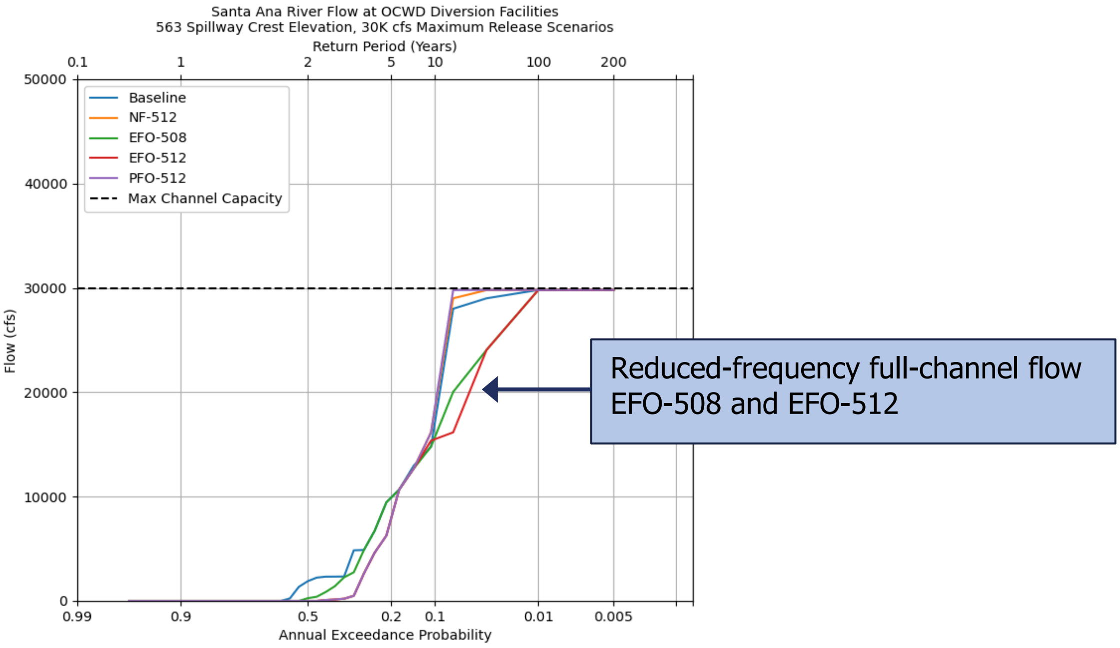


No increase in spill
EFO-508, EFO-512, PFO-512

Reduced-frequency full-channel flow
EFO-508 and EFO-512

Figure 4-4. Annual maximum discharge (cfs) on the Santa Ana River at the OCWD diversion facilities plotted as annual exceedance probability, assuming the 543/30 configuration.

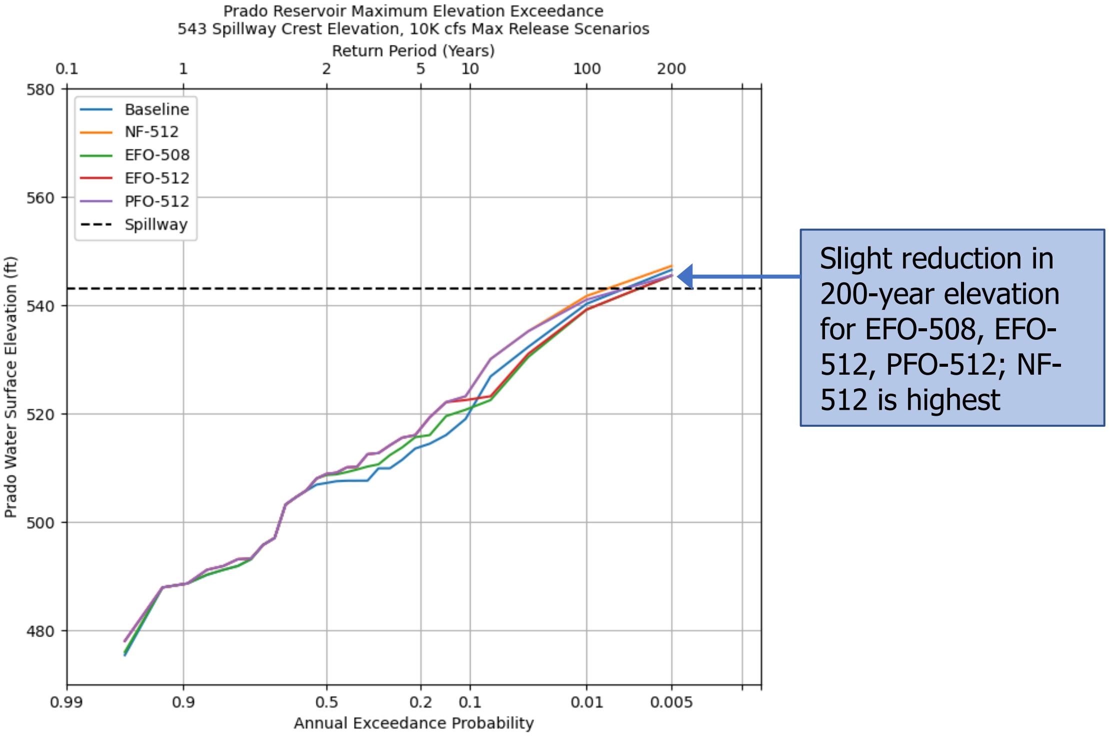
The same analysis for the 563/30 configuration is shown in Figure 4-5. Note here that none of the alternatives simulated spillway flow, but as with 543 feet/30,000 cfs, the alternatives that use forecasts (EFO 508 and EFO-512) had lower flows in the 10- to 100-year range.



Reduced-frequency full-channel flow
EFO-508 and EFO-512

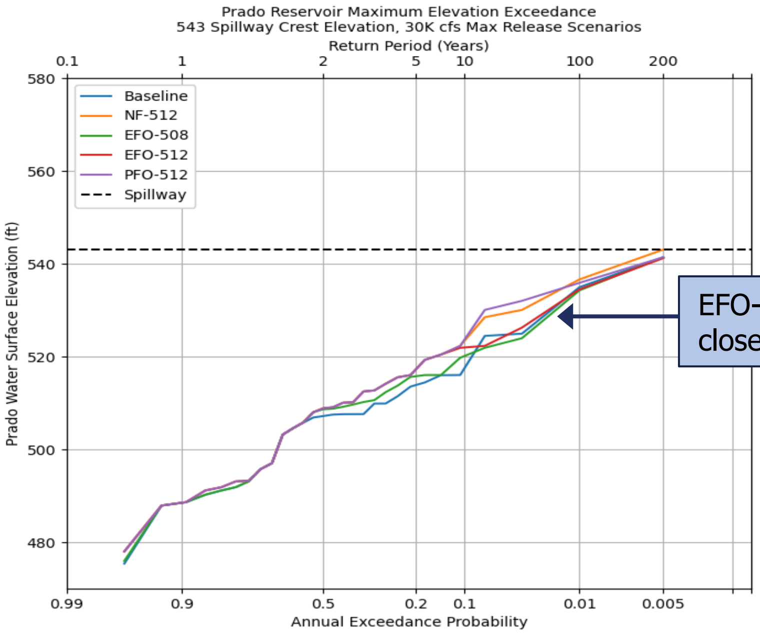
Figure 4-5. Annual maximum discharge (cfs) on the Santa Ana River at the OCWD diversion facilities plotted as annual exceedance probability, assuming a 563/30 configuration.

Figure 4-6, Figure 4-7, and Figure 4-8 compare the annual maximum pool elevation frequency for the 543/10, 543/30, and 563/30 configurations. In the 543/10 configuration, the WCPs that use forecasts resulted in slightly lower maximum pool elevations for the 100- and 200-year return intervals. In the 543/30 configuration, the alternatives that use forecasts (EFO-508, EFO-512) closely trended with the baseline while the others tended to have higher elevations above the 10-year return interval. In the 563/30 configuration, none of the alternatives approached the higher spillway crest, suggesting a high level of flood protection when the SARM is complete.



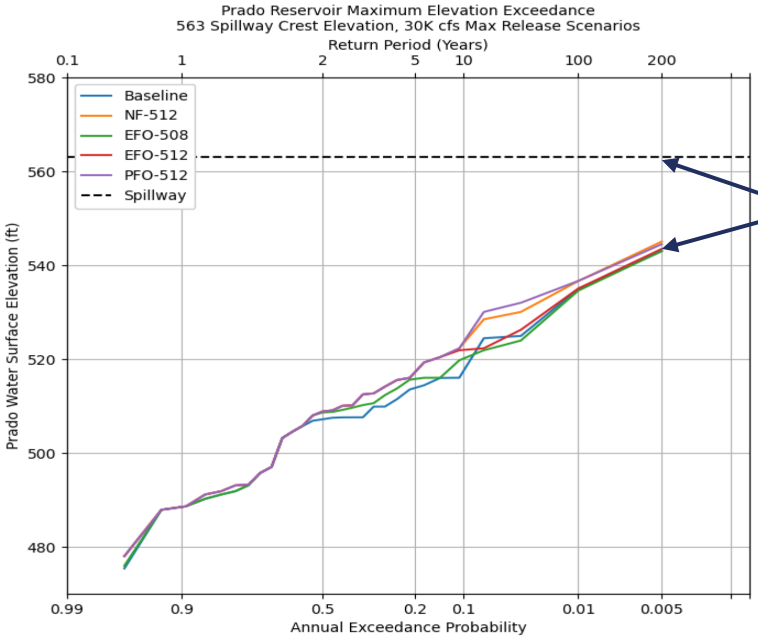
Slight reduction in 200-year elevation for EFO-508, EFO-512, PFO-512; NF-512 is highest

Figure 4-6. Comparison of maximum annual pool elevation frequency for the 543/10 configuration.



EFO-508 and EFO-512 closely trend baseline

Figure 4-7. Comparison of maximum annual pool elevation frequency for the 543/30 configuration.



All alternatives well below the spillway crest

Figure 4-8. Comparison of maximum annual pool elevation frequency for the 563/30 configuration.

Along with maximum pool elevations and downstream discharges, the inundation of Corona Airport (515 feet) and Euclid Avenue (520 feet) pose concerns. Figure 4-9 and Figure 4-10 show the frequency for the number of days of water surface elevation above 515 and 520 feet for the 543/10 configuration.

All alternatives show a low frequency of exceeding the 515-foot threshold, with the highest frequency associated with NF-512. They also show a low frequency of exceeding 520 feet, with the highest frequencies associated with NF-512 and PFO-512. EFO-512 shows a lower frequency due to pre-releases in advance of the 2005 flood event.

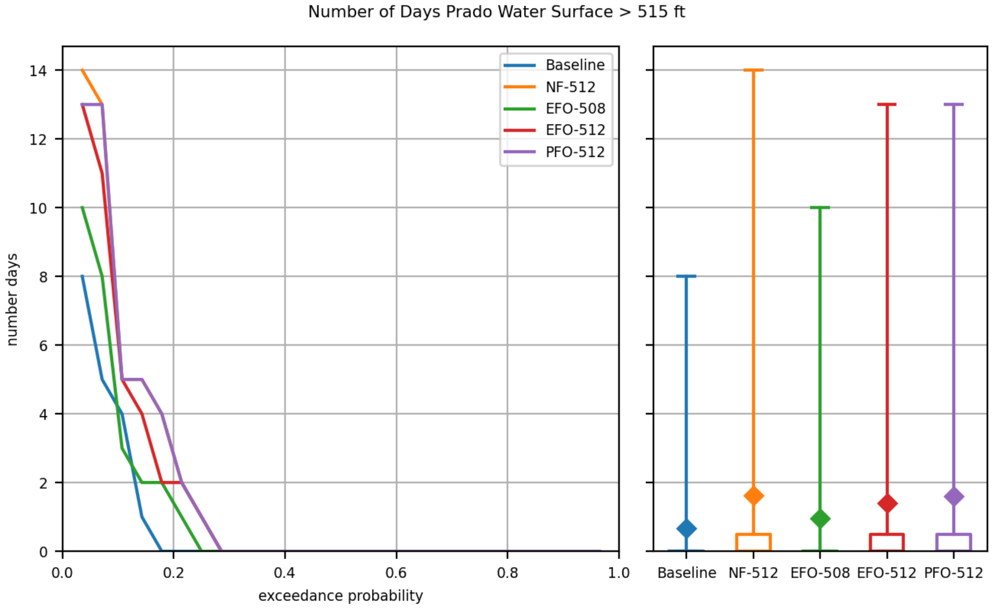


Figure 4-9. Number of days Prado Reservoir water surface water exceeds 515 feet, plotted as probability exceedance (left panel) and in box and whisker plots (right panel) where the upper and lower whiskers are the range of results, boxes are the interquartile range, and diamond markers are the mean.

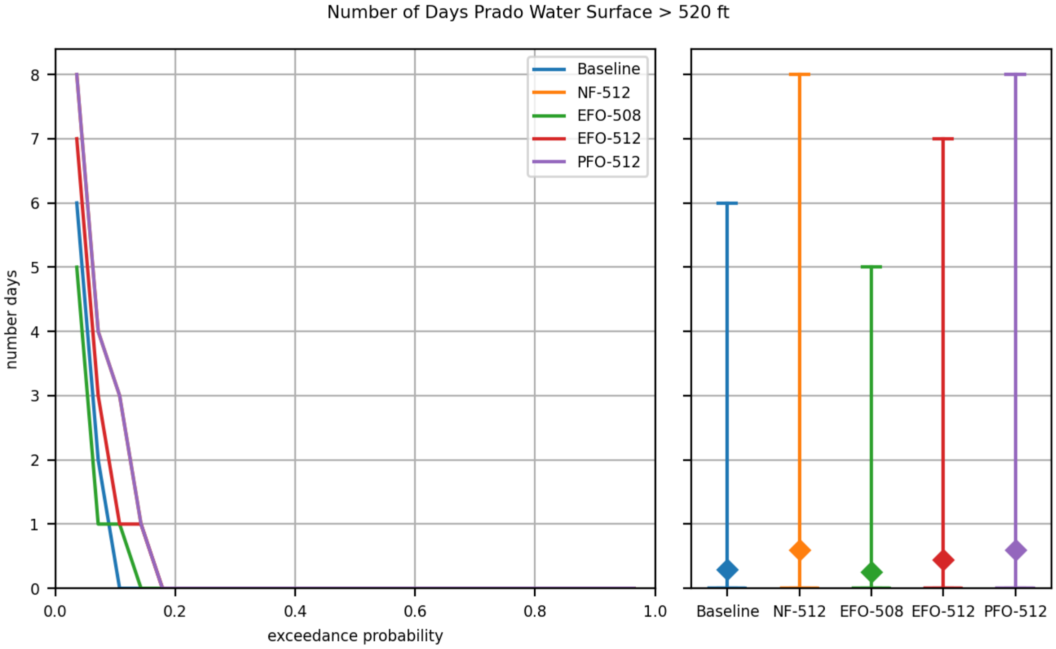


Figure 4-10. Number of days Prado Reservoir water surface water exceeds 520 feet, plotted as probability exceedance (left panel) and in box and whisker plots (right panel) where the upper and lower whiskers are the range of results, boxes are the interquartile range, and diamond markers are the mean.

4.4 Environmental Metrics

The key environmental concerns identified through the workplan are associated with the least Bell's vireo habitat. Repeated long-duration inundation could affect the health of the riparian forest in the flood pool. Figure 4-11 and Figure 4-12 compare the number of days of inundation above 505 and 510 feet for the alternatives associated with the 543/10 configuration. (Number of days above 512 and 514 feet was also analyzed and can be found in Appendix G.)

In Figure 4-11, the 60 to 100 percent exceedance range show no days exceeding 505 feet. This shows the extensive dry periods in the simulation where storage levels are kept below this elevation to meet downstream OCWD diversions demands. Baseline has the lowest buffer pool (505 feet) and therefore the lowest frequency of water surface elevation above this elevation threshold. Water is stored above this elevation only when it is temporarily detained during storm events. EFO-508 shows an increase in the number of days above 508 feet as a result of the increased buffer pool of this alternative. NF-512, EFO-512, and PFO-512 show consistent results, with the greatest number of days above 505 feet. These three alternatives have the same size buffer pool of up to 512 feet.

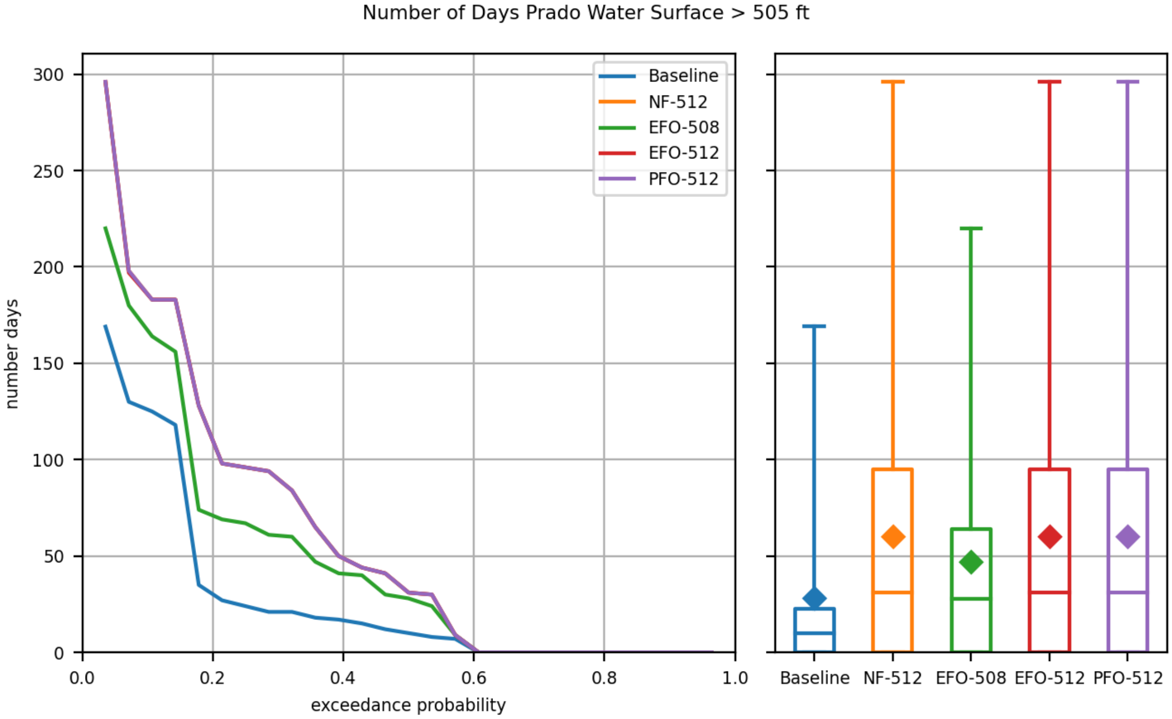


Figure 4-11. Number of days Prado Reservoir water surface water exceeds 505 feet, plotted as probability exceedance (left panel) and in box and whisker plots (right panel) where the upper and lower whiskers are the range of results, boxes are the interquartile range, and diamond markers are the mean. 543/10 configuration.

In Figure 4-12, the 50 to 100 percent exceedance range shows no days exceeding 510 feet. Baseline and EFO-508 show a low frequency of exceeding 510 feet. NF-512, EFO-512, and PFO-512 show consistent results, with the greatest number of days above 510 feet. These three alternatives have the same size buffer pool: up to 512 feet, which exceeds this threshold.

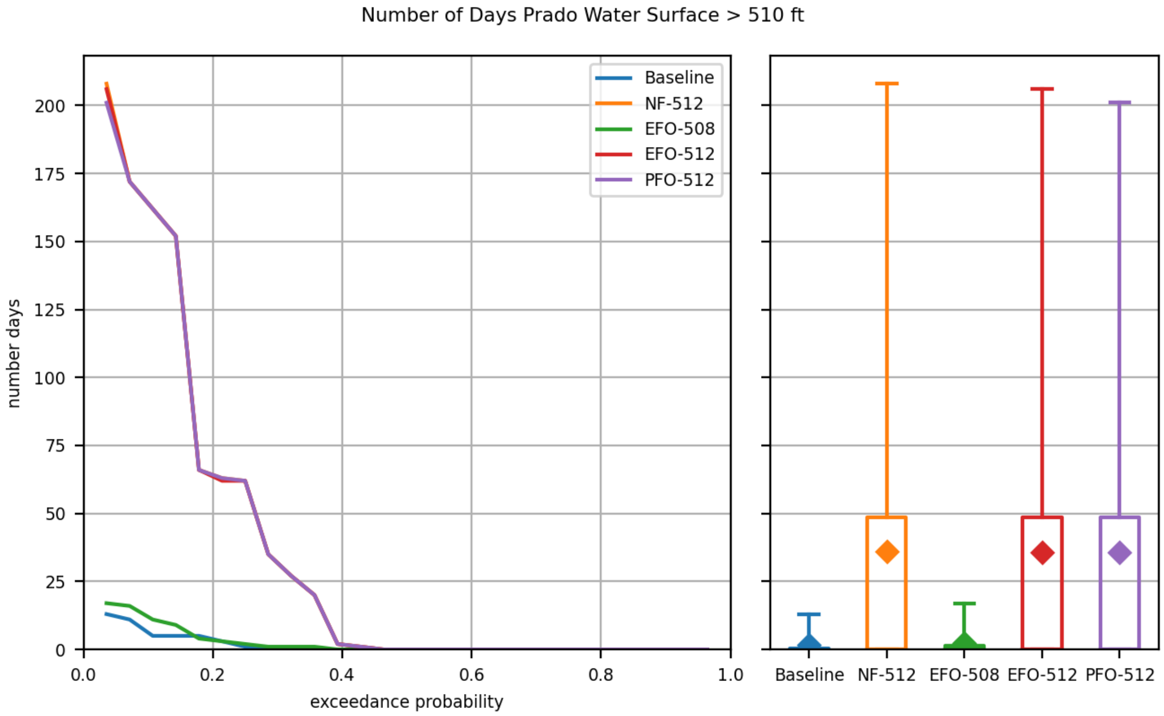


Figure 4-12. Number of days Prado Reservoir water surface water exceeds 510 feet, plotted as probability exceedance (left panel) and in box and whisker plots (right panel) where the upper and lower whiskers are the range of results, boxes are the interquartile range, and diamond markers are the mean. 543/10 configuration.

In addition, when vireos return to nest in the riparian forest in the spring, their nests can be damaged by reservoir rises, as they prefer to nest about 1 meter above the water surface elevation. Figure 4-13 compares the frequency of rises in the March 21–May 1 period for the 543/10 configuration. Note that this suggests a slight increase in 2-meter rises in about 10 percent of years over baseline. Note also that all alternatives resulted in a significantly lower incidence of 2-meter rises than has been observed over the 1985–2011 simulation period.

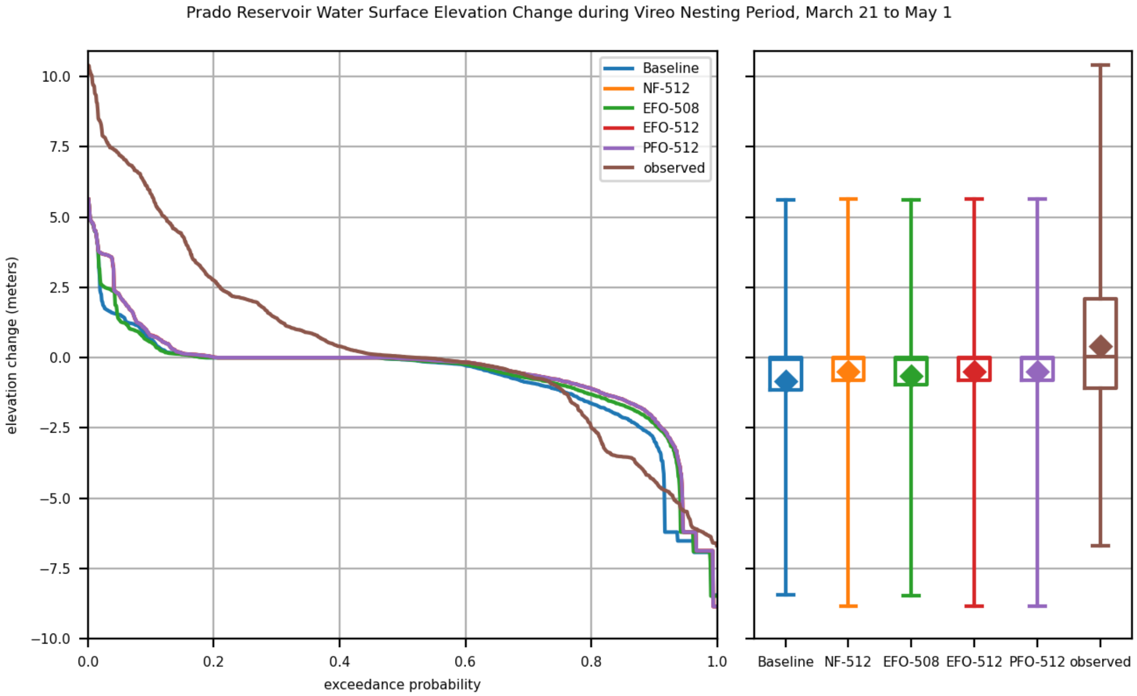


Figure 4-13. Change in Prado Reservoir water surface elevation from March 21 to May 1, plotted as probability exceedance (left panel) and in box and whisker plots (right panel) where the upper and lower whiskers are the range of results, boxes are the interquartile range, and diamond markers are the mean. 543/10 configuration for the 1985–2011 hindcast period of record.

4.5 Conclusions and Recommendations

The simulations and assessments performed generated significant insight into the viability of FIRO at Prado Dam. While the process and assessment will be refined, it is clear that existing streamflow forecasts can improve groundwater recharge outcomes without impacting flood risk management. The potential impacts on environmental objectives need further examination associated with the riparian habitat health. For a better understanding of potential impacts (positive or negative), the results to date (shown above) for the frequency of riparian forest inundation need to be cross-walked with plant physiology information.

Recommended refinements to the simulation and evaluation process are captured in Section 3.4. The simulation of scaled 100-year and 200-year events with a completed SARM (563/30) suggests that FIRO WCP alternatives with buffer pools of 512 or even 515 feet will have no impact on flood risk management objectives. This is because the new storage is massive in comparison to the buffer pools under consideration and the increased maximum release can effectively empty the buffer pool with limited lead time. As such, the limit on the size of the buffer pool is more a community/environmental tolerance of more frequent flood pool inundation in the winter. The FVA analysis should include additional alternatives that will help to define this. Thus, the FVA should:

- Evaluate FIRO alternatives with buffer pools greater than 512 to understand the buffer pool elevation where flood risk management outcomes are compromised.

Evaluate NF (no forecast) alternatives with buffer pools 505 to 512 feet to more clearly define where forecasts become critical to avoiding impacts to flood risk management.

Section 5 Studies, Research, and Development in Support of the PVA

5.1 Overview and Purpose

The Prado Dam Preliminary Viability Assessment (PVA) stands on a foundation of extensive meteorological, hydrological, and biological research; decision support tools; 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.

Section 5.1 summarizes two important aspects of the science behind Forecast Informed Reservoir Operations (FIRO):

- **Scientific advances to date** that have demonstrated FIRO viability at Prado Dam.
- **The coordinated approach that has made such progress possible**—a research and operations framework and partnership that can serve as a blueprint for future success.

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

The potential for 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 season 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 be successful 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. 2020c). The box on the right lists four examples of recent innovations that have improved the underlying science to support FIRO.

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 Weather Service's (NWS'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, development and application of an Ensemble Forecast Operations (EFO) method (Delaney et al. 2020) represents a major contribution to FIRO and the future considerations for Prado Dam Water Control Manual (WCM) update while also enabling continued research and potential integration for improved 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 5.2 through 5.5 provide more detailed information about these efforts and additional advances in weather forecasting, observations, hydrology and water resources modeling, and biological investigations.

5.1.2 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). The application of forecasts in decision making is implemented through designing robust decision support processes and tools with forecasters and operators, then ensuring wide usability of those tools through training and communication. These advances benefit from a collaborative research and operations (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 and 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 5-1 shows a conceptual pathway from research to operations for improved observations, models, and decision support tools. 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.

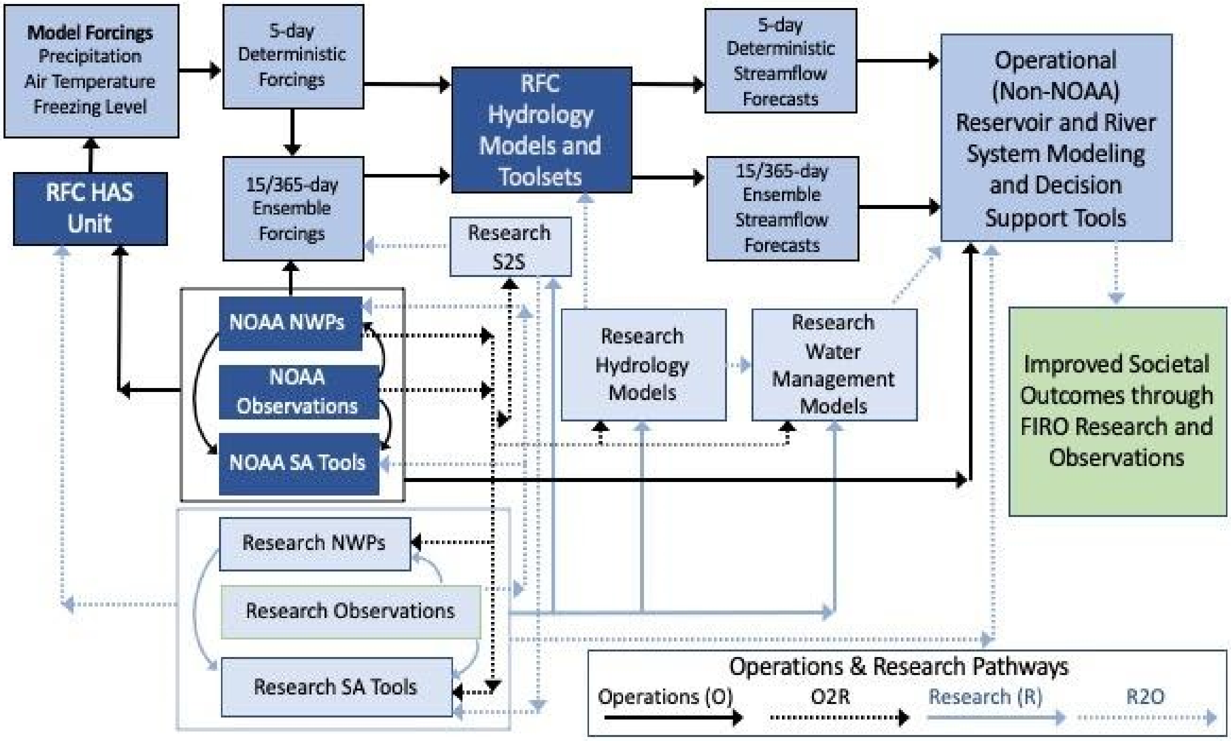


Figure 5-1. Operations and research pathways concept as applied to Prado Dam FIRO.

FIRO creates an environment where ongoing research investments in forecasts and their application leads 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 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.

5.2 Meteorological Analysis, Assessment, and Research

By linking hydrologic prediction to its atmospheric drivers, FIRO can leverage significant opportunities in AR prediction improvement stemming from research advances in numerical weather prediction (NWP) development, process-based research, and back-end decision tool development. This approach to address both quantitative and qualitative pathways for operational forecast improvement and to target both incremental and transformative advances in hydrometeorological prediction embodies the novel RAOP partnership that has come to define FIRO. Understanding the physical processes and quantifying the predictability of extreme events in the Santa Ana River watershed will lead toward improved decision support for reservoir management.

Meteorological research accomplishments in support of FIRO at Prado Dam include:

- Research to establish the primary precipitation processes in the Santa Ana River watershed, including quantifying the importance of ARs to extreme event climatology.
- Assessment of current AR and precipitation forecast skill, determination of sources of uncertainty, and effort toward reduction of errors.
- Development of AR forecasting tools (e.g., the AR landfall tool and AR scale) and communication of their utility in operational decision support.
- Development and implementation of the Western Weather Research and Forecasting (West-WRF) high-resolution forecast model to support forecasting and decision making.
- Progress toward machine learning for bias correction and forecast error reduction of both West-WRF and operational prediction systems.
- Success in airborne reconnaissance field campaigns held during 2016, 2018, 2019, and 2020 to observe ARs before they make landfall on the West Coast and incorporation of observations immediately into global operational NWP models.
- Installation of a ground-based atmospheric sensor network for robust monitoring of watershed conditions (e.g., precipitation characteristics, integrated water vapor, streamflow), complementing existing longer-term observations from other networks.
- Embedding of airborne reconnaissance and ground-based atmospheric sensor network observations into FIRO process-based research studies in addition to using them to monitor the watershed in real time.

Key findings for Section 5.2:

- Two-thirds of extreme precipitation events between 1981 and 2017 were caused by landfalling ARs.
- Extreme precipitation events are generally well predicted out to at least five days and the forecast gradually improves to yield nearly no bias at one-day lead times.
- The regional West-WRF model that is designed specifically for AR conditions improves on the GEFS mean areal precipitation forecast at one- to five-day lead times.
- Machine learning bias corrections in a post-processing framework improve GFS predictions by about 5 percent at the beginning of the forecast to over 20 percent at seven days' lead time.
- The network of precipitation and temperature gages throughout the Santa Ana River watershed is adequate for the current hydrologic forecasting services provided by the CNRFC as well as GSSHA model development.
- Operational scanning radar has limitations for monitoring extreme precipitation in the Santa Ana watershed: topographic blocking and range effects interfere with accurate operational monitoring of intense precipitation over Southern California Bight.
- AR Recon reduces NWP initial condition errors in and around ARs offshore at one to three days' lead time.

5.2.1 Meteorology and Climate of the Santa Ana River Watershed

Southern California precipitation depends on a small number of extreme events each winter season. In the Santa Ana River watershed, precipitation mechanisms associated with regional extreme events are highly variable. Just 107 heavy precipitation events—defined as the 90th percentile of two-day PRISM mean areal precipitation totals (equating to ~50 mm [2 in.] of mean areal precipitation)—contributed nearly half of total precipitation between 1981 and 2017 (Cannon et al. 2018). Two-thirds of these events were caused by landfalling ARs. Preliminary analysis of the relationship between integrated water vapor transport (IVT) and gage-based interpolated precipitation shows that ARs in the Santa Ana watershed explained a maximum of 35 percent of daily precipitation accumulation variance, depending upon orientation (Ricciotti and Cordeira 2020; Figure 5-2). For comparison, watersheds in the central and northern parts of California demonstrate a considerably stronger relationship. This result is partially attributed to sample size (fewer events in Southern California), shorter-duration events with comparatively increased importance of non-orographic precipitation processes, and regional topography that includes a wider range of favorable orientations for upslope transport.

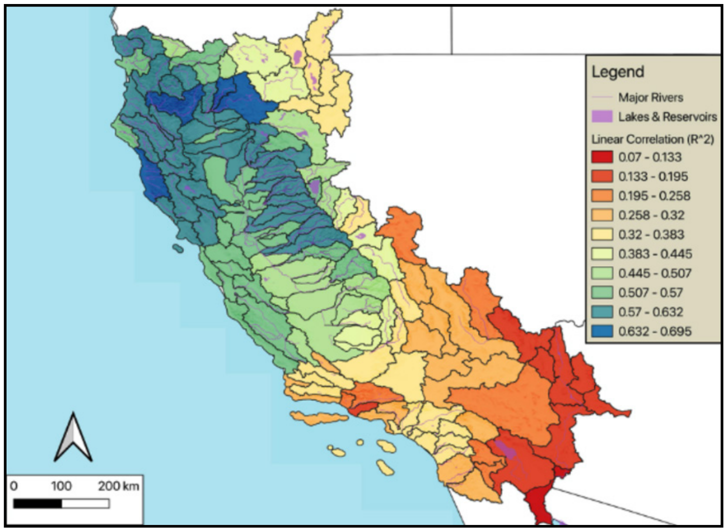


Figure 5-2. *Maximum mean areal precipitation variance explained by directional IVT into each watershed in California (Ricciotti and Cordeira 2020).*

In addition to the orographic forcing signal, research in the Prado FIRO assessment identified the importance of a range of physical mechanisms associated with the AR environment that modify precipitation generation across the record of extreme events, including synoptic-scale forcing (Hecht and Cordeira 2017; Cannon et al. 2018), thermodynamic stability (Oakley and Redmond 2014), mesoscale mountain circulations (e.g., barrier jets; Neiman et al. 2013), and microphysical processes (e.g., cloud physics; Minder et al. 2011). The FIRO Final Viability Assessment (FVA) will evaluate these individual mechanisms' contributions to event-total precipitation and their event-to-event variability, and results will guide precipitation forecast skill assessment and NWP development relative to FIRO requirements.

5.2.2 Predictability of Extreme Precipitation Events

Accurate and reliable precipitation forecasts are a fundamental underpinning of FIRO and are closely tied to the predictive skill of ARs (Ralph et al. 2006). While models are generally capable of predicting the occurrence of a landfalling AR, significant errors remain in predicting AR landfall position, intensity, and orientation (Wick et al. 2013; Lavers et al. 2016; Cordeira et al. 2017; DeFlorio et al. 2018; Nardi et al. 2018; Martin et al. 2018; Waliser et al. 2020). These AR forecast errors can lead to large precipitation and streamflow forecast errors (Ralph et al. 2020a). Convection, microphysics, and terrain-modified flow, among other physical processes, also modify precipitation generation and its predictability in the watershed (Cannon et al. 2018, 2020). Thus, research to quantify and improve forecasts of ARs and other precipitation mechanisms is an essential component of FIRO.

5.2.2.a Precipitation Forecast Skill

The PVA explored forecast skill for each extreme event since 2004 within the CNRFC QPF archive, which included 40 of the 107 events previously noted. Mean-areal QPF errors at 0- and 24-hour lead times prior to 48-hour accumulation events are shown to increase with quantitative precipitation estimate (QPE), although the percentage error does not (Figure 5-3). The most significant mean areal precipitation events in the CNRFC record—123 mm QPE on January 10–11, 2005, and 148 mm on December 22–23, 2010—featured relatively small forecast errors at zero- and one-day lead time (two and three days from the end of the event) as a fraction of the total accumulated precipitation (Figure 5-3). For the remaining smaller events, no two-day totals larger than 50 mm of QPE were under-forecast by more than 20 percent at zero-day lead times. While the percentage error increases for smaller QPE, the actual error was comparably small in those events.

While only short-range QPF is available for evaluation from the CNRFC, further evaluation of the 2005 and 2010 extreme events from a situational awareness perspective indicated that the meteorological conditions for an extreme AR event were predicted by ensemble forecast systems to at least seven days' lead time in both cases (not shown). Again, although QPF was moderately underestimated in terms of the total amount, the forecast system at lead times beyond three days was confident in an extreme event relative to the region's climatology.

Similarly, a comparison of the Global Ensemble Forecast System (GEFS) precipitation forecasts with the QPE for the same 40 dates shown in Figure 5-3 indicates that Santa Ana extreme events are generally well predicted out to at least five days and that the forecast gradually improves to yield nearly no bias at one-day lead times (i.e., the one-day forecast is consistent with the zero-day forecast) (not shown). The lack of forecast surprises is related to the prevalence of large-scale AR's as the predominant precipitation driver and is an important aspect of the feasibility of FIRO at Prado. Continued work toward the FVA will need to assess the frequency of false alarms, as not predicting events that do not occur is also essential to FIRO's success.

Note that condition-dependent predictability is reflected in the event-to-event variability of QPE skill (Figure 5-3). Further comparing the meteorological drivers and sources of ensemble forecast uncertainty at long lead times in the record of extremes will determine how event evolution affects both impacts and predictability. The concept of condition-dependent predictability has also been studied relative to variable AR landfall forecast skill in GEFS over Southern California during 2017–2020 (Cordeira and Ralph 2021) and is further discussed in this subsection's description of efforts to augment forecast skill.

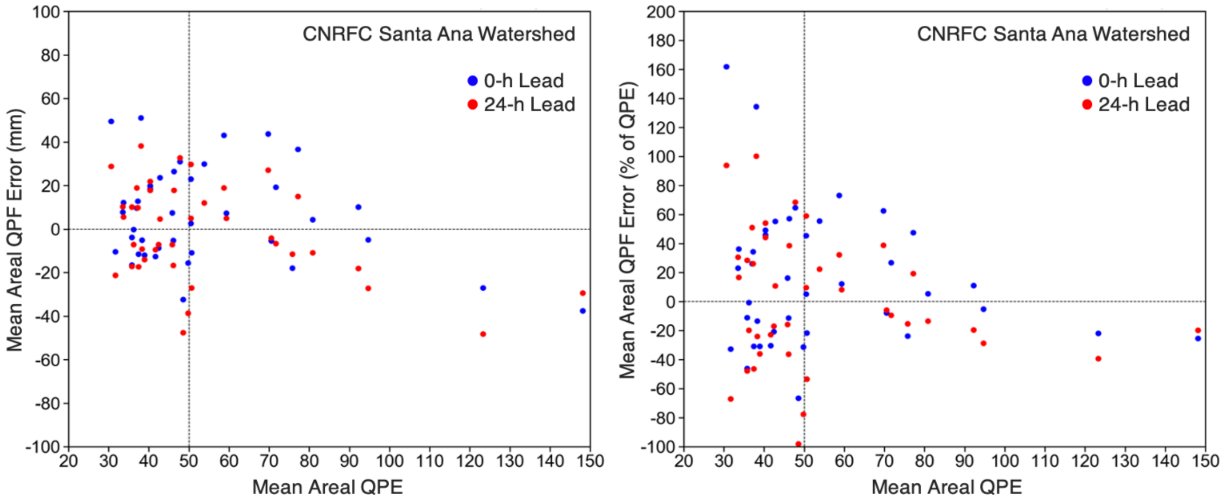


Figure 5-3. CNRFC forecast skill for 40 of 107 extreme events that overlap with the CNRFC QPF record (since 2004). The watershed mean areal QPE (mm) for each two-day accumulation period is plotted against the mean areal QPF error (mm) for predictions issued at the start of the event (0-hour lead; blue dots) and one day before the start of the event (24-hour lead; red dots) (left graph). The mean areal QPE (mm) and forecast error is shown as a percentage of QPE (right graph).

5.2.3 Regional Models: West-WRF

NWP forecast skill is limited by uncertainty in a model's initial state, physical process parameterization, and subgrid-scale unresolved processes (Berner et al. 2015). A coarse model grid is often thought of as a limit to resolving precipitation impacts in a landfalling AR by failing to represent the complex topography that forces moisture ascent and precipitation generation. However, the influence of coarse model resolution on NWP extends beyond local precipitation forcing, as the model's effective resolution also defines the scale of atmospheric processes that can be resolved. Model error from unrepresented subgrid-scale processes can propagate upscale and lead to large errors in synoptic-scale meteorological features at even short lead times (Skamarock et al. 2014), affecting AR evolution in the range of zero to five days.

Operationally, the National Centers for Environmental Prediction (NCEP) runs the High-Resolution Rapid Refresh mode, or HRRR (Benjamin et al. 2016), a version of the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008), to produce hourly 36-hour forecasts at 3 km resolution. In addition to NCEP's operational HRRR, the Center for Western Weather and Water Extremes (CW3E) runs West-WRF, a configuration of WRF that is tailored to AR events (Martin et al. 2018). West-WRF complements the operational HRRR and enables high-resolution forecasting frameworks and decision support tools to be tailored to the West. Small-scale precipitation processes, which are very important in predicting precipitation, are better represented by West-WRF. In addition, West-WRF provides higher spatial resolution for longer lead times than is available from any similar mesoscale NWP model run nationally. The current near-real-time West-WRF configuration includes an outer domain with 9 km resolution covering much of the eastern Pacific Ocean and western United States, and a nested 3 km domain covering California, as shown in Figure 5-4. Forecasts are run once daily from 0000 UTC initializations and are run out to seven-day lead times for the 9 km domain, and out to five-day lead times for the 3 km domain. WRF supports variable model configuration, including its parameterization schemes, and those used in West-WRF largely follow those used in the validation study by Martin et al. (2018) and in subsequent sensitivity testing by CW3E.

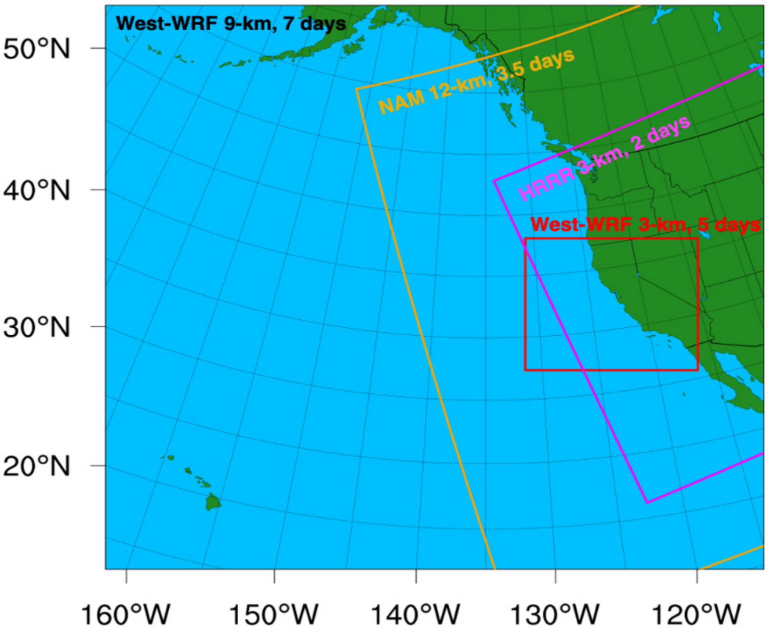


Figure 5-4. Computational domains and forecast maximum lead times for water year 2020: West-WRF 9 km (black) and 3 km (red), North America Model 12 km (orange), and HRRR 3 km (magenta).

During water year 2020, three separate near-real-time West-WRF configurations were run daily, differing in initial and lateral boundary conditions. The primary near-real-time West-WRF configuration employs GFS as forcing while the other two use the European Centre for Medium-Range Weather Forecasts (ECMWF). Additionally, one of the ECMWF-forced members uses only the outermost domain but runs at constant 4 km horizontal resolution. Collectively, these tests enabled preliminary sensitivity testing for both model forcing and grid resolution—efforts that have been fundamental to a planned 32-member ensemble during the 2022 season. See Section 5.2.3.b for more information.

Several automated and post-season verification tools have been developed to run in parallel with the near-real-time West-WRF forecasting system. The forecast accuracy and model skill, precipitation amount, and spatial coverage in AR landfalls are evaluated on daily, event, and seasonal time scales for West-WRF and for national operational forecast models as comparison. For AR landfalls, the Method for Object-based Diagnostic Evaluation (MODE) has been applied to forecasted maps of IVT as a novel approach to NWP skill assessment. AR object forecast analyses of object size and shape distributions (referred to as measure of effectiveness), 90th percentile intensity, angle of orientation, and landfall error are assessed daily as a function of lead time. Results from the object detection statistics have been posted on the CW3E forecast verification viewer page since 2017.

5.2.3.a West-WRF Reforecast

An important part of understanding the utility of any given forecast is having a long-term record of how that forecasting system performed in previous extreme events. The lack of historical forecast information is a major drawback of the HRRR and a host of other mesoscale NWP systems that provide forecasts at high resolution over California. Accordingly, CW3E, with the support of the U.S. Army Corps of Engineers' (USACE's) Engineer Research and Development Center (ERDC), has developed a 34-year West-WRF reforecast to assess model skill. The reforecast effort additionally benefits FIRO by providing a potential higher resolution forecast to force CNRFC operational streamflow forecasts than is provided currently by the NCEP/CNRFC system (Delaney et al. 2020; see Section 5.2.3.a.i). Similar to the near-real-time West-WRF, reforecast verification metrics are being computed for precipitation over several California watersheds, AR strength and landfall position, and near-surface meteorological conditions. To the best of our knowledge, this is the only high-resolution regional reforecast effort at a climate time scale (30+ years) in the United States.

5.2.3.a.i West-WRF Reforecast Verification

The skill of the West-WRF Reforecast relative to operational deterministic and ensemble NWPs is promising. Figure 5-5 shows that the two-day QPF totals at zero- and one-day lead times that were evaluated in Figure 5-3 using CNRFC data are improved in the West-WRF Reforecast's 3 km domain. The largest improvements occur in extreme events on the lower end of the spectrum, where percent error is drastically reduced, likely due to the model's ability to explicitly resolve mesoscale precipitation mechanisms that challenge forecasters and contribute proportionally more to small events. This result implies that mesoscale mechanisms may also be better simulated in big events, but that the gains are less impactful.

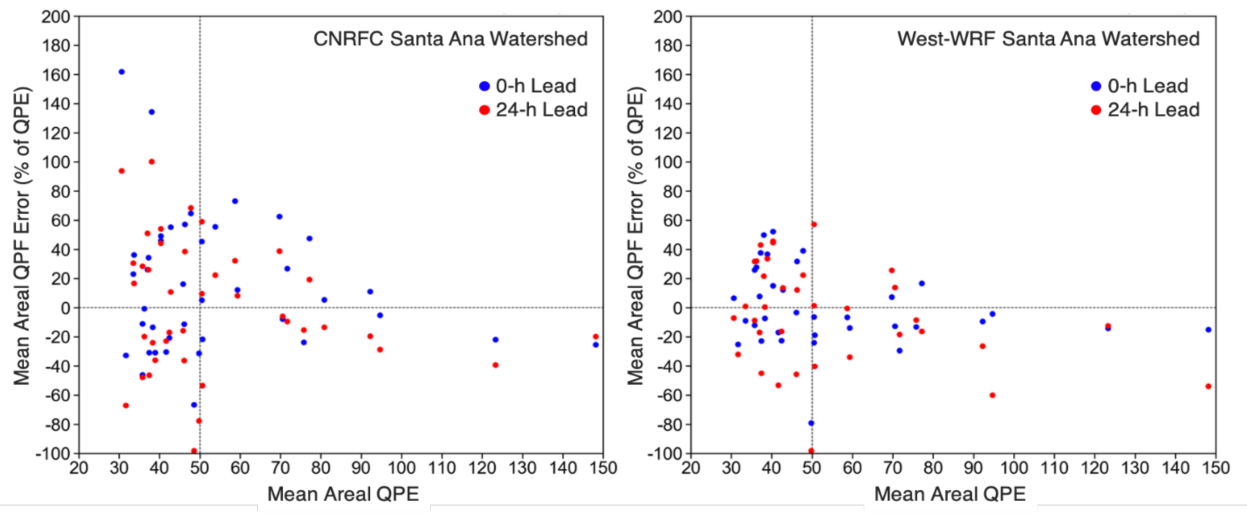


Figure 5-5. CNRFC mean areal QPE (mm) plotted against QPF error as a percentage of QPE (left graph) and the same variables from the West-WRF reforecast 3 km domain (right graph).

Figure 5-6 shows centered root mean squared error and the coefficient of determination for running three-day total forecasts of mean areal precipitation (MAP) over the Santa Ana watershed. The three-day values are a useful indicator for the CNRFC to assess the overall skill of the mean areal precipitation (MAP) for hydrologic forecasts as they tend to inform the hydrologist of the potential for flooding. These results indicate that the West-WRF improves on the GEFS MAP through days 3–5.

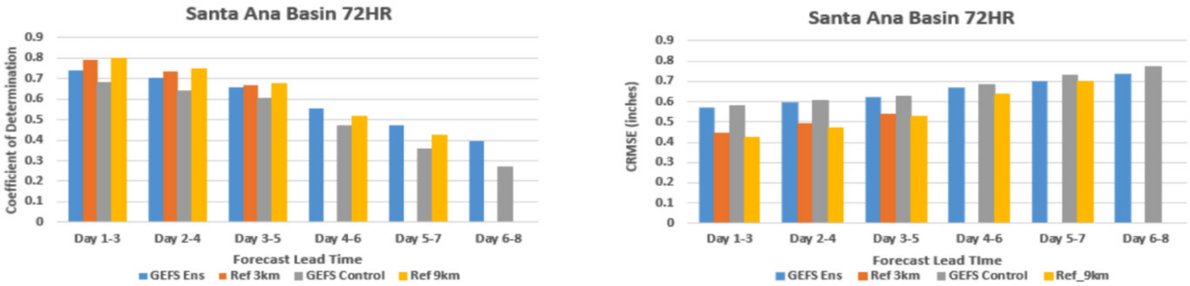


Figure 5-6. *West-WRF 72-hour reforecast analysis (3 km domain) with coefficient of determination (left graph) and the centered root mean squared error (right graph). Bias was low for all watersheds and is not shown.*

5.2.3.a.ii Machine Learning Bias Correction

CW3E is exploring machine learning algorithms in a post-processing framework to correct biases in forecasts. These efforts include a convolutional neural network to improve GFS zero to seven days forecasts of IVT (Chapman et al. 2019) using a 10-year training dataset. The novel approach improves GFS predictions by about 5 percent at the beginning of the forecast to over 20 percent seven days out. The bias correction has been run in real time since water year 2020, with results made available on the CW3E website. Similar methodologies are now being developed to bias-correct West-WRF AR and precipitation predictions. Notably, the reforecast enables development and testing of post-processing techniques and machine learning methods to reduce raw model output biases based on an extensive record of forecast performance in extreme events.

5.2.3.b Uncertainty Quantification Using a West-WRF Ensemble

Uncertainties regarding forecast initial conditions and the model representation of key processes limit the predictability of extreme precipitation. Efforts to understand the sources of West-WRF QPF error during ARs (Martin et al. 2018) and to generate probabilistic precipitation forcing for hydrologic modeling include developing ensemble simulations that attempt to span the range of uncertainties in the model's initial state, unresolved processes, and parameterization error (Berner et al. 2015). These simulations provide robust demonstrations of QPF skill and spread that translate into confidence in the model's representation of extreme precipitation events in the Santa Ana River watershed. Other sources of error in West-WRF simulations have been investigated by evaluating the impact of selected perturbations to the model's representation of extreme precipitation mechanisms, such as upslope flux, mesoscale frontal waves, and frontal rainbands. This research also enables the identification of model deficiencies that highlight opportunities for eventual forecast improvements.

5.2.4 Meteorological Monitoring

Observations and research efforts to improve AR, precipitation, and streamflow forecasts are needed to enhance the application and benefits of FIRO. Observations provide the foundation needed to understand physical processes and to ground truth and initialize models. Effective research efforts combine both modeling and observations and can in turn be applied to operations through prediction as well as situational awareness.

5.2.4.a Existing Instrumentation

5.2.4.a.i Gages

The CNRFC gathers precipitation and air temperature data from about 80 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 3.3). The CNRFC quality controls these station data and produces six-hour mean areal precipitation and temperature for each of the sub-basins used in the CNRFC's hydrologic modeling.

The CNRFC has judged that the network of precipitation and temperature gages throughout the Santa Ana River watershed is adequate for the current hydrologic forecasting services the agency 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. Thus, a much smaller set of temperature gages can adequately capture the spatial variability in temperature. If forecast demands change during this work, enhancements to the gaging network to support CNRFC forecasting may be required.

5.2.4.a.ii Atmospheric River Observatory

A few elements of the California Department of Water Resources (DWR) and National Oceanic and Atmospheric Administration (NOAA) AR observing systems can contribute to the monitoring effort for the Prado Dam FIRO. An AR observatory on the coast 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. Also, a number of GPS-Met stations in the region quantify water vapor concentration in ARs.

5.2.4.a.iii NWS NEXRAD Radar

Four regional NWS NEXRAD installations cover coastal Southern California and adjacent mountains: San Diego (KNKX), Santa Ana (KSOX), Los Angeles (KVTX), and Vandenberg (KVBX). They range in elevation from about 300 to 1,000 meters and have a base scan elevation angle of around 0.5 degrees. 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 5-7 illustrates the minimum elevation of a 0.5-degree scan angle with a 1-degree beam width from each radar to approximate the minimum coverage height over the Southern California Bight. At just 100 km distance, the majority of the radar beam is above 2 km altitude, which is above the elevation of most intense precipitation in most cases. De Orla-Barile et al. (2020) 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 will be targeted by the FIRO field campaign (Section 5.2.4.b), 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.

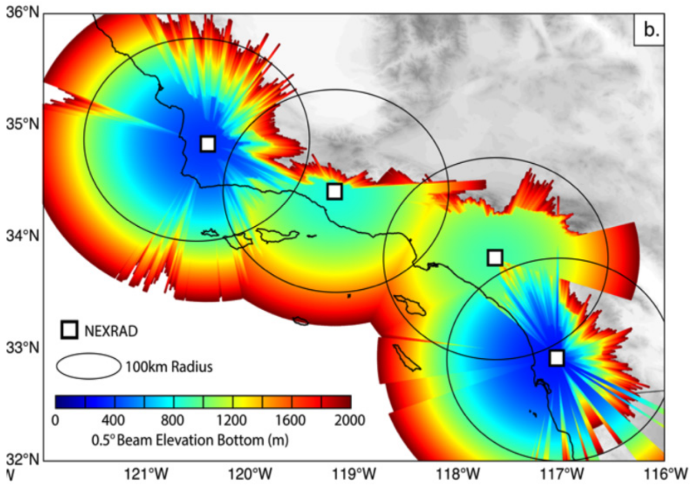


Figure 5-7*. Approximate minimum radar coverage height over the Southern California Bight (colorfill). A 100 km radius (black circles) is plotted around each NEXRAD site (squares).*

5.2.4.b Field Campaign in Support of FIRO at Prado

An annual field campaign conducted by CW3E in the Santa Ana watershed deploys surface meteorology stations (i.e., temperature, relative humidity, wind speed and direction, solar radiation, pressure, and precipitation), disdrometers, GPS, and MicroRain radars at two strategic field sites (Table

5-1). The sites are Santa Catalina Island, upstream of the Santa Ana River watershed, yielding observations of water vapor transport and precipitation characteristics of the storm ahead of landfall, and Seven Oaks Dam, in the San Bernardino foothills, to observe the impact of regional topography on precipitation processes (e.g., orographically forced convection, precipitation microphysics, and barrier jet development). At each site, radiosondes are also deployed at least every three hours during storm events (2020/2021 were affected by COVID restrictions). Data from the radiosondes are transmitted to the World Meteorological Organization's Global Telecommunications System so that they can be assimilated into operational NWP models. Radiosonde observations are also provided directly to interested NWS offices in the region. The data are also available through CW3E web visualizations in near real time (https://cw3e.ucsd.edu/cw3e-surface-meteorology-observations/). In upwind and mountain locations of the Santa Ana watershed, these observations are also being used to develop region-specific radar precipitation diagnostics.

Table 5-1. Instruments at Seven Oaks Dam (SOD) and Catalina Island (CAT).

Instrument or Suite of Instruments	Measurements	Install Status	Data Provided in Near Real Time	Utility for FIRO
Surface meteorology	Air temperature, relative humidity, pressure, wind speed and direction, solar radiation, precipitation	SOD: complete CAT: complete	SOD: yes CAT: planned summer 2021	Monitoring info for decision makers; provides info for GPS
Disdrometer	Rain type, rain rate, raindrop size and velocity	SOD: complete CAT: planned summer 2021	SOD: yes CAT: planned summer 2021	Aid development of West-WRF; develop precipitation diagnostics
GPS	Integrated water vapor	SOD: complete CAT: planned summer 2021	SOD: complete CAT: planned summer 2021	Monitoring info
Micro rain radar	Vertical profile of hydrometeors (backscatter) and fall speed	SOD: complete CAT: some observations in 2020, permanent install planned in summer 2021	SOD: yes CAT: planned summer 2021	Aid development of West-WRF; develop precipitation diagnostics
Radiosonde	Vertical profile of air temperature, moisture, winds, pressure	SOD: storms in 2020 CAT: storms in 2020	SOD: N/A CAT: sent to Global Telecommunications System and Weather Forecast Offices	Aid model initialization; development of WWRF; real-time decision support

5.2.5 Assessment of AR Recon Benefits and Application

AR Recon is an ongoing operational campaign tasked by the Office of the Federal Coordinator for Meteorology's National Winter Season Operations Plan. Dropsonde measurements in and around ARs over the northeast Pacific Ocean improve the prediction of landfalling ARs on the

U.S. West Coast, including their associated precipitation and streamflow (Ralph et al. 2020a). Despite the utility of AR prediction in raising awareness of impending extreme events, initial condition errors at one to three days' lead time remain an important source of NWP error. Operational execution of AR Recon reduces this error by supplementing conventional data assimilation with dropsonde observations of the full atmospheric profile within ARs (e.g., Stone et al. 2020; Cannon et al. 2020).

Ongoing work is underway to evaluate the operational ensemble forecast systems responses to AR Recon data for Southern California extreme events in 2019, 2020, and 2021, including for cases that featured ARs interacting with cutoff lows as well as those generating narrow cold front rainbands (e.g., Cannon et al. 2018) and mesoscale frontal waves, which significantly modulate AR landfall location, intensity, duration and orientation (Martin et al. 2019) and are generally not well observed (Zheng et al. 2020).

AR Recon is testing the value of conducting sequences of aircraft missions daily or every other day before major AR landfall events. Early evidence (Zheng et al. 2021) has found that assimilation of more regularly available observations increases their impact in the data assimilation system, yielding even greater positive impacts on forecast skill per unit of data assimilated. Forecast metrics specific to Prado Dam FIRO are being used in evaluating the impact of these AR observations on global ensemble forecast systems, as their output is the basis for the CNRFC's precipitation and temperature forecasts used in the Hydrologic Ensemble Forecasting System (HEFS). Given the direct linkage between assimilated dropsondes in GFS and inflow forecasts at Prado Dam, AR Recon has considerable potential for improving water management.

5.2.6 Supplemental Forecasting Products for Prado FIRO

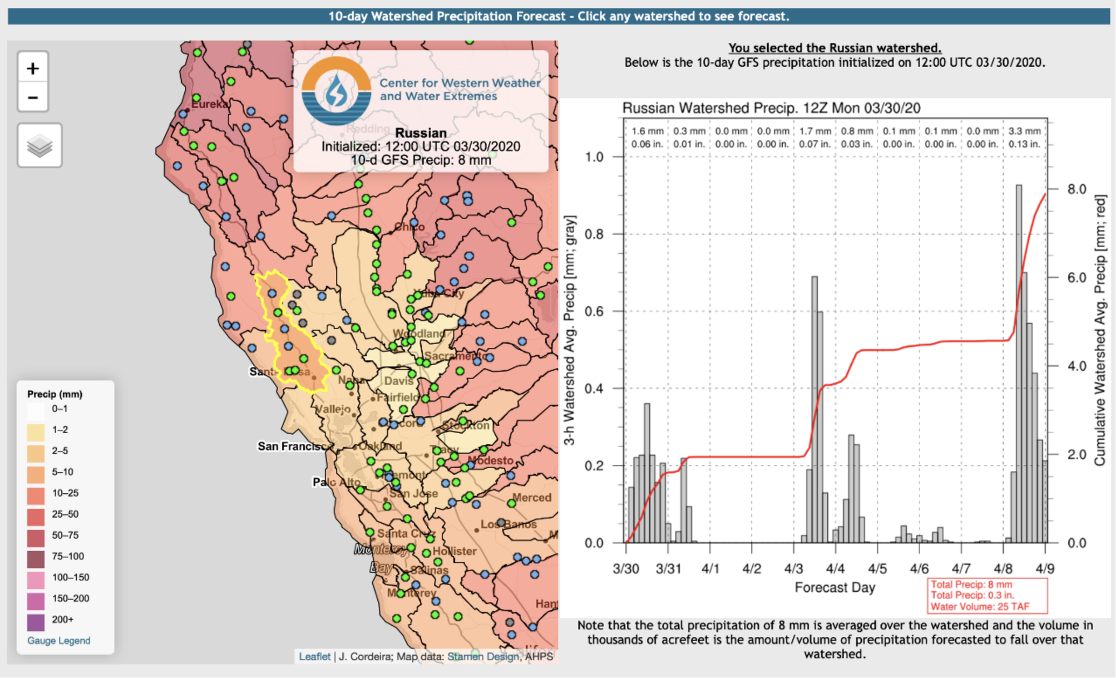
5.2.6.a Overview

FIRO's success is predicated on forecasts with sufficient skill at lead times to support water management decisions. In addition to standard forecast tools available to NWS, CW3E's AR research and forecasting website contains archived and real-time observations, gridded analyses, and gridded NWP forecasts of AR-related information over the northeast Pacific and western United States (https://cw3e.ucsd.edu/). These forecast products identify and track ARs over the northeast Pacific with attention to their structure, intensity, and orientation at landfall along the U.S. West Coast. NWS Weather Forecast Offices and CNRFC, which are responsible for operational forecasts for the area surrounding Prado, have incorporated CW3E AR forecasting tools into storm briefings and frequently use information on the CW3E forecast website to supplement data available through the Advanced Weather Interactive Processing System. The products described in this section are based on over five years of effort to understand AR prediction and impacts and represent collaborative efforts to address stakeholder information needs alongside NWS, CNRFC, USACE, the Orange County Water District (OCWD), and other end users.

5.2.6.b Deterministic (Control) Forecast Products

CW3E provides forecasts of large-scale meteorological conditions from the NCEP GFS and ECMWF Integrated Forecast System (IFS) deterministic runs out to seven-day lead time. These large-scale maps provide a first look at relevant meteorological conditions ahead of precipitation events and can be evaluated by a forecaster to understand a storm's evolution and salient characteristics. The variables available include integrated water vapor and IVT to identify an AR, as well as dynamic and thermodynamic information at multiple atmospheric levels. Forecast maps are derived from NCEP and ECMWF NWP predictions of large-scale and small-scale aspects of landfalling ARs up to seven days in advance. The maps are part of the foundation of CW3E experimental forecast outlooks, and the information is also unique in that national sources of forecast information do not specifically focus on AR diagnostics (e.g., IVT), despite their value to western U.S. water management.

CW3E has also generated interactive tools using GFS to provide watershed-scale forecasts. One such tool shows mean areal precipitation for any regional HUC-8 watersheds from 10-day GFS and ECMWF deterministic forecasts (Figure 5-8). The tool's functionality also includes the ability to query NOAA/NWS River Forecast Center hydrograph forecast products. The California DWR supported the development of these tools and FIRO has supported their maintenance.



10-day Watershed Precipitation Forecast - Click any watershed to see forecast.

You selected the Russian watershed.
Below is the 10-day GFS precipitation initialized on 12:00 UTC 03/30/2020.

Russian
Initialized: 12:00 UTC 03/30/2020
10-d GFS Precip: 8 mm

Note that the total precipitation of 8 mm is averaged over the watershed and the volume in thousands of acrefeet is the amount/volume of precipitation forecasted to fall over that watershed.

Figure 5-8. The shaded polygon layer (left panel) illustrates the 10-day forecast of precipitation from the NCEP GFS model that is averaged over each HUC-8 watershed, whereas the color-coded point data circles illustrate observations of the river stage from the NWS River Forecast Center hydrographs (example image from March 3, 2020). On the CW3E website, these layers are fully interactive. Clicking a circle location pulls up its respective analysis/forecast hydrograph in the panel on the right, while clicking on a watershed pulls up three-hourly precipitation (right panel).

5.2.6.c Probabilistic Forecast Products—Uncertainty Information

Synoptic maps from a deterministic forecast model provide a "control" representation of how the atmosphere is expected to behave, but FIRO requires additional information on how likely that prediction is. An ensemble of forecasts is needed to provide actionable information about forecast uncertainties from NWP for decision support. Currently, CW3E generates its suite of forecast products using both the GFS and IFS ensembles (21 and 51 members, respectively, at present). The ensembles are intended to account for model uncertainty in initial conditions, sub grid-scale processes, and model physics that lead to forecast error. The differences between the ensemble members provide information about the forecast's certainty, and the performance of the ensemble mean and spread through time define the ensemble's skill. Collectively, these pieces of information can be used for any given forecast scenario to establish confidence in a forecasted outcome.

For example, CW3E uses ensemble forecasts to convey forecast confidence regarding landfalling AR conditions via the AR landfall tool (Figure 5-9). The AR Landfall Tool provides ensemble forecast guidance of duration and timing of landfalling ARs up to 16 days in advance. The example from February 11, 2019, can be used to infer model agreement (p = 1.0, or all 21 ensemble members forecast IVT > 250) in AR landfall at the latitude of the Santa Ana River watershed on February 14 (three days after initialization), though the shading beyond a four-day lead time indicates considerable ensemble disagreement in the duration of landfalling AR conditions. This event led to rapid changes in the hydrologic forecast for the Santa Ana River, which can be interpreted through a lens of forecast uncertainty in AR duration.

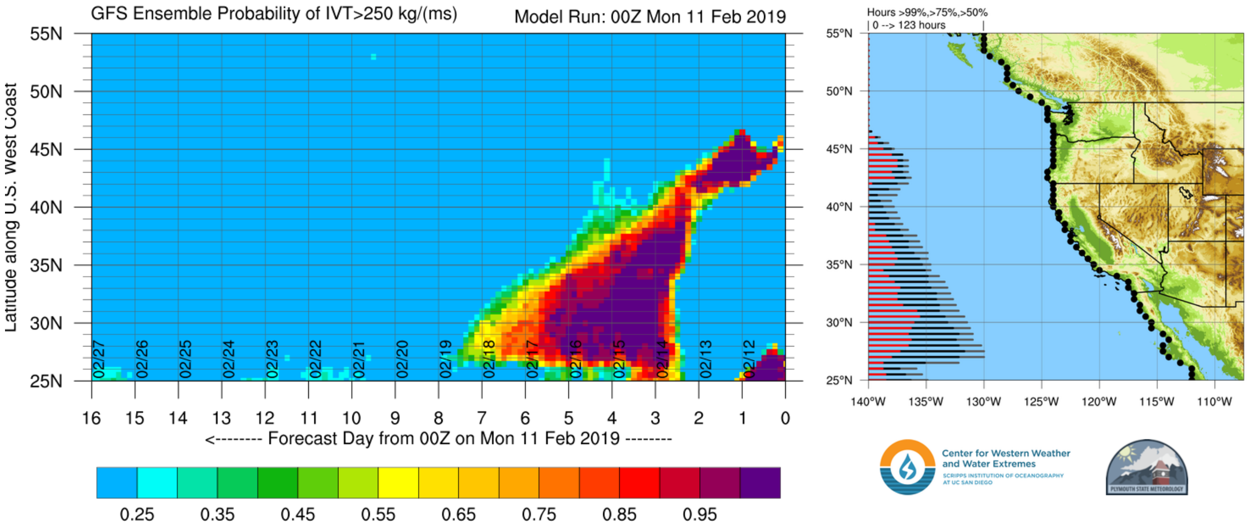


Figure 5-9. AR landfall tool taken from the CW3E website on February 11, 2019. The probability of AR conditions at a coastal point through time is displayed as the percentage of ensemble members with IVT > 250 (colorfill) (left), and the duration of landfalling conditions according to ensemble probability thresholds of 99 percent, 75 percent, and 50 percent (right).

The forecasted intensity of AR conditions is also paramount to hydrologic impact prediction. The plume diagram is a specific ensemble-based tool to provide improved information on predicted AR intensity uncertainty via ensemble spread at a given location as a function of lead time (Figure 5-10). These ensemble products are also generated using IFS ensemble members.

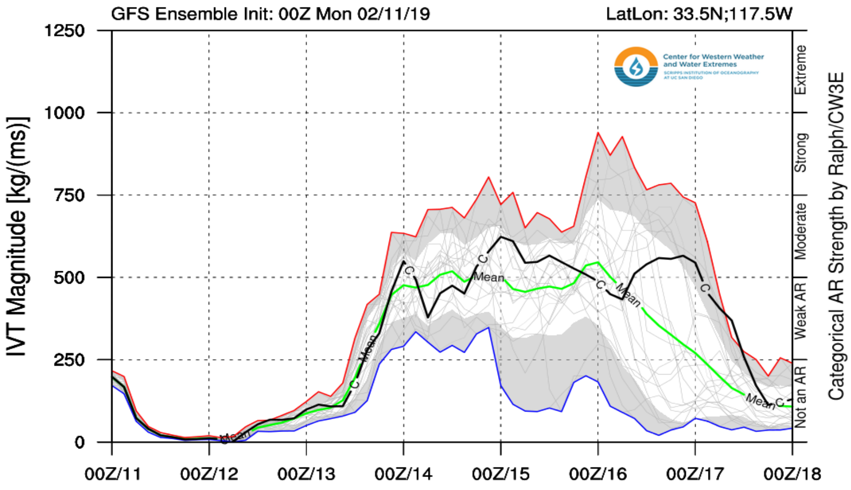


Figure 5-10. AR plume diagram on February 11, 2019. The variability of forecasted AR conditions at a coastal landfall point through time is demonstrated by individual traces of IVT magnitude through the forecast period. The maximum and minimum values at any given time are traced by the red and blue lines, respectively. The black line identifies the deterministic "control" member, and the green line identifies the ensemble mean.

The above examples highlight some of the most frequently used forecast products in briefings issued by CW3E ahead of AR events. These are also the products that receive the most public attention. A growing collection of other deterministic and probabilistic products are also available through the website and, depending on event conditions, can provide beneficial information on event evolution, predicted impacts, and forecast confidence.

5.2.6.d Evaluation of Forecast Tools

A necessary ingredient for turning forecasts into truly reliable decision support products is understanding their performance through time. The skill of forecasts must be assessed by lead time to determine the range of times for which they are reliable for decision support at Prado Dam. Cordeira and Ralph (2021), for example, provided detailed metrics of AR landfall probability verification across the West Coast. An iterative approach to developing forecast diagnostics and decision support tools that meets end user needs via constant interaction (e.g., technical workshops and individual meetings between forecasters and operators) is essential to FIRO success (Schick et. al., 2020)

5.2.6.e Integrating and Improving Forecast Products

CW3E has developed many tools to make modern forecast products more accessible to a variety of stakeholders and has done so in a manner that exemplifies a RAOP partnership. An iterative approach to developing forecast diagnostics and decision support tools that meets end user needs in a simple and effective manner via constant interaction (e.g., technical workshops and individual meetings between forecasters and operators) is essential to FIRO success (Schick et al. 2020).

In addition to direct interactions with reservoir managers, the aforementioned forecast products are also routinely used by NWS, as demonstrated by many conversations, collaborations, and CW3E website statistics. CW3E forecast products both inform the official operational meteorology and hydrology forecasts and are frequently used in NWS pre-event briefings. The CW3E website also supports community preparation for predicted events by publishing summary discussions of forecasted information via "AR Outlooks" and abridged "AR Quick-Looks" that focus on individual-watershed scales (e.g., FIRO at Prado).

5.2.6.f Conclusions and Recommendations

As the name implies, the integration of forecast information into reservoir operations is central to FIRO. Because ARs account for a considerable portion of precipitation in the Santa Ana River watershed and are the cause of extreme events in the basin, the online forecast products specific to ARs supplement standard QPF products for FIRO. The probabilistic tools are especially beneficial in conveying forecast uncertainty, and the recent addition of the ECMWF products provides further guidance on NWP confidence or disagreement. The CW3E website aims to integrate a considerable amount of forecast information from various sources into succinct decision support tools that are designed based on reservoir operator and other stakeholder inputs.

The following recommendations will enhance the benefits of FIRO:

- Quantify the contribution of different precipitation mechanisms to event-total precipitation in the FIRO FVA to provide guidance on the most important areas for precipitation forecast skill assessment and NWP development.
- Develop diagnostic tools based on the FIRO FVA that provide guidance on the influence of key storm mechanisms in forecast models.
- Continually assess the skill of upgraded NWP models and new systems (e.g., the Unified Forecast System) for FIRO-specific metrics.
- Use the observations collected from AR Recon, including high-vertical-resolution dropsondes, airborne radio occultation measurements, and buoy surface pressure, to improve data assimilation in NWP.
- Develop high-resolution probabilistic precipitation forecasts and relevant data visualization for FIRO at Prado decision support. Also, provide a long-term skill assessment of any new products.
- Develop machine learning algorithms to aid the generation of sharp and reliable probabilistic predictions, leveraging the recently developed high-resolution reforecast dataset based on West-WRF.
- Test the impact on FIRO outcomes of using West-WRF as a driver of NWS's HEFS and of the National Water Model.
- Continue and expand AR Recon capacity as a RAOP partnership (as described in Ralph et al. 2020a - AR Recon) to ensure forecast skill enhancements are sustained and available for FIRO applications.
- Explore co-development with NWS/NCEP of a regional operational weather prediction model for the West Coast, optimized for accurate prediction of ARs in the cool season, building on the methods demonstrated in West-WRF.
- Continue to work with forecast agencies, reservoir operators, and stakeholders to ensure that research addresses FIRO needs and that results are effectively transitioned to operations.
- Regularly evaluate the in situ monitoring network and implement enhancements where needed.

5.3 Hydrologic Monitoring and Modeling

Existing operations of Prado Dam are supported by streamflow forecasts issued by the CNRFC. The CNRFC uses a well-tested set of semi-lumped models to simulate and predict flow upstream of Prado and Prado inflow that was developed in the 1970s. The models use existing data, are calibrated for current watershed conditions, and are 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 gridded hydrologic model that can be coupled with a mesoscale NWP model run on a similar scale. The efforts described in this section are not expected to yield immediate operational results, but rather to improve the understanding of runoff processes in the Santa Ana River watershed and show where research has the best opportunities to improve reservoir management outcomes through FIRO.

Key findings for Section 5.3:

- Improvements in stream gaging for the Metropolitan Water District (MWD) Crossing location are needed to support both model calibration and development and operations.
- The precipitation gaging network in the Santa Ana River basin is sufficient to support the development and calibration of a contemporary hydrologic model, such as the Gridded Surface Subsurface Hydrologic Analysis (GSSHA).
- Soil moisture observations in the Santa Ana River watershed are lacking.
- The initial GSSHA model configuration and calibration efforts yielded encouraging results for both the Santa Ana River watershed and tributaries.
- More work is needed to fully assess GSSHA's potential to provide refined streamflow forecasts in support of FIRO. Surface-groundwater interactions modeled by GSSHA may prove useful in monitoring, simulating, and forecasting changes in the basin resulting from shifting recharge practices above Prado Dam.

5.3.1 Assessment of Data in the Prado Basin

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 soil moisture data are key performance criteria. The study team assessed the adequacy of these data for use in modeling and operations.

5.3.1.a Stream Gages

5.3.1.a.i Assessment of Stream Gages for GSSHA Model Calibration

There are 134 historical U.S. Geological Survey (USGS) stream gaging stations in the Santa Ana River basin that have collected data at some point in time (Figure 5-11, red diamonds). Data were available for the chosen calibration/verification periods from 21 gages (Figure 5-11, green circles).

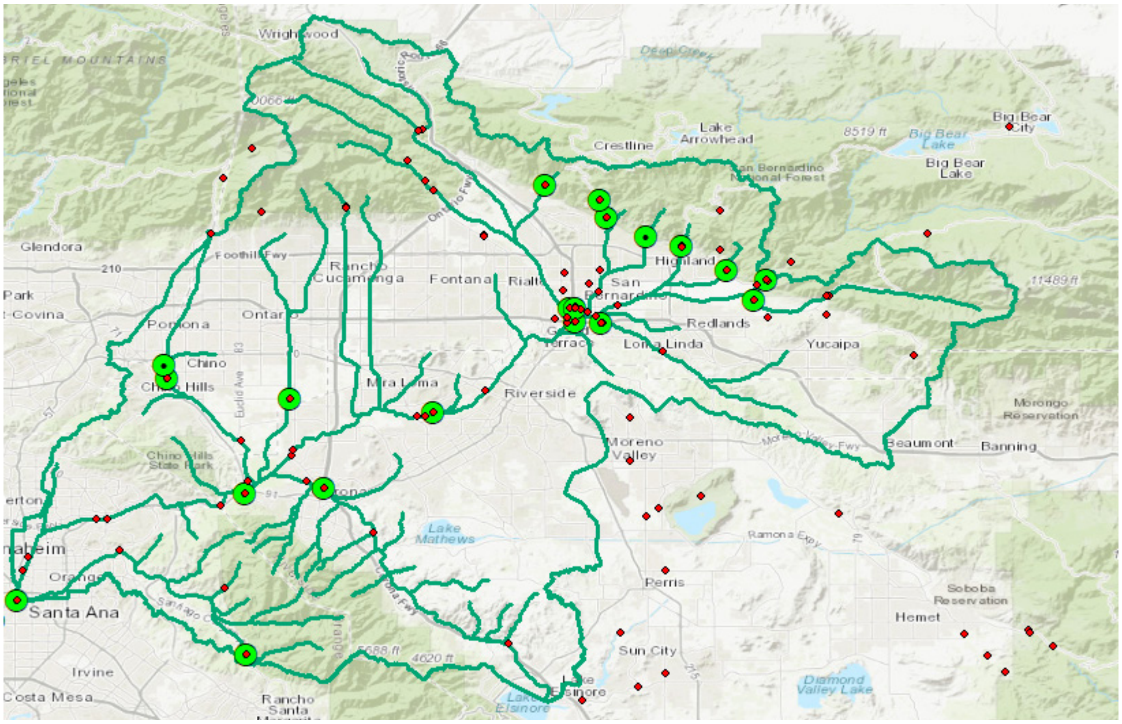


Figure 5-11. Location of historical USGS stream gages in the GSSHA Santa Ana River watershed (red diamonds are historical gages, green circles are gages with data for calibration/verification periods).

Many of the existing gages did not provide enough data to be included in the initial calibration effort. Five gages, shown in Figure 5-12, were used: two on the main channel of the Santa Ana River (MWD Crossing and E Street) and three on smaller creeks (Chino, Temescal, and San Timoteo). The period duration and quality of data at the gages were adequate for an initial calibration of the GSSHA watershed model. 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).

The watershed model is compared to two periods for calibration: November 2004 to January 2005 and December 2009 to January 2010. These two periods contain the largest precipitation events that have occurred in the last 50 years. Larger events have been observed in the past, such as 1938, but the archived data for these periods are not sufficient for GSSHA model calibration.

Figure 5-12. *Santa Ana River gages used in initial GSSHA model calibration effort.*

5.3.1.a.ii Operational Considerations

Caution should be exercised when using stream gages on the Santa Ana River for operational purposes. While there are currently 21 USGS stream gages in the Santa Ana basin that record instantaneous flows, large flows could cause false readings from some of these gages.

The USGS gage on the Santa Ana River below Prado Dam (USGS 1107400) is important for Prado Dam operations. The USACE Los Angeles District (LAD) reports that the rating curve at this location is inaccurate, especially when comparing flows associated with known flood control releases from Prado Dam.

5.3.1.a.iii MWD Crossing Gage

The MWD Pipeline Crossing Gage (USGS 11066460) on the Santa Ana River is in Riverside County, California (33.9686111, -117.447500) and reflects a drainage area of 852 square miles. USGS measures stage from the bridge crossing, about 50 feet above the river during low flows, where the logger also resides. Stage has been recorded at this stretch of the river since 1985, with adjustments to the exact location or technology about every 10 years. Current instrumentation (in place since 2005) consists of a Design Analysis H-3611 radar sensor and Design Analysis H-522+ data logger with GOES transmitter.

Control conditions in this stretch of the Santa Ana River are unstable throughout the full range of stage due to heavy vegetation, stream braiding, sand transport, and high velocities. These characteristics contribute to channel instability, debris pileups, washouts, and rapid changes in the streambed elevation. Some of these changes can occur directly below the radar, creating confounding measurements. Low-flow manual velocity measurements can be made by wading in a preferred section just downstream of the gage. Medium- to high-flow measurements must be made from the pipeline catwalk and require three technicians. Records at MWD Crossing are considered fair to poor.

CW3E and OCWD have been in discussions with Xylem Inc. about new technologies for measuring river flow, specifically the possibility of installing Xylem's Space-Time Image Velocimetry (STIV) technology at MWD Crossing. This technology consists of cameras recording video footage of the water surface, which can then be analyzed to track particles and determine flow speeds. Xylem's STIV is in testing. If this site meets STIV requirements, the team will move forward with the installation to improve discharge measurements at MWD Crossing.

5.3.1.b Precipitation

There are many rain gages in and around the Santa Ana River watershed. To ensure sufficient coverage of the watershed, buffers were created based on the Santa Ana GSSHA watershed boundary. The precipitation stations were narrowed down to a 10-mile buffer to the east and west of the watershed boundary, and to a 2-mile buffer to the north and south of the watershed boundary. About 200 precipitation gages fell within the buffered region.

For the three periods of interest, 59 gages had sufficient data for the 2004–2005 period, 77 gages had sufficient data for the 2009–2010 period, and 191 gages had sufficient data for the 2018–2020 period. Figure 5-13 shows the rainfall gages in the area based on the period of interest and the amount of coverage for each period. Only gages with hourly or sub-hourly recording intervals were considered. For the initial 2004–2005 calibration, all data were converted to hourly.

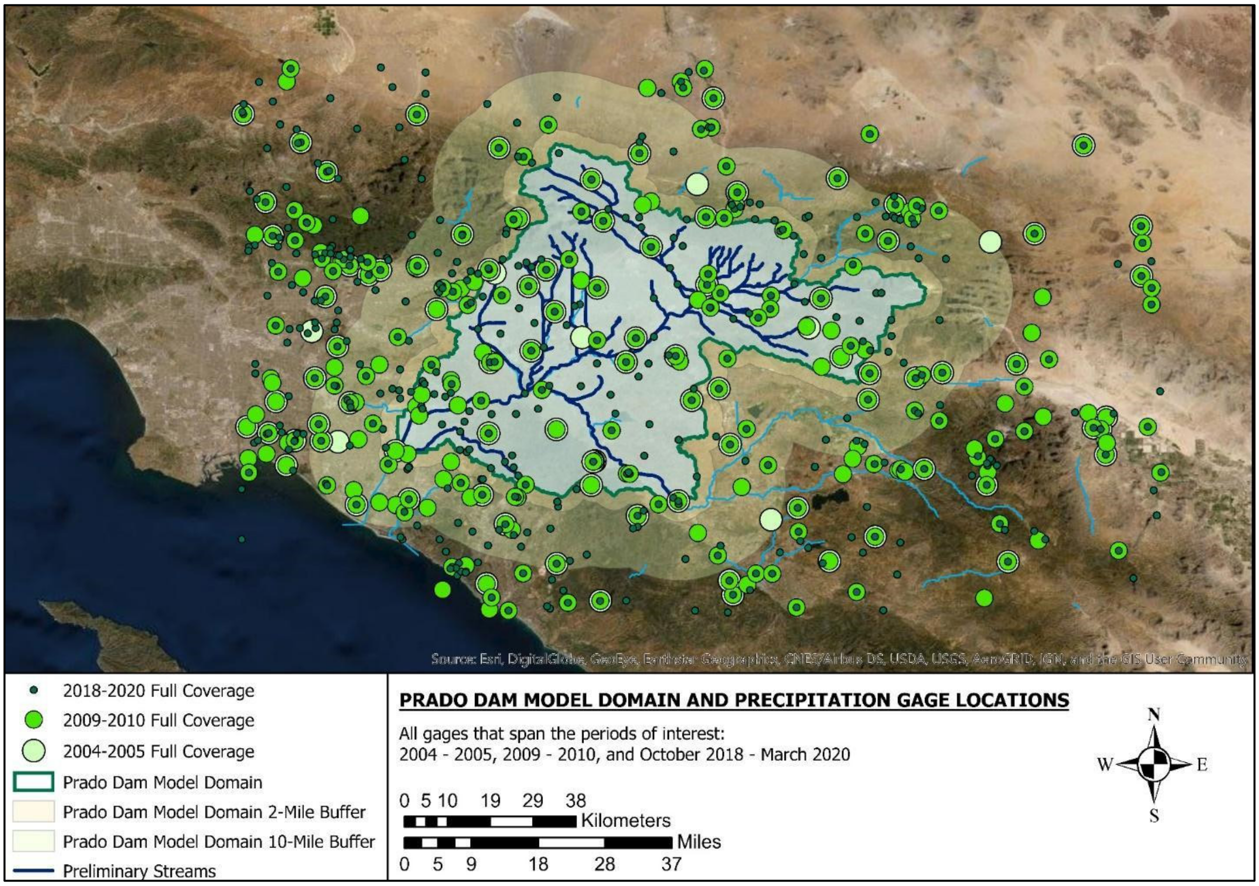


Figure 5-13. Location of precipitation gages with full coverage of the periods of interest.

5.3.1.c Soil Moisture

There are currently no soil moisture data being collected in the Santa Ana River watershed that can be incorporated into the GSSHA model. Potential sites for soil moisture gage installation are being investigated as part of the field data collection efforts. Satellite-based soil moisture data are also being considered.

5.3.2 Modeling and Forecasting of Flows into Prado Lake and the Local Contributing Area Below Prado Dam and Recharge Area

A GSSHA watershed model was prepared for the Santa Ana River watershed above and below portions of Prado Dam. CW3E is using these GSSHA models to investigate uncertainty in forecasting runoff by examining atmospheric forcing data. The model domain is shown in Figure 5-14.

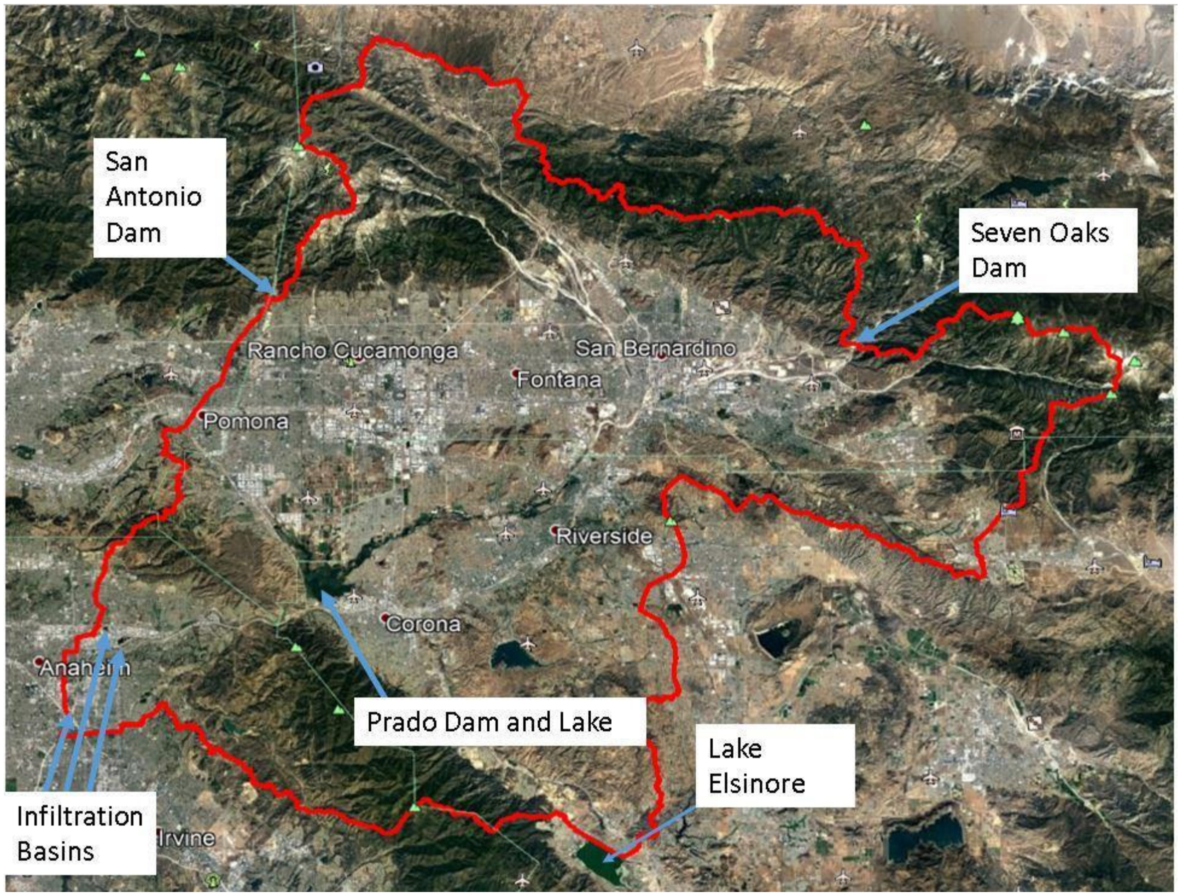


Figure 5-14. *GSSHA Santa Ana River and Prado Dam model domain.*

5.3.2.a Model Development

The model domain encompasses a 3,783 km^2 area, shown in Figure 5-15. At a resolution of 250 meters, the model grid contains 60,526 cells. The model extends below Prado Dam to simulate flow of incoming creeks that drain into the Santa Ana River below the dam and above OCWD's groundwater recharge diversions.

For expediency, several areas are left out of the model domain that are considered extremely unlikely to contribute significant flow to the Santa Ana River during a large event. This includes Lake Elsinore, as it is assumed that water entering Lake Elsinore does not discharge from the lake. Additionally, the portions of the watershed above Seven Oaks Dam and San Antonio Dam are not included as there would be minimal discharge from these dams during large events. These assumptions were consistent with other watershed models developed for the Santa Ana River (SARW 2019). Any flows from these excluded areas can be added to the model later if necessary.

For the Santa Ana River watershed model, a stream network was developed within the two-dimensional overland flow surface. The model includes sufficient streams to capture runoff from the mountains, as well as flow from the river valley that also includes concrete-lined channels throughout the basin. The stream network consists of 137 stream links, with computational stream node spacing of 500 m.

Stream cross sections are assigned based on a 1-meter digital elevation model, where available. The widths and depths of the channels were estimated from Google Earth maps for areas not covered by the digital elevation model.

Soil types are used to assign soil hydraulic properties for infiltration and evapotranspiration parameters. The soil types used in the model are taken from Soil Conservation Service data, with the number of soil types reduced by previous efforts of the USACE LAD.

Percent impervious surfaces are used to reduce the infiltration area in each cell. A specification of imperviousness was used in the model, with each model cell assigned a value from 0.0 to 1.0 (1.0 being 100 percent impervious to infiltration).

The land use map assists in assigning overland flow roughness and evapotranspiration parameters. The land use map is taken from the National Land Cover Database (MRLC 2020).

The GSSHA model also includes a simulation of the Prado Dam reservoir pool within the watershed model, allowing for the pool to shrink and grow based on the storage elevation. The simulated pool is defined by an embankment with a crest elevation of 182 meters. The pool elevation at the outlet is 142.5 meters.

5.3.2.b Simulation and Forecast Performance Compared to Baseline

The GSSHA watershed model is currently undergoing calibration using the Shuffle Complex Evolution (SCE) auto-calibration method. Initially, the calibration period is for the large precipitation event that occurred during the period January 1 to January 15, 2005. This period includes the event that produced the largest available flow observed in the last 50 years. The period also includes one additional event before that large event to allow the model to simulate appropriate initial soil moisture conditions. This event is not considered in the calibration cost function. The model is being calibrated using both the raw gage and PRISM-adjusted gridded CNRFC precipitation data due to potential model dependence on the precipitation data source and spatial and temporal distribution. It is anticipated that the model calibrated to the CNRFC precipitation data will also function well with the West-WRF short-term forecast (Downer et al. 2020).

Sample simulation results from the currently available model with the best calibration parameters to date are shown in Figure 5-15 and Figure 5-16. These results represent the simulations using the best parameter sets produced from the SCE calibration at the time, after approximately 300 model simulations. The SCE method typically takes from 500 to 3,000 simulations to converge on the optimal parameter set for the given cost function.

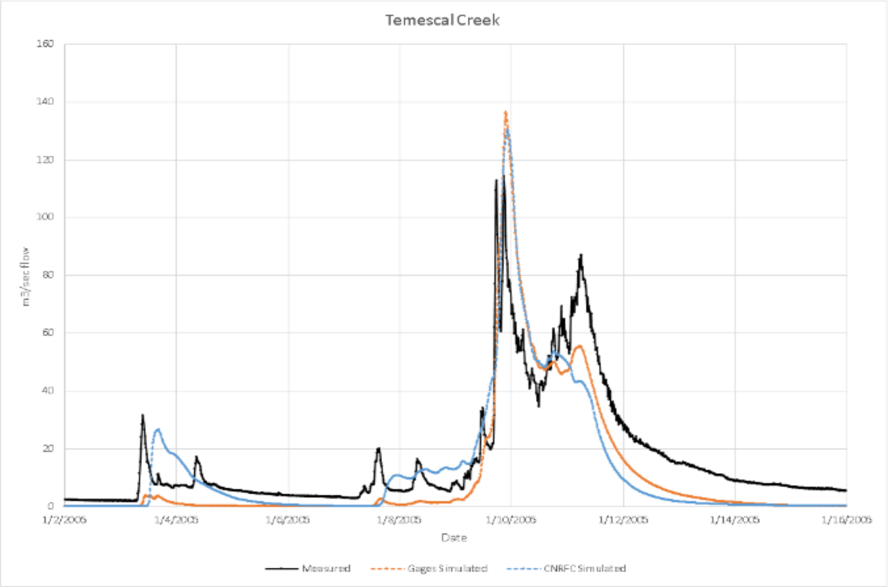


Figure 5-15. Intermediate calibration results at Santa Ana River at E Street.

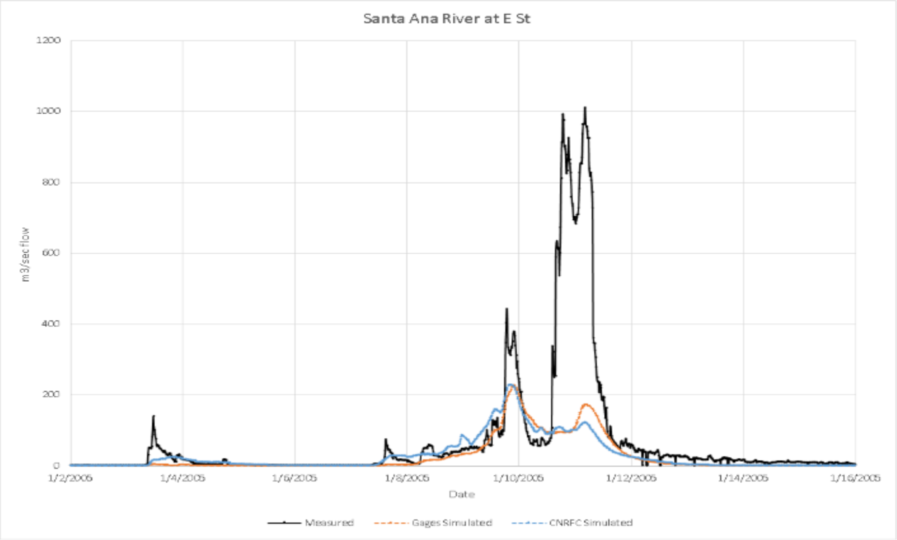


Figure 5-16. Intermediate calibration results at Temescal Creek.

Figure 5-15 shows the simulated flow versus measured flow for the main Santa Ana River at E Street. One simulation uses the CNRFC gridded precipitation forcings and the other uses the raw precipitation gage-based forcings. The CNRFC PRISM-corrected precipitation data show a better match to the measured flow. Figure 5-16 shows the simulated flow versus measured flow for Temescal Creek, a tributary of the Santa Ana River. Here, the model with the raw gage-based forcings provides a better match of the simulated flows when compared to the measured flows.

Once the calibration effort is complete, verification of the parameter sets will be pursued with data from the second largest event during the period of record (January 2010). At that point, decisions can be made on additional calibration and/or adjustments to the GSSHA model configuration.

5.3.2.c Coupling With West-WRF

West-WRF rainfall and hydrometeorology data were provided to ERDC by CW3E for January to March 2020. These data are currently being processed and will initially be simulated with the model calibrated to the CNRFC gridded precipitation product. Further efforts to improve the GSSHA/West-WRF forecast will be pursued as described in Section 5.3.3.

5.3.2.d Use of Alternative Sources of Meteorological Forcings

ERDC is working with CW3E to evaluate alternative sources of meteorological forcings.

5.3.3 Ongoing Work and Recommended Studies for the FVA

Based on the results of the PVA and experience gained through the Lake Mendocino FIRO effort, the following recommendations are offered for continuing hydrologic modeling research at Prado Dam:

1. Install soil moisture instrumentation to support hydrologic modeling efforts, including areas representative of the different soil characteristics found in the basin.
2. Continue to explore new technologies to improve discharge measurements at the MWD Crossing steam gage location.
3. Expand the current GSSHA calibration effort using raw precipitation observations, CNRFC quality-controlled precipitation estimates, West-WRF analysis data, and potentially other datasets including WSR-88D and CW3E-installed RADAR data.
4. Develop data assimilation capacity within GSSHA with an initial focus on streamflow, soil moisture, and groundwater observations.
5. Develop GSSHA processes for leveraging West-WRF and potentially other forecast sources to generate streamflow forecasts with lead times up to seven days.
6. Compare GSSHA streamflow simulation quality and forecasting skill with (1) HEC-HMS and (2) CNRFC CHPS.
7. Based on a positive outcome of (6):
    a. Develop a near-real-time instance of GSSHA for the Santa Ana basin that can be used for experimental FIRO decision support.
    b. Process downscaled (post-processed) West-WRF ensembles through GSSHA to create ensemble streamflow forecasts.
    c. Process the forecast streamflow ensembles created through 7B through the Prado Dam EFO model and HEC-ResSim as a proof of concept.

5.4 Environmental Considerations

Prado Dam supports a rich riparian habitat in the lower reaches of the reservoir pool that is critical for the least Bell's vireo, a federally endangered species. FIRO must consider and ensure impacts are avoided to the least Bell's vireo and other natural resources such as the Santa Ana sucker. This section describes work that supports a better understanding of the relationship between the least Bell's vireo and the temporary storage of water behind Prado Dam. This information contributes to the viability of FIRO and its potential implementation regarding the timing and upper limits of increased water elevations in the reservoir.

Findings of this section include:

- Except for the understory, no data to date suggest irreparable forest damage due to prolonged inundation, and wetter conditions may even improve vireo habitat. Further research is needed to assess impacts of temporary or prolonged inundation at elevations greater than 505 feet (Section 5.4.1).
- Predicting the arrival date of nesting least Bell's vireos in future years is extremely difficult given multiple variables; further efforts to predict their arrival will not be pursued (Section 5.4.2).
- OCWD owns 2,000 acres in Prado Basin, which are managed to maximize natural resource values. If more mitigation is needed for impacts of FIRO on riparian vegetation, sufficient lands are available (Section 5.4.3).
- Regarding potential increases in sedimentation downstream of Prado Dam and impacts on the Santa Ana sucker, more than 95 percent of all sediment carried into the Prado Basin remains in the basin. Modeling results comparing water elevations between 498 and 505 feet indicate nearly identical aggradation (Section 5.4.4), indicating no additional impact at higher elevations up to 505 feet.

5.4.1 Effects of Flood and Conservation Pool Inundation on Riparian Vegetation

The two major threats to the Prado Basin forest and vireos are drought and fire, including proliferation of non-native weeds that carry fire. Additional threats include prolonged inundation (which also has side benefits) and late season inundation, nest parasitism by non-native brown-headed cowbirds, and the onslaught of a non-native beetle that is killing healthy trees and reducing the forest canopy and overall viability. Assessment of the impact of pool inundation on riparian vegetation should be viewed within the context of all threats.

Water conservation at Prado Dam may subject riparian vegetation to periods of prolonged inundation. Because the dominant riparian trees are winter dormant, inundation during winter should have minimal effects on the forest, but it could affect perennial evergreen species in the understory and the trees in spring during and after leaf-out.

Reservoir elevations at 505 feet typically occur after a series of small to intermediate storms or at the end of large storms that generate stormflow into the reservoir area. In many cases, when there is enough inflow to get to elevation 505 feet, the inflow significantly exceeds that elevation, and flood risk management takes precedence. Dam maintenance and construction also take precedence over water conservation unless the work can be safely scheduled for a later date. USACE has the discretion to release water held up to 505 feet (i.e., buffer pool) and lower the water level to an elevation of 490 or 494 feet within 24 hours to accommodate anticipated inflow volume and ensure sufficient reservoir capacity for flood risk management.

Temporary habitat damage has occurred at lower elevations in Prado Basin from prolonged inundation since monitoring began in 2001. OCWD continues its work to understand and quantify habitat changes associated with inundation timing, extent, periodicity, and duration by using aerial imagery and other remote sensing tools; photo stations; plant cover estimates using the “stacked cube” method, descried in further detail below, in the lower elevations of the Basin; and drone flights and photographs to quantify plant health under varying conditions.

In the 18-year period ending in 2019, water elevations in the buffer pool have occurred between 498 feet and 505 feet five times (OCWD 2020). Interestingly, four of the five highest counts of reported vireo territories occurred during relatively wetter years (2004, 2005, 2010, 2019) when there was enough stormwater inflow to hold stormwater. The prolonged presence of a flood pool and wetter conditions were associated with high vireo counts in part because of the extra foliage volume and insect food available under those conditions.

Observations from OCWD’s ongoing habitat monitoring program indicate that an inundation duration of more than 10 days within a two-week period could adversely affect mule fat *(Baccharis salicifolia)* and other understory species. Mule fat is a perennial evergreen and will not defoliate unless under stress. Black willow *(Salix gooddingii)* is the dominant species of riparian tree in the Prado Basin and is deciduous. Whenever water levels exceed 498 feet for more than 10 days within a two-week period during the flood season, OCWD works with USACE to calculate the prolonged duration where the water level would have remained above 498 feet in the absence of water conservation through Planned Deviation operations. OCWD makes this estimate by accounting for the volume of water stored in the buffer pool between 498 and 505 feet during that period, as well as inflow, and then determining the days required to drain this volume of water under two scenarios: (1) assuming that water conservation is not in place and the water would be drained as rapidly as possible until the level reaches 498 feet, and (2) assuming that water conservation is in place and the water release rate is reduced upon reaching 505 feet in coordination with OCWD. If under the first scenario it is estimated that habitat between 498 and 505 feet would be inundated at least 11 consecutive days, the study team will assume that any resulting habitat degradation is not due to water conservation. However, if the pool would have been drained below 498 feet earlier than 11 consecutive days if not for water conservation operations, then water conservation will be assumed responsible for habitat effects based on monitoring results. OCWD monitors vegetation below 505 feet to assess conditions and effects due to the water level exceeding 498 feet. OCWD focuses on habitat conditions in the water conservation pool elevations between 498 and 505 feet for the existing water conservation program but will expand the monitoring program to higher elevations for FIRO.

Habitat monitoring to date indicates that mule fat is killed or dies back significantly when subject to two to three weeks of inundation. A high percentage of mule fat eventually sprouts from the base and regrows, but recovery after a major dieback is often not complete enough to provide nesting habitat that year. Black willow typically survives inundation, but if foliage is submerged more than three to seven days, it is unavailable for nest placement when the water recedes. Typically, the willow foliage nearest to the ground is heavily used for vireo nest placement.

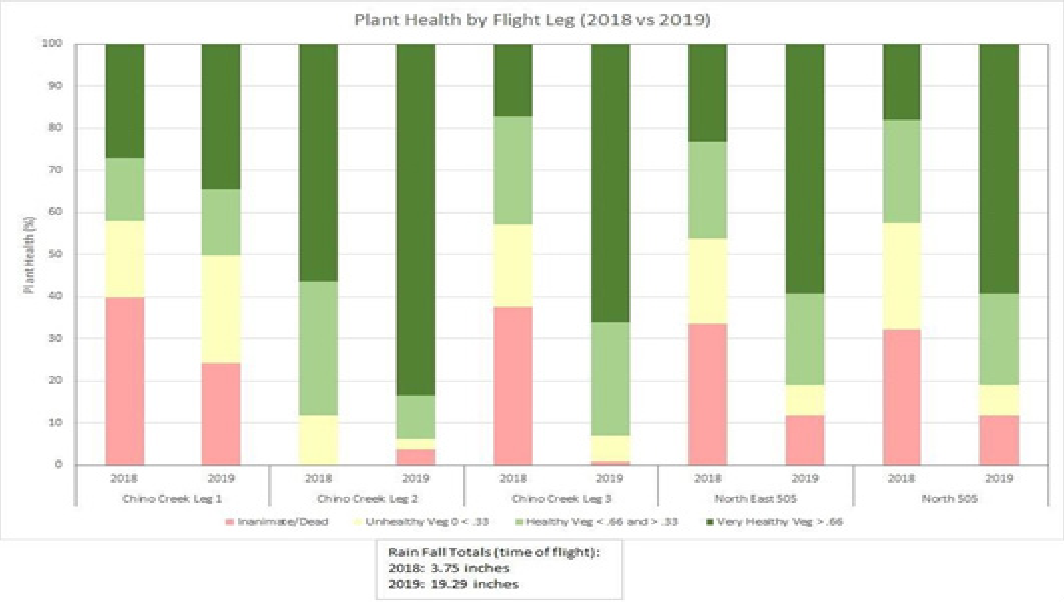
Habitat damage attributable to water conservation is complicated by the associated, initial prolonged inundation caused by flood risk management. For example, in the winter of 2010–2011, construction activity and facilities protection in and below Prado, combined with flood risk management operations, resulted in the highest inundation level on record in the Prado Basin at 529.35 feet on December 23, 2010. The water conservation pool was exceeded for one month and nine days and substantial short-term damage was incurred by mule fat stands on the basin edge that had never been flooded before. Most of the mule fat growing at and below water conservation elevations died back considerably and some patches appeared lost. However, most of these patches did recover, slowly reaching a stature useful to riparian nesting birds by 2012. Patches of mule fat at the lowest elevations were the slowest to recover from crown sprout, and some did not come back from the 2010–2011 submergence.

5.4.1.a Aerial Photo Analyses

A review of historical aerial photographs will be compiled to examine and quantify the extent and general composition of the forest, focusing on the lower elevations in the basin (below 505 feet). Preliminary review has revealed that pre-dam condition in the basin was heavily influenced by agricultural activities, with forest elements mostly confined to channel banks. The forest became widespread in the lower basin only after installation and operation of the dam and its associated flood irrigation. Over the decades, the forest became dominated by black willows, the species most tolerant of prolonged inundation and saturated soils. With recent drought conditions and low-flow reductions in the river, the basin forest appears to be evolving back toward greater species diversity and patchiness—which, unfortunately, will give greater opportunity for an abundance of understory weeds to dominate. While flood irrigation may reduce the vigor of riparian evergreen understory species like mule fat, it also removes problematic understory weeds like perennial pepperweed.

5.4.1.b Forest Health Assessment with Drone Flights

The OCWD is attempting to document habitat health by flying vegetational transects with drone-mounted cameras. A consultant—HANA Resources, Inc.—has flown transects over the Basin in 2018–2020 to collect thermal photographs that can then be used to calculate foliage types and conditions in detail. HANA then produced a report depicting the vegetation along two transects through the basin: the first from Prado Dam and up Chino Creek in three flight legs (Chino Creek Leg 1, Chino Creek Leg 2, Chino Creek Leg 3), and a second from the dam to the wetland ponds in two flight legs (505 North, 505 Northeast). The analyses assessed plant health in low and high rainfall years (Figure 5-17).



Rain Fall Totals (time of flight):
2018: 3.75 inches
2019: 19.29 inches

Figure 5-17. Prado Basin vegetation study transects.

The purpose of the baseline assessment in 2018 was to evaluate the health of the riparian forest across the lower Prado Basin using HANA Resources' patented modeling program. In the subsequent months and years, this assessment will be replicated and used as the baseline to assess plant health over seasonal changes as well as to evaluate long-term trends.

HANA Resources' plant growth health measurement and prediction system may include both high-resolution multispectral images and high-resolution aerial images. The imagery data are processed to create an orthomosaic image of the land cover, within which each pixel of the image is analyzed with the Normalized Difference Vegetation Index (NDVI). The pixel generated values reflect the amount of chlorophyll/active photosynthesis generated by the plant, reflecting and quantifying plant growth.

Surveys over two years during the same season indicated that the increased rainfall in 2019 had a strong, positive, linear correlation with increased plant health. There was also a high percentage of NDVI variance that is accounted for by the rainfall variable. Figure 5-17 compares the vegetation between a dry year (2018) and a wet year (2019).

This technique is being used to monitor 85 acres of vegetation in the lower Prado Basin from the dam to the wetlands—tracking plant response to differing hydrologic conditions.

OCWD is also investigating ways to assess the utility of the different vegetation sampling techniques by comparing results from ground measurements, drone flights, and measurements using the LiDAR remote sensing method.

5.4.1.c Tracking Changes over Time with On-the-Ground Vegetational Measurements

A vegetation study was conducted in the spring and summer of 2018 and 2019. The study used the "stacked cube" method developed by USGS's Barbara Kus (Kus 1998, 2002). Vegetation volume is estimated by species within a series of visualized, stacked 2×2×1 meter cubes extending from the ground to the highest point of vegetation canopy occurring within the "column" of stacked cubes. This method helps understand the vireo's habitat requirements and serves as a tool to compare with other habitat patches to quantify vegetation profiles and assist in determining the presence of suitable vireo habitat.

In each season studied, 40 survey points of mule fat and black willow stands were randomly chosen in the Prado Basin, with 10 plots in each of four areas below 490 feet, between 490 and 497 feet, between 498 and 505 feet, and above 505 feet. The stacked cube method was conducted at each of these points once during spring 2019 and a second time in summer 2019. Another 40 points were randomly selected for nest/territory sampling around 2018 and 2019 least Bell's vireo nests and territories (Whitcraft 2020).

The spring 2018 and 2019 OCWD analyzed survey data to compare whether there were any significant differences in cover among the elevation ranges and compared to the Least Bell's Vireo Habitat Suitability Model. Overall, in both years sampled for this study, the Prado vegetation profiles align with the Habitat Suitability Model with minor variability among elevations, meaning Prado riparian habitat is suitable for vireos. In both spring 2018 and spring 2019, the plant community at the higher elevations (498–505 feet and above 505 feet) had a lower percent cover at the higher canopy classes (i.e., less tree cover) than at the lower elevations.

Total vegetation cover (combined across elevations) did not vary much between years except in the 0–1 meter height class, where total cover was higher in spring 2018 than in spring 2019 Figure 5-18). This difference seen (0–1 meters) was due to increased inundation and duration of the pool.

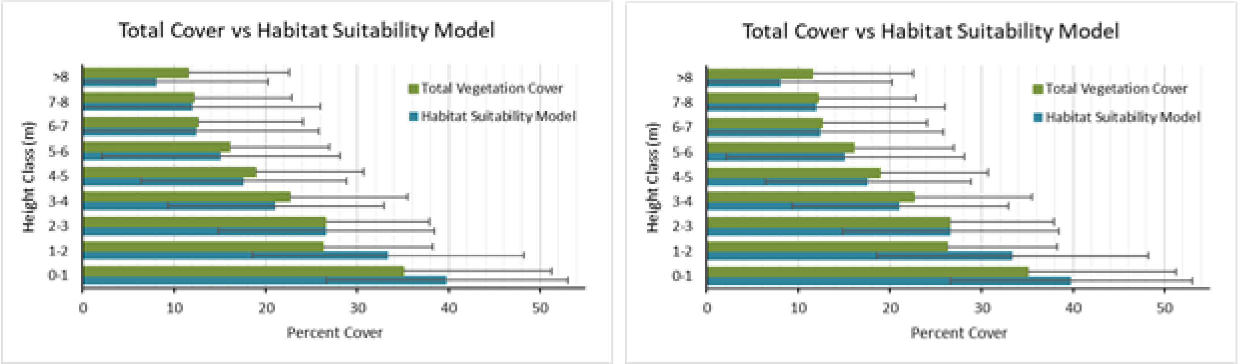


Figure 5-18. *Total vegetation cover for spring 2018 (left) versus spring 2019 (right). OCWD will explore the use of LiDAR measurements to replace the stacked cube estimates of cover. If comparable or more precise, LiDAR data could be collected in timing with vireo arrival and territory selection.*

5.4.1.d Photo Point Documentation of Habitat Conditions

Various methods of photography are used to capture habitat conditions in the Prado Basin. Permanent photo stations and transects photographed by drones were employed to monitor habitat. The photographs yield visual documentation of varying conditions over time relative to water surface elevation.

OCWD has set up nine perimeter and 10 interior monitoring stations, beginning in 2018, to capture understory growth following inundation events. The stations feature a time-lapse camera to show understory height over time.

The photo stations demonstrated slower recovery of understory in 2019 due to inundation into May but much greater growth and persistence of the understory into the summer than in drought years. The multiyear drought up to and including 2018 was used for comparison (McMichael et al. 2021).

5.4.1.e Prolonged Inundation and Timing

Except for understory plant species, no data suggest that the Prado forest has ever been irreparably damaged by prolonged inundation; however, OCWD will conduct a rigorous examination of the past aerial and inundation data to verify this. Instead of doing irreparable damage, flood irrigation replenishes the shallow groundwater, rids the understory of weeds, and allows the phreatophytic trees to grow and evapotranspire ad libitum, producing abundant foliage and food for wildlife. The changes to the understory and low tree foliage are all but forgotten by the following season because very wet years have been rare and the inundated tree foliage and ground cover grows back. The lower basin should continue to be monitored and strategies for augmenting tree recruitment developed, if needed.

There are two cautions: a very wet year or multiple years in sequence might be different, and a big storm that allows inundation to higher elevations might arrive late after the vireos have placed nests at lower elevations. The latter circumstance has happened at least twice in the past and there is no documented issue of a vireo nest being inundated, although extensive observations are problematic due to limited access during a storm. Two observations in 2020 identified one vireo nest blown apart by a late (April) storm's wind and rain. That same storm brought enough water to allow inundation, although the damaged nest was nowhere near the pool. Also, in 2020, vireos chose to nest abundantly over water, higher in the tree foliage than they usually nest.

5.4.2 Prediction of the Arrival Date of Nesting Least Bell's Vireos in Future Years

With three exceptions during 1986–2018, vireos have arrived annually in the Prado Basin over a two-week period from March 11 to March 24. The three exceptions were March 30, 1999; April 2, 1987; and April 8, 2006. Analyses were conducted comparing weather phenomena such as wind, rainfall, temperature. Further analyses were conducted on the hurricane that struck the Baja California wintering grounds in the fall of 2014 during migration and in the Prado Basin environs, but no discernible patterns or correlations could be found that explain or predict arrival dates. Given these results, OCWD was not encouraged to continue investigations within the scope of the FIRO project.

5.4.3 Opportunities for Vireo Habitat Mitigation

OCWD has implemented mitigation requirements for habitat damage due to water conservation in the past based on the expected days of increased inundation of habitat below the pool elevation. Mitigation activities include planting native plants and controlling non-native plants. Most of the habitat damage associated with inundation is temporary and ascribable to the much higher and longer inundation associated with flood risk management. Also, the vireos sometimes do not nest over standing water unless it pools after the nest is in use, but they do routinely forage in emergent vegetation, so the issue is the potential reduction of nest site location options, not outright or long-lasting habitat destruction. The lack of sufficient water has become the larger issue for vireos in southern California, including the Prado Basin.

OCWD owns 2,000 acres of property in Prado Basin and manages these lands to maximize natural resource values. If more mitigation is needed for impacts of FIRO on riparian vegetation, sufficient lands are available.

5.4.4 Magnitude and Impact of Increased Sedimentation with Periodic Increases in Water Surface Elevation Above 505 Feet

Nearly all the sediment that enters Prado Reservoir with surface water inflow is deposited in the area upstream of the dam. This occurs regardless of the water surface elevation in the reservoir. The sediment removal efficiency of Prado Basin has been estimated at greater than 95 percent (Warrick and Rubin 2007; Brownlie and Taylor 1981). A storm event on December 24, 2016, with a peak inflow of approximately 3,000 cfs, was sampled above the dam at River Road Bridge and below the dam at Green River Golf Course. The measured sediment removal efficiency rate of the dam during this storm event was 99.99 percent (Scheevel Engineering 2020).

Previous studies associated with increasing the maximum elevation of the buffer pool from 498 to 505 feet in the flood season assessed potential impacts of this change on sediment transport in the Santa Ana River and Prado Basin. These studies included an assessment of available topographic data collected through time, deposition trends, and development of a sediment transport model using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software. The sediment transport model was used to evaluate potential changes in deposition and sediment gradation (Scheevel Engineering 2020; Golder Associates 2015).

The sediment transport model was used to assess the then-existing condition flood season maximum buffer pool elevation of 498 feet and the proposed increase to 505 feet. Comparing model results for the existing condition and the proposed increase indicates that nearly identical aggradation trends are predicted.

The sediment transport model results also indicated that increasing the buffer pool maximum water surface elevation to 505 feet will cause no appreciable change to the riverbed gradation. The overall quantity of sediment and particle size distribution entering Prado Basin will be the same. The alteration to the Santa Ana River morphology caused by the proposed flood season increase to 505 feet is limited primarily to the spatial distribution of sediments between elevations of 498 and 505 feet.

Based on these analyses, the impact on sedimentation in Prado Reservoir associated with increasing the water surface elevation above 505 feet as part of FIRO is anticipated to be limited in spatial extent to the topographic elevations at and below the increased water surface elevations. However, the evaluation of the potential impact of increasing the water surface elevation on sedimentation as a result of FIRO will be assessed with updated information in the FVA. The sediment transport model previously used will be updated with new information that is being collected. Additionally, OCWD has committed to an ongoing data collection program to measure the Santa Ana River channel topography at multiple locations upstream from Prado Basin. Using the updated model, the FVA will assess potential impacts to aggradation and sediment grain size associated with the higher water surface elevations considered with FIRO.

OCWD has implemented sediment removal activities in the last five years to offset increased sediment accumulation estimated to occur in Prado Basin with the existing water conservation program. OCWD will expand on the sediment removal activities, if needed, to offset increased sediment accumulation related to FIRO.

5.4.5 Ongoing Work and Recommended Studies for the FVA

OCWD has an ongoing Habitat Monitoring Program that tracks changes in the vegetation and distribution of vireo habitat below 505 feet in elevation. The monitoring will document changes in vegetation suitability for vireos that may occur and identify locations where habitat restoration is needed to offset any effects of prolonged inundation. OCWD's existing program funds wildlife management and habitat restoration activities focused on endangered least Bell's vireos watershed-wide. These ongoing conservation activities have led to greatly increased habitat quantity and quality in the Prado Basin and throughout the watershed over the last 30 years. In addition to continuing these monitoring efforts, the following studies are recommended for the FVA:

- Expand the existing monitoring program and assess elevations above 505 feet. The monitoring program will be assessed and revised as new tools become available. A combination of measurements, visual observations, photo monitoring, and USACE inundation data will be used to observe and document any habitat degradation associated with increased inundation due to FIRO. The monitoring program will also identify any mitigation needed to offset impacts.

- Explore advanced mitigation. For example, OCWD could plant 2 acres of riparian habitat per year in the Prado Basin at higher elevations, continue vireo monitoring and management, and expand Arundo control and restoration activities in the future.

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Section 6 Findings and Recommendations

The execution of this Preliminary Viability Assessment (PVA) 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. Specific findings and recommendations are identified and described here within the categories of weather and water forecasting (Section 6.1), understanding and managing environmental objectives (Section 6.2), hydrologic modeling (Section 6.3), and water resources engineering (Section 6.4).

6.1 Meteorological Analysis, Assessment, and Research

6.1.1 Findings

1. Two-thirds of extreme precipitation events between 1981 and 2017 were caused by landfalling ARs.
2. Extreme precipitation events are generally well predicted out to at least five days and the forecast gradually improves to yield nearly no bias at one-day lead times.
3. The regional Western Weather Research and Forecasting (West-WRF) model, designed specifically to simulate the formation and development of atmospheric rivers (ARs), improves on the Global Ensemble Forecast System (GEFS) mean areal precipitation forecast at one- to five-day lead times.
4. Machine learning bias corrections in a post-processing framework improves Global Forecast System (GFS) predictions by about 5 percent at the beginning of the forecast to over 20 percent at seven days lead time.
5. The network of precipitation and temperature gages throughout the Santa Ana River watershed is adequate for the current hydrologic forecasting services provided by the California Nevada River Forecast Center (CNRFC) as well as Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model development.
6. Operational scanning radar has limitations for monitoring extreme precipitation in the Santa Ana Watershed: topographic blocking and range effects interfere with accurate operational monitoring of intense precipitation over Southern California Bight.
7. AR Reconnaissance reduces numerical weather prediction initial condition errors in and around ARs offshore at one to three days lead time.

6.1.2 Recommendations for the FVA

1. Quantify the contribution of different precipitation mechanisms to event-total precipitation in the FIRO Final Viability Assessment (FVA) to provide guidance on the most important areas for precipitation forecast skill assessment and numerical weather prediction (NWP) development.
2. Develop diagnostic tools based on the FIRO FVA that provide guidance on the influence of key storm mechanisms in forecast models.

3. Continually assess the skill of upgraded NWP models and new systems (e.g., the Unified Forecast System) for FIRO-specific metrics.
4. Use the observations collected from the AR Reconnaissance Program, including high-vertical-resolution dropsondes, airborne radio occultation measurements, and buoy surface pressure, to improve data assimilation in NWP.
5. Develop high-resolution probabilistic precipitation forecasts and relevant data visualization for FIRO at Prado decision support. Also, provide a long-term skill assessment of any new products.
6. Develop machine learning algorithms to aid the generation of sharp and reliable probabilistic predictions, leveraging the recently developed high-resolution reforecast dataset based on West-WRF.
7. Regularly evaluate the in situ monitoring network and implement enhancements where needed.
8. Evaluate forecast products (e.g., AR toolkit, CNRFC streamflow, qualitative precipitation forecast) to provide a quantitative basis for confidence (and limits on confidence) in forecasted events.
9. Continue to work with forecast agencies, reservoir operators, and stakeholders to ensure that research addresses FIRO needs and that results are effectively transitioned to operations.

6.2 Hydrologic Monitoring and Modeling

6.2.1 Findings

1. Improvements in stream gaging for the Metropolitan Water District (MWD) Crossing location are needed to support both model calibration and development as well as river forecasting and reservoir management operations.
2. The U.S. Geological Survey stream gage on the Santa Ana River below Prado Dam has a suspect (inconsistent with releases) stage-discharge relationship above 500 cubic feet per second due to insufficient sampling above that flow level.
3. An adequate number of precipitation gages are available in the Santa Ana River basin to support the development and calibration of a contemporary hydrologic model (e.g., GSSHA).
4. Soil moisture observations, useful for understanding GSSHA model performance, are lacking in the Santa Ana River watershed.
5. The initial GSSHA model configuration and calibration efforts yielded encouraging results for both the full Santa Ana watershed and several tributaries.
6. More work is needed to fully assess GSSHA's potential to provide refined streamflow forecasts in support of FIRO. Surface–groundwater interactions modeled by GSSHA may prove useful in monitoring, simulating, and forecasting changes in the basin resulting from shifting recharge practices above Prado Dam.

6.2.2 Recommendations for the FVA

1. Install soil moisture instrumentation to support hydrologic modeling efforts, including areas representative of the different soil characteristics found in the basin.

2. Continue to explore new technologies to improve discharge measurements at the MWD Crossing steam gage location.
3. Expand the current GSSHA calibration effort using raw precipitation observations, CNRFC quality-controlled precipitation estimates, West-WRF analysis data, and potentially other datasets including WSR-88D and CW3E-installed RADAR data.
4. Develop data assimilation capacity within GSSHA with an initial focus on streamflow, soil moisture, and groundwater observations.
5. Develop GSSHA processes for leveraging West-WRF and potentially other forecast sources to generate streamflow forecasts with lead times up to seven days.
6. Compare GSSHA streamflow simulation quality and forecasting skill with (1) HEC-HMS and (2) CNRFC CHPS.
7. Based on a positive outcome of (6):
    a. Develop a near-real-time instance of GSSHA for the Santa Ana basin that can be used for experimental FIRO decision support.
    b. Process downscaled (post-processed) West-WRF ensembles through GSSHA to create ensemble streamflow forecasts.
    c. Process the forecast streamflow ensembles created through 7b through the Prado Dam EFO model and HEC-ResSim as a proof of concept.

6.3 Water Resources Engineering

6.3.1 Findings

1. Improved rates of groundwater recharge are possible using FIRO Water Control Plan (WCP) strategies and currently available streamflow forecasts without impacts on flood risk management. Improvements are intermittent (not every year) and enhanced with multiple storage rises above 505 feet in elevation.
2. When the maximum buffer pool was set to 512 feet and forecasts were not used, flood risk management outcomes were slightly compromised over baseline (505-foot buffer pool). This suggests forecasts are needed but does not clearly define at what elevation above 505 feet they become important.
3. Within the range tested (up to 512 feet), the upper limit of the buffer pool is a function of community/environmental tolerance of more frequent flood pool inundation as flood risk management is not compromised (may be enhanced) when forecasts are used.
4. The Ensemble Forecast Operations (EFO) model was successfully generalized and applied to Prado Dam for the simulation of operations needed to assess various WCP strategies (Section 4).
5. The function of the OCWD groundwater recharge system was accurately replicated using a process less rigorous and computationally intensive than the existing GoldSim model. This process was then used to simulate system recharge operations associated with the WCP alternatives.
6. The HEMP process provided a consistent framework within which the selected WCP alternatives could be simulated and compared. The HEMP execution within the PVA resulted in the identification of numerous refinements that will improve the quality of the FVA.

7. The need to evaluate WCP alternatives across the range of Santa Ana River Mainstem (SARM) states (543/10, 543/30, and 563/30) increased the simulation and analysis workload considerably.
8. The completion of the SARM will dramatically increase the level of flood protection below Prado Dam. The increased maximum release of 30,000 cfs provides for a total evacuation of the buffer pool (tested to 512 feet but likely much higher) with more than adequate forecast lead time.
9. The hindcast period of record simulations (1985–2011) with 543/10 and 543/30 did not reach the spillway crest for any of the alternatives and therefore did not provide any change in flood risk management outcomes. Scaled events (100-year and 200-year) were needed to discriminate between alternatives.

6.3.2 Recommendations for the FVA

1. Include a refined HEMP for the evaluation of FIRO WCPs that can yield a recommendation for potential implementation in the updated Prado Dam WCM. These refinements should include the following:
    a. Evaluate NF (no forecast) alternatives with buffer pools between 505 and 512 feet to more clearly define where forecasts become critical to avoiding impacts to flood risk management.
    b. Evaluate FIRO alternatives with buffer pools greater than 512 to understand the buffer pool elevation where flood risk management outcomes are compromised.
    c. Review the metrics described in Section 3 and used in Section 4 and refine them as needed.
    d. The scaled events used to define the upper tail of the flood risk management metrics should be based on 100- and 200-year three-day inflow volumes and Hydrologic Ensemble Forecasting System scalings provided by the CNRFC.
    e. The Hydrologic Ensemble Forecasting System period of record hindcasts and scaled events should be based on the newer GEFSv12 forcings (1990–2019, plus February 1986).
    f. Simulation for SARM completion states should be limited to 543/30 and 563/30.
    g. Historical simulations (period of record and scaled events) for the FVA should reflect the decreased baseflow conditions above the dam due to greater recapture of wastewater and recharge above the dam (down from ~150,000 to ~70,000 acre-feet annually over the past 20 years). To ensure that the FVA assessment reflects the current and anticipated future state, (1) the historical observations associated with the 1985–2011 hindcast period need to be adjusted to reflect current baseflow conditions and (2) the CNRFC simulation and forecasting of Prado Dam inflow needs to be calibrated to the current baseflow conditions.
    h. Risk curve development for the EFO-type models should include scaled events that challenge the flood risk management capacity of Prado Dam.
2. As with the PVA analysis, perform the period of record simulations with a daily time step, because none of the events within this period created a spillway event at the existing spillway elevation (543 feet). Perform scaled event simulations with an hourly time step to properly accommodate the balance between spillway and outlet works flows.

3. Since the maximum buffer pool elevation appears to be more a function of community/environmental tolerance of longer duration, more frequent flood pool inundation, conduct an economic impact study to estimate the impact costs of inundation for comparison with the value of increased groundwater recharge.
4. Refine the Corps Water Management System (CWMS) implementation for the Santa Ana River basin for operational use by the U.S. Army Corps of Engineers' Los Angeles District. Integrate applicable key FIRO water management models and tools into CWMS to improve the potential for operational use.

6.4 Environmental Considerations

6.4.1 Findings

1. Except for the understory, no data to date suggest irreparable forest damage due to prolonged inundation, and wetter conditions may even improve vireo habitat. Further research is needed to assess impacts of temporary or prolonged inundation at elevations greater than 505 feet.
2. Predicting the arrival date of nesting least Bell's vireos in future years is extremely difficult given multiple variables; further efforts to predict their arrival will not be pursued.
3. OCWD owns 2,000 acres in Prado Basin, which are managed to maximize natural resource values. If additional mitigation is needed for impacts of FIRO on riparian vegetation, sufficient lands are available.
4. Regarding potential increases in sedimentation downstream of Prado Dam and impacts on Santa Ana sucker habitat, more than 95 percent of all sediment carried into the Prado Basin remains there. Modeling results comparing sediment impacts when holding water in the buffer pool between 498 feet and 505 feet indicate nearly identical aggradation except for a slight increase in deposition within Prado Basin between the 498-foot and 505-foot topographic contours.

6.4.2 Recommendations for the FVA

1. Expand the existing OCWD monitoring program and assess habitat health above 505 feet to observe and document any habitat degradation associated with increased inundation, in particular prolonged inundation, due to FIRO. The monitoring program will also identify any mitigation needed to offset impacts.
2. Explore advanced mitigation: for example, planting riparian habitat in the Prado Basin at higher elevations.
3. Experiment with enhancing tree recruitment in the lower basin by planting higher islands to support mule fat or willows.
4. Assess any sedimentation impacts associated with holding water at elevations greater than 505 feet and expand sediment removal, if needed, to offset increased sediment accumulation related to FIRO.

Section 7 Roadmap for the Final Viability Assessment

This section builds on findings and recommendations identified in Section 6 to create a roadmap for the development of the Final Viability Assessment (FVA).

The goal of the FVA is to establish the basis and pathway for updating the Water Control Manual (WCM) to explicitly incorporate forecasts in order to improve water supply reliability in the Santa Ana River watershed.

7.1 Coordination, Communication, and Timing

Specific activities include:

1. Define relationships between the timing of the FVA and
    a. The completion of each phase of the Santa Ana River Mainstem (SARM)
    b. The Interim WCM
    c. The pathway for WCM update with a Forecast Informed Reservoir Operations (FIRO) Water Control Plan (WCP) alternative
    d. Community/stakeholder engagement
    e. Other basin initiatives
2. Develop materials that communicate the project status and results to sponsors and other interested parties.

7.2 Research and Development

7.2.1 Atmospheric River Science

Pursue targeted research that will lead toward an improved understanding of atmospheric river (AR) behavior and AR prediction in the Santa Ana River watershed.

Specific activities include:

1. Assess forecast skill and impact of improved forecast skill on FIRO outcomes.
2. Conduct research to improve AR, extreme precipitation, and runoff forecast skill by better understanding the underlying physical processes.
3. Analyze AR processes to guide precipitation forecast skill assessment and improve numerical weather prediction, including through the development of machine learning post-processing methods.
4. Provide guidance on the influence of key storm mechanisms on forecast model skill.
5. Provide data for research and situational awareness of extreme events through a meteorological field campaign.

6. Continue AR Recon and assess how offshore observations affect forecasts of landfalling ARs through data assimilation in global models.
7. Conduct evaluations of forecast products to provide a quantitative basis for confidence in forecasted events. Respond to requests for specific tools and information that enhance the research and operations partnership.

7.2.2 Monitoring and Environment

Continue and expand enhanced monitoring, observations, and enhancements to support research and operational decision support.

Specific activities include:

1. Begin and maintain a multi-year meteorological field campaign to observe and understand links between ARs, precipitation mechanisms, and watershed hydrology.
2. Install soil moisture sensors to support hydrologic modeling efforts.
3. Explore new technologies to improve discharge measurements at the Metropolitan Water District (MWD) stream gage location.
4. Test new method at the MWD Crossing (upstream gage) by using cameras to observe flows and using real-time images for improved flow rates.
5. Calibrate the Santa Ana River below Prado Dam stream gage (500 yards downstream of dam) for flows exceeding 500 cubic feet per second.
6. Expand the existing biological monitoring program and assess pool elevations above 505 feet to document effects on riparian habitat and least Bell's vireo; identify mitigation to offset any measurable impacts.
7. Explore options for advanced (build-ahead) vireo habitat mitigation.
8. Assess tree recruitment in the lower basin for creating higher islands to improve vireo habitat at higher pool elevations.
9. Assess any sedimentation impacts associated with pool elevations greater than 505 feet.

7.2.3 Hydrologic Monitoring and Modeling

Pursue targeted research to improve understanding and prediction of hydrologic events in the Santa Ana River watershed.

Specific activities include:

1. Pursue opportunities to improve stream gaging on the Santa Ana River at MWD Crossing and below Prado Dam.
2. Expand the current GSSHA calibration effort using raw precipitation observations, CNRFC quality-controlled precipitation estimates, West-WRF analysis data, and potentially other datasets including WSR-88D and CW3E-installed RADAR data.
3. Develop data assimilation capacity within GSSHA with an initial focus on streamflow, soil moisture, and groundwater observations.
4. Develop GSSHA processes for leveraging West-WRF and potentially other forecast sources to generate streamflow forecasts with lead times up to seven days.
5. Compare GSSHA streamflow simulation quality and forecasting skill with (1) HEC-HMS and (2) CNRFC CHPS.

6. Based on a positive outcome of (4):
    a. Develop a near-real-time instance of GSSHA for the Santa Ana basin that can be used for experimental FIRO decision support.
    b. Process downscaled (post-processed) West-WRF ensembles through GSSHA to create ensemble streamflow forecasts.
    c. Process the ensembles created through 5b through the Prado Dam EFO model and HEC-ResSim as a proof concept.

7.2.4 Water Resources Engineering

Pursue development and evaluations that support engineering and decision support in the Santa Ana River basin.

Specific activities include:

1. Refine and re-execute HEMP for the evaluation of WCP alternatives with lessons learned from the PVA.
2. Inform interim operations.
3. Inform an eventual WCM update.
4. Explore, develop, and apply the concepts of FIRO Space and FIRO 2.0.
5. Refine and operationalize the application of the Corps Water Management System in the Santa Ana River watershed for U.S. Army Corps of Engineers Los Angeles District use with FIRO.

7.3 Interim Operations

Gain experience with FIRO operations and develop, evaluate, and refine operational decision support tools needed for FIRO implementation.

7.3.1 Deviations (Minor/Major)

Develop and propose a multi-year planned deviation for water year 2023 (October 2022) to gain operational experience with FIRO maximum buffer pools above 505 feet.

7.3.2 Decision Support

Develop AR and FIRO products specifically designed to support reservoir operations release decisions. Provide training. Leverage the research and operations partnership.