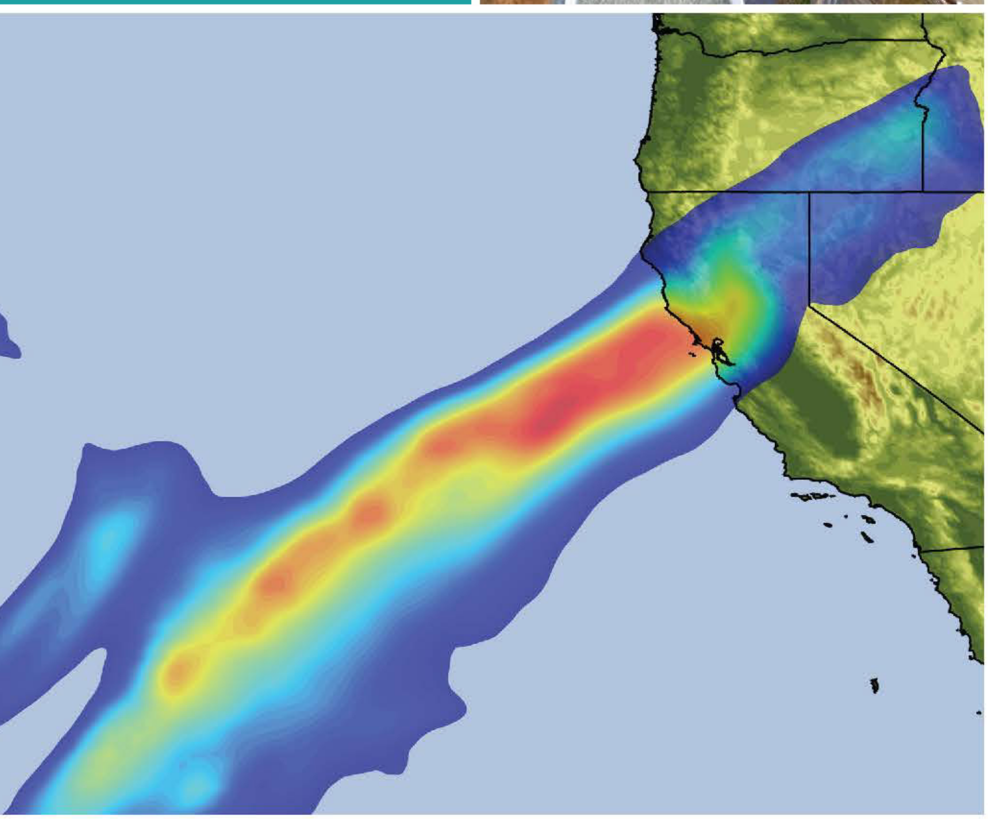
Yuba-Feather
FORECAST INFORMED RESERVOIR OPERATIONS

Preliminary Viability Assessment

December 2022



Yuba-Feather FIRO Steering Committee

- **F. Martin Ralph:** CW3E (Co-chair)
- **John James:** Yuba Water (Co-chair)
- **John Leahigh:** California Department of Water Resources (DWR) (Co-chair)
- **Michael Anderson:** DWR
- **Cary Talbot:** USACE, Engineer Research and Development Center
- **Alan Haynes:** California Nevada River Forecast Center
- **Joseph Forbis:** USACE
- **Molly White:** DWR
- **Steven Lindley:** NOAA Fisheries

Center for Western Weather and Water Extremes
Scripps Institution of Oceanography at UC San Diego
Scripps Institution of Oceanography
Yuba Water Agency

Acknowledgments

This document is the result of hard work and collaboration by the Yuba-Feather Steering Committee and many work team members. We are grateful for the contributions of the following:

Co-Chairs

- **F. Martin Ralph:** Director, Center for Western Weather and Water Extremes (CW3E), Scripps Institution of Oceanography, UC San Diego
- **John James:** Director of Resource Planning, Yuba Water
- **John Leahigh:** Water Operations Executive Manager, California Department of Water Resources (DWR)

Members

- **Michael Anderson:** State Climatologist, DWR
- **Joseph Forbis:** Chief, Water Management Section, U.S. Army Corps of Engineers (USACE) Sacramento District
- **Alan Haynes:** Hydrologist-in-Charge, National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS), California Nevada River Forecast Center (CNRFC)
- **Steven Lindley:** Director, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries
- **Cary Talbot:** Division Chief, USACE, Engineering Research and Development Center (ERDC)
- **Molly White:** Chief, State Water Project, Water Operations Office, DWR

Work Team Members

- **CW3E:** Ava Cooper, Jason Cordeira, Chad Hecht, Julie Kalansky, Tom Corringham, Mike DeFlorio, Anna Wilson, Duncan Axisa, Forest Cannon, Ming Pan, Edwin Sumargo, Luca Delle Monache, Matthew Simpson, Mike Dettinger, Rachel Weihs, Chris Delaney, Laurel DeHaan, Christopher Castellano, Peter Yao, Ava Cooper
- **DWR:** Angelique Fabbiani-Leon, Cale Nasca, Jason Kindopp, Stephanie Chun, Jeremy Hill, Dustin Jones, Chris Orrock, Tracy Pettit, Mitch Russo, Nathan Burley, Sarah Zorn
- **ERG:** Arleen ODonnell, Eliza Berry
- **GEI:** Roger Putty
- **HDR:** Nathan Pingel, Donna Lee, Michael Konieczki, Joanna Leu, Jeffery Weaver
- **MBK:** Ben Tustison, Carly Narlesky, Sophie Danielson, Olivia Alexander, Carissa Abraham
- **RKH Consulting Services:** Rob Hartman

- **NOAA Fisheries:** Eric Danner
- **NOAA NWS CNRFC:** Brett Whitin
- **San Diego State:** Hillary McMillan
- **Scripps Institution of Oceanography:** Chris Castillo, Nancy Allen
- **Sonoma Water:** John Mendoza
- **University of Colorado Boulder:** Dave Reynolds
- **University of Nevada, Reno:** Adrian Harpold
- **USACE ERDC:** Elissa Yeates
- **USACE Hydrologic Engineering Center:** Beth Faber
- **USACE Sacramento District:** John Nielson, Chris Tennant, Brian Walker, Lauren Wood, Jenny Fromm, Jonathan Moen, Marchia Bond
- **Yuba Water:** Bonnie Dickson, Charles Johnck, DeDe Cordell

Steering Committee and work team members who attended the May 2022 meeting in Sacramento. From left: Duncan Axisa (CW3E), Dustin Jones (DWR), Ben Tustison (MBK), Nathan Pingel (HDR), Elissa Yeates (USACE), Rachel Weihs (CW3E), Carly Narlesky (MBK), Mike Konieczki (HDR), Molly White (DWR), Joe Forbis (USACE), Donna Lee (HDR), Marty Ralph (CW3E), Rob Hartman (RKH Consultants), John Leahigh (DWR), Jenny Fromm (USACE), John James (Yuba Water), Arleen O'Donnell (ERG), Ava Cooper (CW3E), Cary Talbot (USACE), Roger Putty (GEI), Chris Delaney (CW3E). Photo by Bonnie Dickson, Yuba Water.

Table of Contents

Appendices

Suggested Citation

Ralph, F.M., James, J., Leahigh, J., Anderson, M., Forbis, J., Haynes, A., Jasperse, J., Lindley, S., Talbot, C., White, M. (2022). *Yuba-Feather Forecast Informed Reservoir Operations: Draft Preliminary Viability Assessment.* UC San Diego. Retrieved from https://escholarship.org/uc/item/xxxxx

List of Tables

List of Figures

Abbreviations

This document uses the following acronyms and other abbreviations:

Abbreviation	Definition
ac-ft	acre-feet
AR	atmospheric river
ARC	Atmospheric River Control
AR Recon	Atmospheric River Reconnaissance
ASO	Airborne Snow Observatory
CDEC	California Data Exchange Center
cfs	cubic feet per second
CNRFC	California Nevada River Forecast Center
CW3E	Center for Western Weather and Water Extremes
CVHS	Central Valley Hydrology Study
CWMS	Corps Water Management System
DSS	decision support system
DST	decision support tool
DWR	California Department of Water Resources
ECMWF	European Centre for Medium-Range Weather Forecasts
EFO	Ensemble Forecast Operations
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
ERDC	Engineer Research and Development Center
F-CO	Forecast-Coordinated Operations
FIRO	Forecast Informed Reservoir Operations
FMCW	Frequency-Modulated Continuous Wave
FVA	Final Viability Assessment
GEFS	Global Ensemble Forecast System
GFS	NCEP Global Forecast System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System

Abbreviation	Definition
HEC	USACE Hydrologic Engineering Center
HEC-ResSim	HEC Reservoir System Simulation
HEFS	Hydrologic Ensemble Forecasting System
HEMP	hydrologic engineering management plan
hPa	hectopascal
IVT	integrated water vapor transport
IWV	integrated water vapor
kcfs	thousands of cubic feet per second
MAP	mean areal precipitation
MEFP	Meteorological Ensemble Forecast Processor
MODE	Method for Object-based Diagnostic Evaluation
MODIS	Moderate Resolution Imaging Spectroradiometer
NAVD 88	North American Vertical Datum of 1988
NBB	New Bullards Bar Reservoir and Dam
NCEP	National Centers for Environmental Prediction
NGVD 29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NRT	near real-time
NWP	numerical weather prediction
NWS	National Weather Service
ORO	Lake Oroville and Oroville Dam
PVA	Preliminary Viability Assessment
QPE	quantitative precipitation estimation
QPF	quantitative precipitation forecast
RFC	River Forecast Center
RMSE	root-mean-square error
R^2	coefficient of determination
SAC-SMA	Sacramento Soil Moisture Accounting Model
SEDI	symmetric extremal dependence index

Abbreviation	Definition
SMOIL	surface meteorology with soil moisture
SPF	Standard Project Flood
SPK	USACE Sacramento District
SWE	snow water equivalent
SWP	State Water Project
USACE	United States Army Corps of Engineers
WCM	Water Control Manual
WCP	Water Control Plan
West-WRF	Western Weather Research and Forecasting
WRE	water resources engineering
WRF	Weather Research and Forecasting
WY	water year
Z_{FL}	freezing level height

Executive Summary

California has one of the most variable climates in the United States, and it's getting more extreme, marked by long periods of warm, dry conditions punctuated by stronger and wetter atmospheric river (AR) storms. ARs provide half of the state's annual precipitation but cause more than 90 percent of the floods in Northern California. Communities in parts of the Yuba-Feather watersheds still haven't fully recovered from devastating floods in 1986 and 1997.

Recognizing the importance of ARs in a changing climate, Yuba Water and the California Department of Water Resources (DWR) are working with Scripps Institution of Oceanography's Center for Western Weather and Water Extremes (CW3E) at UC San Diego, the U.S. Army Corps of Engineers (USACE), the National Weather Service, and other members of the Yuba-Feather Steering Committee to implement Forecast Informed Reservoir Operations (FIRO) at New Bullards Bar (NBB) and Lake Oroville (ORO) in the Yuba and Feather River watersheds. FIRO is a flexible water management strategy that uses improved weather and runoff forecasts to help water managers retain or release water from reservoirs to increase resilience to droughts and floods. The primary objective of this FIRO project is to reduce flood risk; a secondary objective is to achieve water supply benefits where possible, while supporting environmental needs.

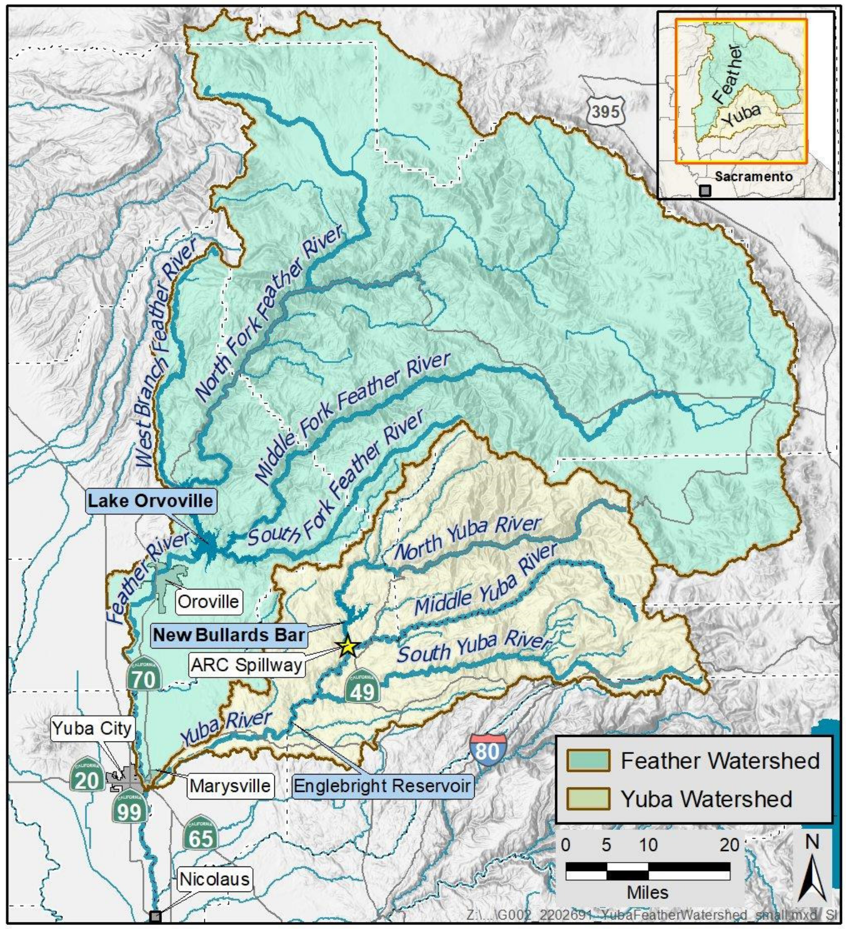


Figure E-1. *Yuba-Feather watersheds.*

This FIRO Preliminary Viability Assessment (PVA) indicates strong potential for FIRO to be a viable water management strategy for reducing flood risk in the Yuba and Feather River watersheds.

Figure E-2. *Lake Oroville (left) and New Bullards Bar (right) in the Yuba-Feather watersheds*

Unique Aspects of the Yuba-Feather FIRO Assessment

- Flood risk reduction as a primary objective
- Complex operational constraints
- Rain and snowmelt driven hydrology
- Multiple reservoirs under different ownership
- Forecast-Coordinated Operations in place
- Simultaneous Water Control Manual (WCM) updates

The Yuba-Feather FIRO research and operations partnership, formed in 2019, has two primary elements: improving precipitation and runoff forecasts, especially for large AR events, and integrating improved forecasts into new reservoir operations to improve operational flexibility. Data driving FIRO include weather data collected from reconnaissance flights over the Pacific Ocean, weather balloons launched during AR storms, and a growing network of weather stations that collect continuous real-time data to ground-truth conditions, including soil moisture, which is critical for more accurate runoff predictions. A robust AR research program is central to improving precipitation forecast accuracy and lead times, thus achieving greater benefits in meeting FIRO objectives over time.

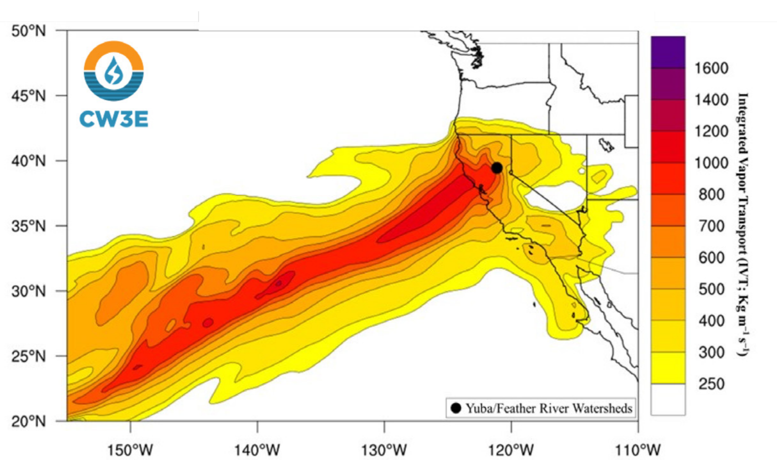


Figure E-3. *Image of a strong AR that impacted the Yuba-Feather watersheds on February 7, 2017.*

The PVA assessed whether improved precipitation and runoff forecasts can reduce flood risk below the NBB and ORO reservoirs, based on multiple flood risk metrics. The primary flood risk reduction method is reservoir releases ahead of large storm events (i.e., pre-releases), which creates additional temporary flood storage space for anticipated inflows. However, there are limitations on downstream flows, so flood storage volume, elevation to spillway crest, and peak downstream flows all need to be considered in the analysis.

FIRO evaluation considered current operations and two FIRO alternatives that were assessed within the context of Forecast-Coordinated Operations, the system DWR and Yuba Water use to coordinate releases from ORO and NBB. Based on the PVA experience, refinements will be made for the Final Viability Assessment (FVA) to determine how best to meet the objectives for each reservoir, as well as points downstream.

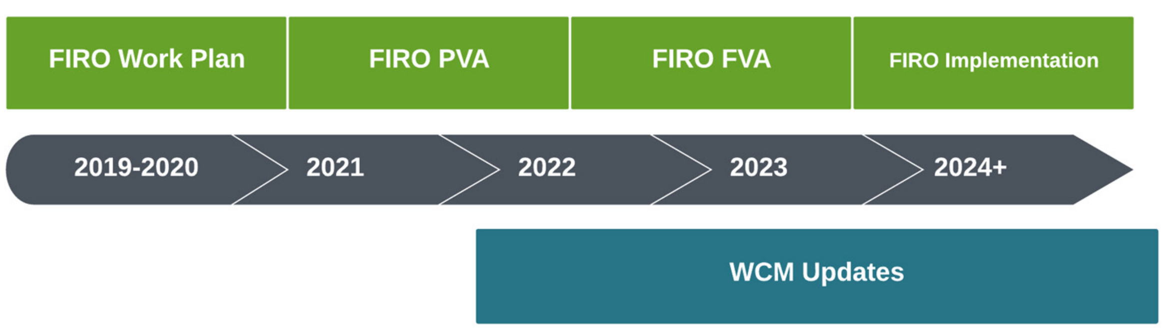
Key Findings of the Preliminary Viability Assessment

- FIRO has the potential to enhance flood risk management without impacting water supply.
- Frequency of exceeding key pool elevations, outflows, and downstream flows is generally reduced with the preliminary FIRO alternatives when compared to existing WCM operation.
- End-of-event storage, a cursory indication of water supply reliability, is generally increased.

To better leverage forecasts, Yuba Water is designing a second spillway for NBB that allows for greater forecast-informed pre-releases at lower reservoir elevations. Using FIRO with the planned spillway will enable the management of up to an additional 117,000 acre-feet of reservoir space and the potential to reduce water levels on levees near Marysville by 2 to 3 feet.

The FVA, to be completed in 2023, will further refine and assess the alternatives and test them against projected climate change hydrology, with the FIRO implementation phase beginning in 2024. USACE is updating its WCMs, which govern reservoir flood operations for both reservoirs, in parallel with the FVA to ensure FIRO integration into reservoir operations by 2026.

Yuba-Feather FIRO & WCM Timeline



Yuba-Feather FIRO Steering Committee: *John James (Yuba Water, co-chair), John Leahigh (DWR, co-chair), Marty Ralph (CW3E, co-chair), Cary Talbot (USACE), Joe Forbis (USACE), Mike Anderson (DWR), Molly White (DWR), Alan Haynes (National Weather Service), and Steven Lindley (National Marine Fisheries Service).*

Funding for Yuba-Feather FIRO is provided by DWR, USACE, and Yuba Water.

Section 1. Introduction

Forecast Informed Reservoir Operations (FIRO) is a flexible water management approach that helps water managers selectively retain or release water from reservoirs for increased resilience to droughts and floods. The FIRO process consists of interagency collaboration and a rigorous assessment that includes operational considerations, observations, hydrologic modeling, forecast skill assessment, water resources engineering, research, and applied science. To date, FIRO results as applied at Lake Mendocino show that reservoir operators can use forecast information and tools to store more water when forecasts indicate low risk of flooding and release more water in advance of expected precipitation (see Figure 1-1).

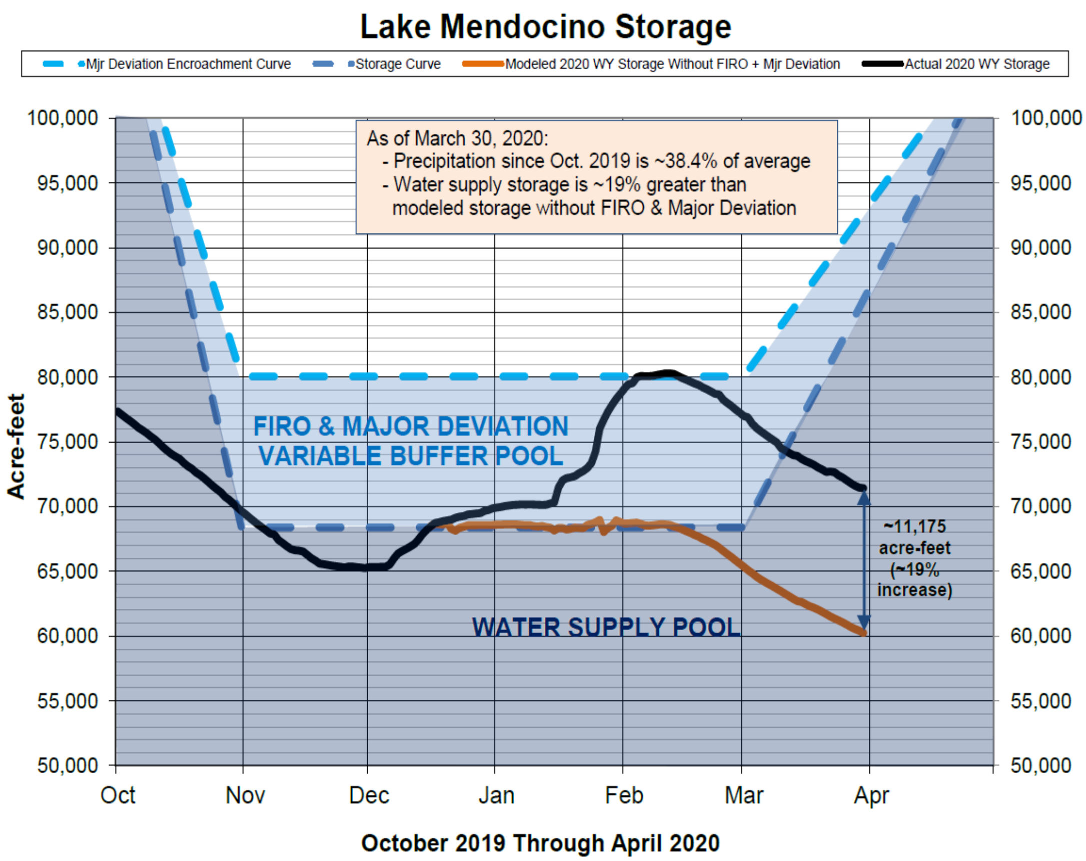


Figure 1-1. *Success with the first FIRO project (at Lake Mendocino) demonstrates that FIRO can be successfully implemented with major benefits. Lake Mendocino storage increased by 19 percent (more than 11,000 acre-feet) during major deviation operations in water year 2020.*

The Yuba-Feather FIRO project builds on the successes and lessons learned from the first FIRO project at Lake Mendocino. Work initiated in 2014 with the creation of the Lake Mendocino FIRO Steering Committee. The Steering Committee determined FIRO to be viable after a Preliminary Viability Assessment (PVA), published in 2017. Following completion of the PVA, FIRO was tested under multiple major deviation approvals, which demonstrated significantly improved water supply impacts. For example, for water year 2020, which was the third driest in 127 years, water supply storage in Lake Mendocino with FIRO was about 20 percent greater than without FIRO (see Figure 1-1 above). The Final Viability Assessment (FVA) was completed in December 2020 (Jasperse et al. 2020). The goal of the Lake Mendocino FIRO project and all FIRO projects is to incorporate favorable FIRO viability assessment results into an operational framework, in the form of U.S. Army Corps of Engineers (USACE) Water Control Manual (WCM) updates that govern dams operated by USACE.

FIRO is now being assessed in the Yuba and Feather River watersheds. The Yuba Water Agency (Yuba Water) and the California Department of Water Resources (DWR) are collaborating with USACE; the UC San Diego Scripps Institution of Oceanography, Center for Western Weather and Water Extremes (CW3E); and other key partners. The Yuba-Feather FIRO project is the largest FIRO assessment to date and the first one conducted in parallel with WCM updates. It is also the first FIRO partnership with the California State Water Project and the first FIRO project with major snowpack considerations. New Bullards Bar (NBB) and Oroville (ORO) reservoirs receive a large portion of their seasonal runoff from snowmelt. For example, in 2016, in terms of seasonal storage volumes, snow melt contributed an additional 43 percent (Feather) and 87 percent (Yuba) of the reservoir storage volume totals (Margulis et al. 2016). However, during extreme inflow events, that contribution is estimated at less than 15 percent of the total volume. Precipitation falling as rain up to the highest elevations of the watershed is considered the most significant driver of extreme inflow events. Applying FIRO in snowmelt-fed watersheds will provide an important example for other snow-fed watersheds.

USACE received partial funding from the U.S. Congress in 2020 to update the NBB and ORO WCMs concurrently with the development of FIRO in the Yuba and Feather watersheds. This alignment ensures the updated WCMs can operationalize FIRO in a timely manner to realize expected benefits.

1.1 FIRO and Atmospheric Rivers Research

Improving precipitation forecasts is central to FIRO, and atmospheric rivers (ARs) are the dominant drivers of extreme precipitation in California. ARs are potent flows of water vapor that originate in the Pacific Ocean and make landfall along the U.S. West Coast. ARs provide up to half of the Yuba-Feather watersheds’ annual water supply in the form of rain and snow, and they account for more than 98 percent of the surrounding counties' flood damages.

Predicting the landfall location, timing, and intensity of these key storms is essential to providing water managers and dam operators with the information they need and with enough lead time to operate reservoirs in anticipation of floods and drought.

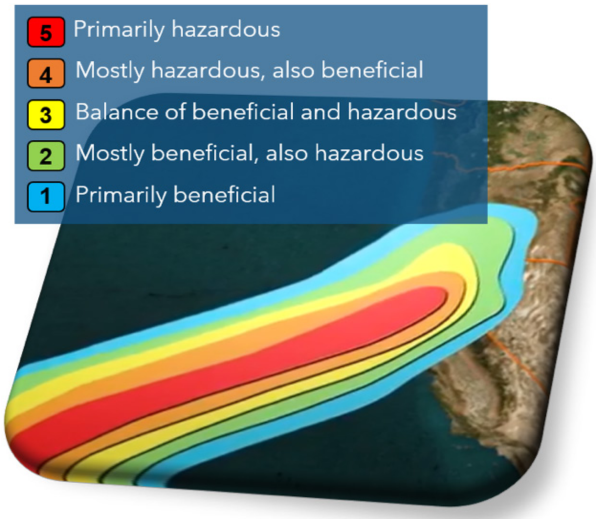


Figure 1-2*. ARs are long, narrow bands of concentrated water vapor that come in all strengths from weak to extreme, bringing both water supply benefits and the risk of catastrophic flooding. ARs are responsible for more than 90 percent of the flood damages in the Yuba-Feather watersheds. (Conceptual drawing of AR scale, credit: CW3E.)*

Incorporating forecasts into reservoir operating rules represents a paradigm shift for USACE and water managers. Currently, most reservoirs operate without the benefit of skilled AR forecasts. Water Control Plans (WCPs) used to manage USACE flood control space have traditionally been designed to use observations (i.e., water on the ground) as the basis for release decisions. In some cases where forecasts have proven adequately skillful, water managers take forecasts into account when making release decisions. However, until recently, there was not a formal process for integrating forecasts into reservoir operations.

As AR forecast skill improves along the West Coast, FIRO provides a crucial opportunity to continue investing in AR forecast skill and identify when skill is great enough to formally integrate forecasts into reservoir operations and WCPs.

CW3E, in close collaboration with the USACE Engineer Research and Development Center (ERDC), the California Nevada River Forecast Center (CNRFC), and DWR, has significantly improved AR forecast skill and has developed several important tools that reservoir operators use to implement FIRO. As AR forecasts improve, more flexible and resilient water resources management practices will be possible, helping to mitigate the impacts of climate change.

1.2 FIRO Project Objective

The Yuba-Feather Steering Committee, in its Terms of Reference, established this key question to guide the viability assessment:

> Can current and improved forecasts of landfalling atmospheric rivers and associated precipitation and runoff be used to inform reservoir operations at NBB and ORO dams to enhance flood risk management and water supply reliability while supporting environmental needs?

The proposed Marysville Reservoir on the lower Yuba River, which was never built, would have provided a flood storage volume of 260,000 acre-feet (ac-ft). The Steering Committee decided to use this previously designed storage volume as an aspirational goal. Figure 1-3, below, shows that, had FIRO been in place during the devastating flood of 1997, reservoir releases could have hypothetically started sooner, and river levels may have been reduced by 2 to 3 feet. Please note that this graphic depicted is from previously simulated FIRO operations and not from a FIRO PVA alternative.

The planned but unconstructed Marysville Reservoir was designed to prevent flows from exceeding 300,000 cubic feet per second on the Feather River downstream of the Feather-Yuba confluence for a standard project flood (SPF). The Yuba-Feather FIRO project will analyze if enhanced observation and forecast information can enable NBB and ORO operational strategies to provide a "functional equivalent" of up to 260,000 ac-ft of space without reallocating water supply for flood space. This "functional equivalent" could be feasible through pre-releases of water before major floods.

As an example, existing studies inform how the "functional equivalent" of up to 260,000 ac-ft could potentially be achieved. In April 2020, Yuba Water conducted a reservoir operations study to document the magnitude of potential pre-releases using forecasts to inform the reservoir operations with a proposed secondary spillway for an epic flood event, like the 1997 flood. The study indicates that, with three days of pre-releases, it is possible to evacuate 87,000 ac-ft of water from NBB before the storm.

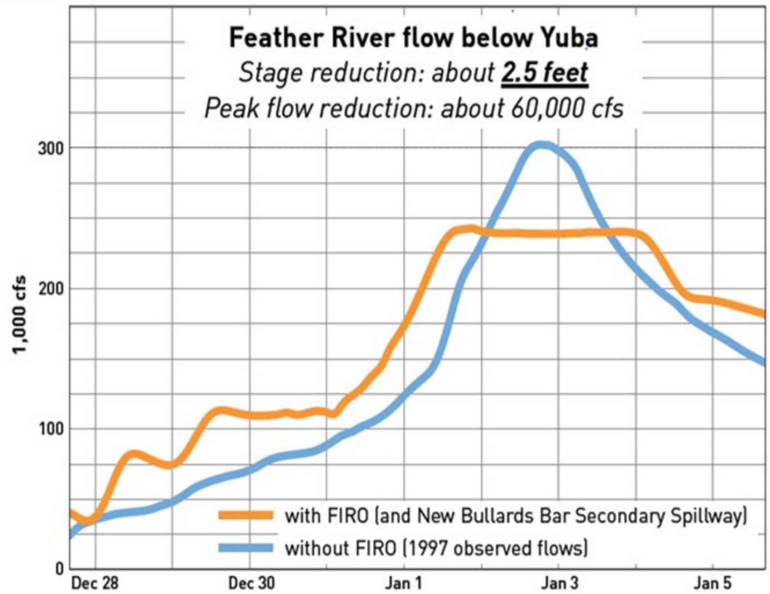


***Figure 1-3**. Hypothetical flood reduction with FIRO. Credit: Yuba Water.*

Another example of "functional equivalency" could be achieved with respect to the use of the emergency spillway at ORO. The current USACE WCM for ORO provides routing of the SPF under various scenarios, some that assume construction of the Marysville Dam and some that do not. Without the Marysville Dam, activation of the emergency spillway is necessary under some flood routings in order to manage the SPF without exceeding downstream flow objectives. With Marysville Dam in place, activating the emergency spillway would not be necessary in managing the SPF. A demonstration of "functional equivalency" could therefore be achieved if new capabilities associated with FIRO, including proactive release of storage in advance of a major storm event at both ORO Dam and NBB Dam, could preclude the need for activating the emergency spillway even without the Marysville dam when managing a SPF scale event.

As an alternative to functional flood control space, "functional equivalency" could also be defined in terms of other flood performance metrics, such as downstream flood flow frequency, magnitude, and duration. Yuba-Feather FIRO will assess the viability of using improved inflow forecasts along with pre-releases to regain flood operation performance that would have been achieved with the Marysville Reservoir flood pool. The 260,000 ac-ft "functional equivalent" target value will be a useful goal in analyzing alternatives to support the Yuba-Feather FIRO primary objective of flood risk reduction.

Recognizing drought impacts on water supply, FIRO will secondarily explore whether some ancillary water supply benefits may also be realized. If no storms are forecasted during the late winter and early spring period, storage gains during the last major storm event could be retained rather than released.

1.3 FIRO Viability Assessment Process and Timeline

Figure 1-4 shows the general evaluation process used to conduct the Yuba-Feather PVA, which will support the FVA and, ultimately, the update of USACE's WCMs for NBB and ORO. FIRO scenarios were tested in the PVA and then progressed in a clockwise (not yet viable) or counterclockwise (viable) flow path, with research and operations working together to define requirements for needed scientific improvements to support decision tools or how a tested strategy that was proven viable could be safely incorporated into practice. In the course of the PVA and work to evaluate FIRO scenarios, a more comprehensive FIRO evaluation process began to take shape.

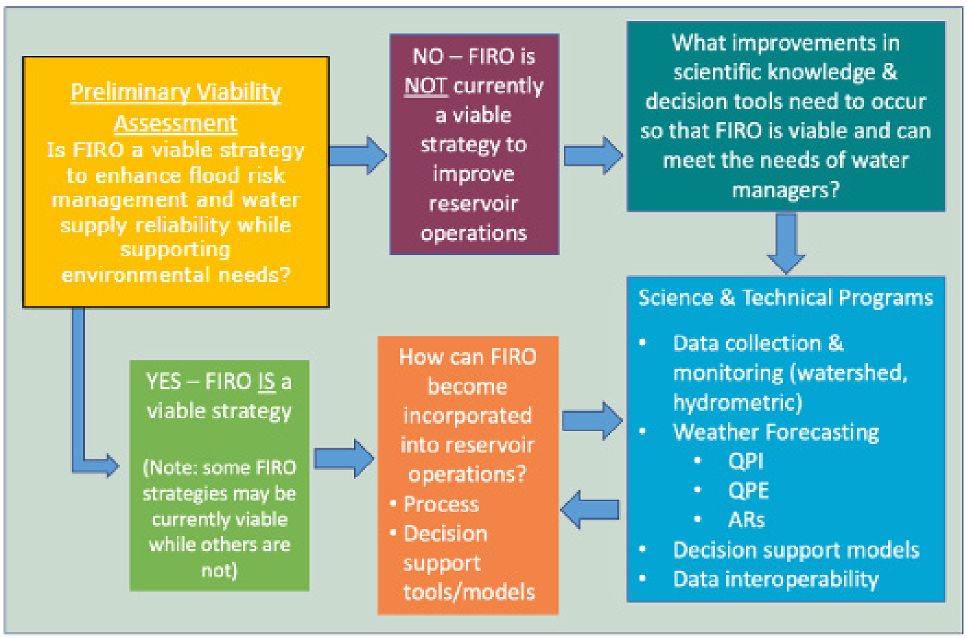


Figure 1-4. *Generalized FIRO PVA process.*

The timeline in Figure 1-5, below, shows the entire FIRO process for the Yuba-Feather, including integration with WCM updates. The PVA builds on and follows the work plan, which was completed in the spring of 2021. This PVA work directs the additional assessment required under the FVA. The FVA will definitively determine FIRO viability, as well as which FIRO alternative is best.

If the FVA provides a viable alternative, its findings will contribute to and inform the WCM updates, as shown in the aligned schedules.

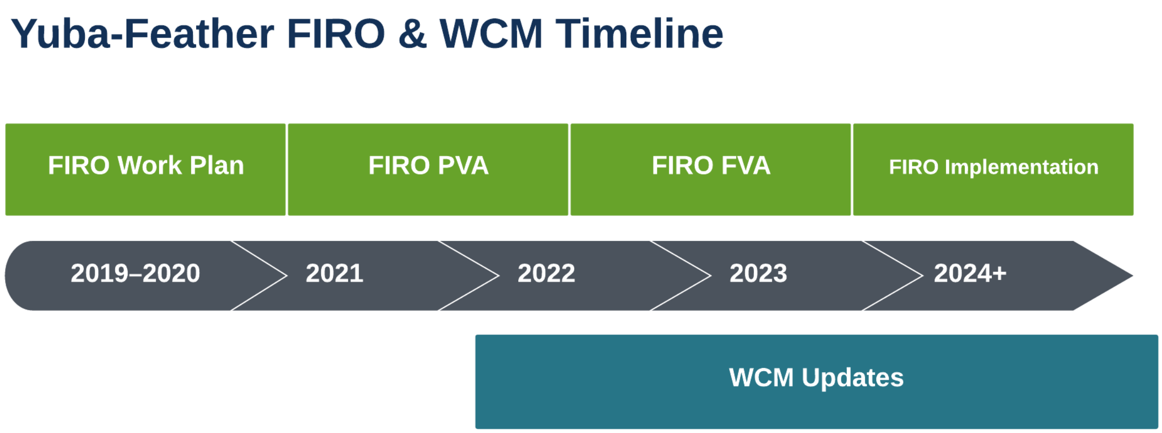


***Figure 1-5**. Alignment of Yuba-Feather FIRO, Atmospheric River Control (ARC) Spillway, and WCM timeline. Note: The Environmental Impact Statement (EIS) timeline is being used as a proxy, since it is the longer of the National Environmental Policy Act process timelines; the actual timeline may be shorter.*

1.4 Yuba-Feather FIRO Steering Committee

The Yuba-Feather Steering Committee first met in June 2019. Members were selected to represent key organizations, and they bring together innovative leaders from those organizations to collaborate and contribute expertise and resources to accomplish common goals.

Yuba-Feather Steering Committee membership is listed and pictured below (Figure 1-6). The Steering Committee developed and agreed to its operating principles called the "Terms of Reference," which consist of its mission, vision, goals, and strategies to achieve these goals; processes and procedures; and importantly, the project objective and target goal described above.

Co-Chairs

- **F. Martin Ralph:** Director, CW3E, Scripps Institution of Oceanography, UC San Diego
- **John James:** Water Operations Project Manager, Yuba Water
- **John Leahigh:** Water Operations Executive Manager, DWR

Members

- **Michael Anderson:** State Climatologist, DWR
- **Joseph Forbis:** Chief, Water Management Section, USACE Sacramento District

- **Alan Haynes:** Hydrologist-in-Charge, National Oceanic and Atmospheric Administration (NOAA) National Weather Service, CNRFC
- **Steven Lindley:** Director, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries
- **Cary Talbot:** Division Chief, USACE ERDC
- **Molly White:** Chief, State Water Project, Water Operations Office, DWR

***Figure 1-6**. Photo of Yuba-Feather Steering Committee (from left): Molly White, Joseph Forbis, Marty Ralph (co-chair), John Leahigh (co-chair), John James (co-chair), and Cary Talbot. Not in photo: Alan Haynes, Mike Anderson, and Steve Lindley.*

Steering Committee vision, mission, goal, and strategies

- **Vision:** Develop robust forecast data and tools that support increased flexibility in reservoir operations to improve water conservation, flood control, and habitat management outcomes.
- **Mission:** Guide a highly collaborative engagement process to ensure deliverables reflect interdisciplinary perspectives and interagency input.
- **Goal:** Develop clear pathways for assessing the viability of FIRO at NBB and ORO.
- **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, as well as work team meetings as needed.
- Hold an annual workshop to coordinate with, and learn from, other FIRO projects.
- Pursue communication and outreach opportunities.
- Develop a strategy for launching the viability assessment, including funding and implementation commitments.
- Coordinate FIRO and the WCM update processes for NBB and ORO (added after Steering Committee formation).

1.5 References

Jasperse, J., Ralph, F. M., Anderson, M., Brekke, L., Malasavage, N., Dettinger, M. D., Forbis, J., Fuller, J., Talbot, C., Webb, R., & Haynes, A. (2020). *Lake Mendocino Forecast Informed Reservoir Operations Final Viability Assessment.* Technical Report, UC San Diego. Retrieved from https://escholarship.org/uc/item/3b63q04n

Margulis, S. A., Cortés, G., Girotto, M., & Durand, M. (2016). A Landsat-era Sierra Nevada snow reanalysis (1985–2015). *Journal of Hydrometeorology*, 17(4), 1203-1221.

Section 2. Background

2.1 Watershed Characteristics

The Yuba and Feather Rivers originate in the Sierra Nevada Mountains in Northern California, which have ridgelines rising to more than 8,000 feet above the Pacific Ocean. The rivers join 70 feet above sea level at Marysville and Yuba City before flowing into the Sacramento River 40 miles north of the state's capital (Figure 2-1).

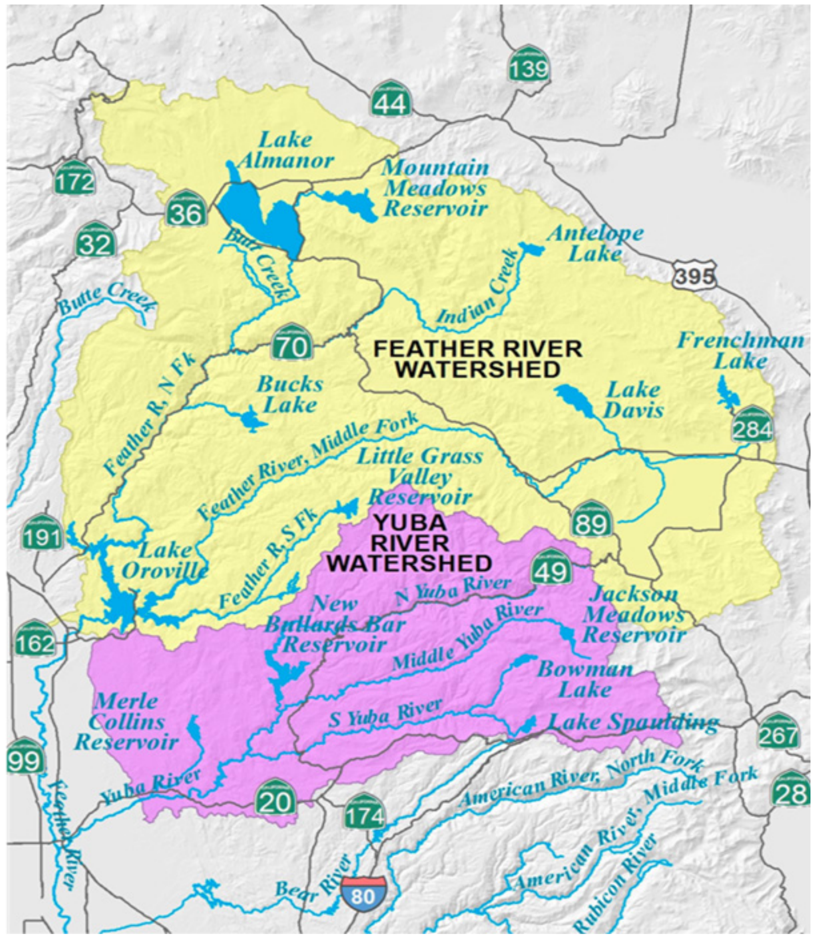


Figure 2-1. Map of the Yuba and Feather watersheds and location of New Bullards Bar Reservoir and Lake Oroville. Credit: Yuba Water.

The watersheds receive 80 to 90 percent of their annual rainfall from November through April. Heavy rains and snowfall at higher elevations, usually above 5,000 feet, result from large-scale, multiday storms flowing west to east from the Pacific Ocean, mostly in the form of atmospheric rivers. Mean annual precipitation in the Yuba River watershed is 80 inches in the upper watershed and 20 inches in the lower watershed. Mean annual precipitation in the Feather River Watershed ranges from 70 inches on the western slopes to 12 inches on the arid eastern slide. These watersheds are among the most productive watersheds in the state in terms of overall runoff.

With an area of 3,200 square miles, the Feather River watershed is the largest in the Sierra Nevada and a major tributary of the Sacramento River. The Yuba River watershed is 1,495 square miles. Both rivers respond quickly to winter storm events, especially during warm storms when snow only falls at the higher elevations.

2.1.1 The Yuba River

The Yuba River is made up of three tributaries: the North Yuba, Middle Yuba, and South Yuba. All three flow westward on the eastern side of the Sacramento Valley. The North and Middle Yuba Rivers come together below New Bullards Bar (NBB) Reservoir and form the main stem of the Yuba River.

The mountainous terrain is steep, rugged, and sparsely populated. Lakes and reservoirs in the Middle and South Yuba Rivers provide very limited and incidental flood water retention. Retention is more common in the early winter as reservoirs recover from the dry summer months when they provide water supply and hydropower generation. NBB serves as the primary infrastructure to reduce flood risk to Yuba River's downstream communities.

The Yuba River supports populations of several special status fish species, including spring-run Chinook salmon and steelhead trout, which were historically abundant in the Yuba River, as well as green sturgeon. All three species are listed as threatened under the federal Endangered Species Act, and the lower Yuba River has been designated as critical habitat.

Yuba Water has a long history of working with local, state, and federal agencies; environmental groups; and tribes to protect the fisheries resources of the lower Yuba River through agreements like the Lower Yuba River Accord. Signed in 2008, the accord is a landmark, multi-partner settlement agreement that ensures higher, more protective instream flows to benefit fish and provide one of the most suitable water temperature profiles of any Central Valley River across all water years.

2.1.2 The Feather River

The Feather River, the principal tributary of the Sacramento River, rises high in the Sierra Nevada, and flows for about 200 miles to its junction with the Sacramento River on the valley floor. Its upper reaches branch into several forks: West Branch and South Fork lie on the western slope of Sierra Nevada, and the North and Middle Forks rise on a high plateau east of the mountains. These snowmelt-dominated streams flow in an overall southwesterly direction, cutting through steep, rugged canyons to their respective confluences with the mainstem in the foothills above the mouth of Feather River Canyon. The Oroville (ORO) Dam is located below the junction of these forks, six miles above the town of Oroville. After leaving the mountains near Oroville, Feather River turns south and flows through the rich agricultural lands of the Sacramento River Valley for about 50 miles to its mouth at Verona on the Sacramento River, 20 miles above the city of Sacramento. The Feather River has two main tributaries that join it in the valley: Yuba River at Yuba City and Bear River at Nicolaus.

The Feather River Basin, which has been extensively modified over the years for power generation, irrigation, water supply, and flood control, forms the headwaters of the California State Water Project (SWP). Eighty percent of the Feather River's upper watershed is managed by the U.S. Forest Service. Situated just downstream of the confluence of the Feather River's South Fork, Middle Fork, North Fork, and the West Branch of the North Fork, Lake ORO, the reservoir behind ORO Dam, stores winter and spring runoff that is released into the Feather River to meet SWP needs. Capable of holding about 3.5 million acre-feet (ac-ft) of water, ORO is the largest water storage facility for the SWP and has second largest human-made lake in California. It provides water to 27 million Californians and irrigation to over 750,000 acres of farmland.

As part of the SWP, ORO Dam and its associated facilities are operated for water supply, flood management, power generation, water quality, and flows to benefit fish in the Sacramento–San Joaquin River Delta, recreation, and fish and wildlife enhancement. ORO Dam serves as the primary infrastructure to reduce flood risk to the Feather River's downstream communities.

2.1.3 Drought, Floods, and Climate Impacts

The valley reaches of the Yuba-Feather watersheds have a history of catastrophic flooding exacerbated by the region's gold rush era and hydraulic mining debris, which raised riverbeds and altered flows. Poorly constructed, aging levees built by early settlers also compounded flood risk. Levee breaches from extreme flood events in December 1955, February 1986, and January 1997 resulted in 43 deaths and more than $500 million in flood damages. These events were caused by what we now know are atmospheric rivers (ARs). A 2017 study on levee breaks in the Central Valley since 1951 found that, historically, 81 percent of 128 well-recorded breaks coincided with wintertime ARs (Florsheim and Dettinger 2015).

Recent investments exceeding $1 billion by local, state, and federal agencies have significantly reduced flood risk in the region; however, the economic and environmental consequences of catastrophic floods that hit the region in 1955, 1986, and 1997 are still felt today and reinforce the need for bold actions to protect people and property from future flood events.

California's Climate Extremes

After experiencing exceptional drought from 2013 to 2015, the 2016–2017 water year was the wettest year of California's historical record dating back to 1895. In early 2017, a major AR contributed to the infrastructure damage at the ORO Dam. Climate change resulted in approximately an 11 to 15 percent increase in precipitation over the Feather River Basin at that time.

Most recently, starting in 2020, the lack of ARs has contributed directly to California's ongoing drought. In August 2021, Lake Oroville fell to only 24 percent capacity, causing hydropower operations to shut down at the reservoir. A historic low in ORO was reached on September 30, 2021, at about 790,000 ac-ft.

ARs are projected to increase in intensity and duration in California in a warming climate, with the most intense AR storms becoming more frequent (Baek and Lora 2021, Gershunov et al. 2019). Frequent and powerful ARs are associated with major flood events, including those in 1955, 1964, 1986, 1997, and 2017. A 2022 study by Michaelis et al. estimated that climate change increased precipitation in the ORO drainage from the 2017 AR event by 11 to 15 percent. The study also showed that climate change affects ARs differently depending on the atmospheric dynamics.

Recent research shows that warming since the preindustrial era is responsible for reducing average snowpack by about 25 percent in the Sierra Nevada (Berg and Hall 2017). Figure 2-2, below, shows this warming to date in California. The UC San Diego Scripps Institution of Oceanography, Center for Western Weather and Water Extremes and the California Department of Water Resources (DWR) are working to better understand changes in snowpack and the rain-snow elevation in the Yuba-Feather watersheds, as it directly impacts inflow projections and critical flood and water management decisions. The absence of ARs is associated with periods of drought, including 2013 to 2015 and the current dry period, which began in 2020 (Dettinger 2016).

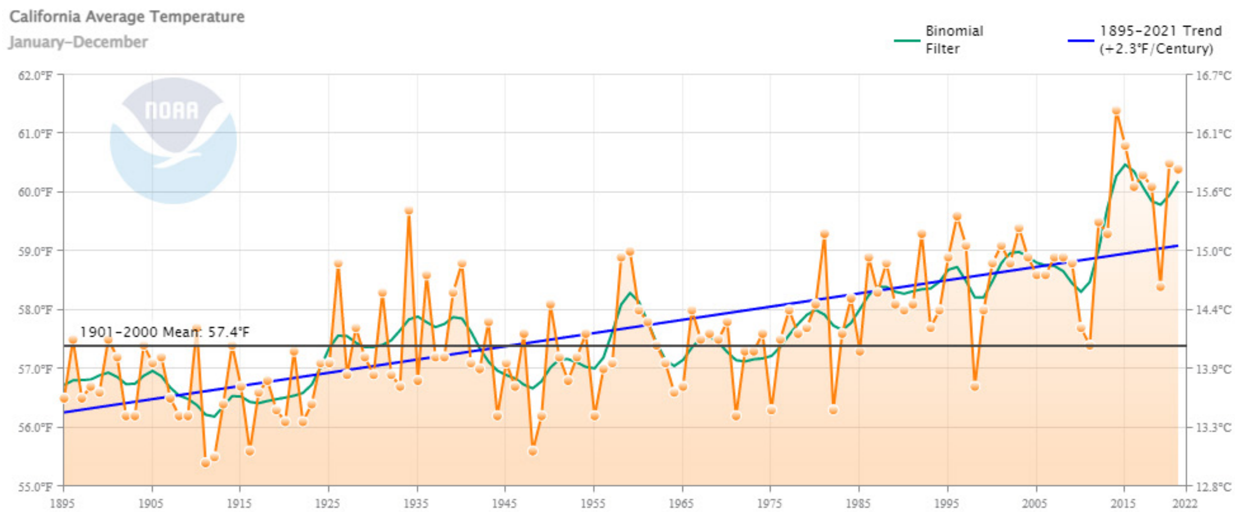


Figure 2-2. *Increase in average annual temperature in California. Credit: NOAA 2022.*

2.2 Dam Authorizations

Community Perspectives

In Yuba County, more than half of census-designated communities are considered disadvantaged under Water Code §79505.5(a), that is, communities with an annual median household income less than 80 percent of the statewide annual median household income, or $56,982. FIRO's forecast and operational improvements have the potential to reduce flood risk, improve water supply reliability, and improve climate resilience of underserved and disadvantaged communities.

The ORO and NBB dams are the primary flood management features on the Feather and Yuba Rivers, respectively. They were constructed to reduce flood risk, improve water supply, generate hydroelectricity, provide sources of recreation, and produce environmental benefits. The dams provide water supply to areas adjacent to each of their respective rivers, as well as downstream to the Sacramento River and eventually to the Sacramento–San Joaquin Delta. Together, ORO and NBB provide flood protection for properties and interests downstream of the structures, including the communities of Oroville, Palermo, Biggs, Gridley, Marysville, and Yuba City.

Table 2-1 below, shows a summary of NBB and ORO. NBB Dam was completed in 1969 and is owned and operated by Yuba Water as the primary feature of the Yuba River Development Project. The dam forms NBB Reservoir, which extends about 15.3 river miles upstream on the North Yuba River. The reservoir has an estimated gross storage capacity of 966,103 ac-ft, a surface area of 4,790 acres, a shoreline of about 71.9 miles, and a drainage area of 488.6 square miles. The dam includes an overflow-type spillway with a maximum design capacity of 160,000 cubic feet per second (cfs). Under the contract between the U.S. Army Corps of Engineers (USACE) and Yuba Water that was entered into on May 9, 1966, Yuba Water agreed to reserve 170,000 ac-ft of storage space in NBB Reservoir for flood control.

Table 2-1. Basic summary of ORO and NBB.

New Bullards Bar Reservoir	Lake Oroville
	
Capacity: 970,000 ac-ft	Capacity: 3,537,600 ac-ft
Flood Pool: 170,000 ac-ft	Flood Pool: 750,000 ac-ft
Year Built: 1969	Year Built: 1967
Watershed: 313,000 acres[a]	Watershed: 2,320,000 acres
Normal max surface water elevation: 1956 ft[b]	Normal max surface water elevation: 901 ft[b]
Owner: Yuba Water	Owner: Department of Water Resources
Purpose: Flood protection, water supply, recreation, environmental, hydropower	Purpose: Water supply, flood protection, recreation, environmental, hydropower

a. The NBB Reservoir is on the North Yuba River; the entire Yuba River watershed is 957,000 acres.

b. When USACE updates the Water Control Manuals for both projects, the existing elevations will be converted from NGVD 29 to NAVD 88.

ORO Dam, which has the distinction of being the tallest dam in the United States, was completed in 1970. It impounds the 3.54 million ac-ft ORO Reservoir on the Feather River and is owned by DWR and operated as part of the SWP. DWR operates ORO Dam as a key component of the SWP that delivers water to contractors serving both agricultural and municipal interests in Northern California, the Bay Area, the San Joaquin Valley, the Central Coast, and Southern California. In addition to providing water supply benefits to cities and farms throughout the state, the SWP operates Lake ORO to meet water quality standards in the Sacramento–San Joaquin River Delta in coordination with the U.S. Bureau of Reclamation's Central Valley Project. The federal government paid for the top 750,000 ac-ft of seasonal flood pool storage and issued regulations for managing this storage in USACE's Water Control Manual (WCM) for ORO. After a gated spillway chute failed in February 2017, DWR temporarily reconstructed the chute in November 2018 and fully completed reconstruction of the main and emergency spillways in November 2019.

USACE's Englebright Dam was completed in 1941 on the mainstem of the Yuba River about 17 miles downstream of NBB Dam and about 24 miles from the confluence of the Yuba and Feather Rivers. It is a smaller project that was constructed to trap sediment from the historical hydraulic mining operations in the upper Yuba River watershed. Englebright Dam provides some water rights benefits, but it delivers no flood control capacity to the system.

Congress authorized a third reservoir, called Lake Marysville, with 260,000 ac-ft of seasonal flood storage, but it was never constructed. The USACE WCMs for both NBB and ORO still reference reliance on this unconstructed Marysville Dam to help meet Feather River flood control objectives.

2.3 Current Operations

Following devastating flooding in January 1997, a Flood Emergency Action Team formed by the California governor released a report outlining more than 50 long-term actions and recommendations for improving the state's flood management practices. Yuba Water also initiated a $1 million Supplemental Flood Protection Study that identified numerous actions to improve flood protection. Both reports recommended closer coordination of reservoir operations between DWR's ORO and Yuba Water's NBB.

The existing WCMs for ORO and NBB acknowledge the need for communication among regional flood management agencies, noting that interagency coordination is needed on a daily or even hourly basis to ensure flood control operations are as effective as possible. The Yuba-Feather Forecast-Coordinated Operations (F-CO) program provides real-time coordination of reservoir operations during flood events. Implemented in 2006, the multi-agency initiative includes the State-Federal Flood Operations Center, the Operations Control Office of DWR's SWP, USACE Sacramento District, the California-Nevada River Forecast Center (CNRFC), DWR, and Yuba Water. These agencies have a history of working together to prepare flood-related information, operate and maintain flood control structures, and serve the public during flood emergencies.

F-CO is designed to improve data collection, flood flow forecasts, and communications among operating entities during a flood emergency response to protect life and property with minimal impacts to water supply. Coordinating and communicating reservoir releases from ORO and NBB reduces the chance of exceeding channel capacity downstream of the confluence of the Yuba and Feather Rivers.

Forecast-Coordinated Operations (F-CO) Purposes

- Coordinated decision making
- Real-time data collection and runoff forecasting
- Decision support system for coordinated reservoir operations
- Reporting to downstream flood emergency personnel

The interconnection of the Yuba and Feather Rivers at their confluence near two urban areas of Marysville and Yuba City demands that reservoir releases be coordinated to avoid excessive flows, while harnessing the full capacity of each channel to safely contain flow during high-water events. F-CO increases information exchange between forecasters, reservoir operators, USACE, the State-Federal Flood Operations Center, and the communities downstream of the reservoirs.

Using the latest CNRFC reservoir inflow and watershed streamflow forecasts, the F-CO decision support system helps coordinate release schedules that reduce the likelihood of damages at and below the confluence of the Yuba and Feather Rivers. These reservoir releases are then integrated into updated CNRFC real-time downstream flow forecasts, which are used to inform local, state, and federal flood emergency responders.

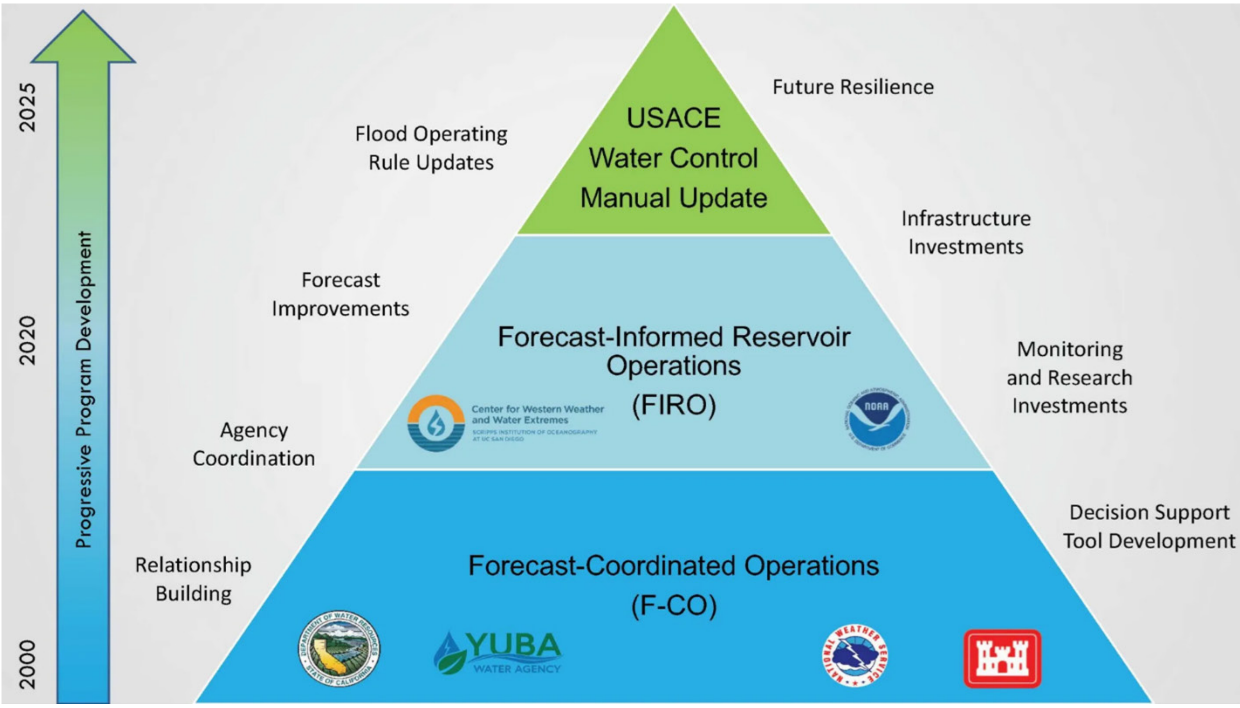


Figure 2-3. *Diagram showing progressive program development from a foundation of F-CO, followed by FIRO and, ultimately, revised WCMs that incorporate F-CO and FIRO into operations, leading to improved resilience to droughts and floods.*

F-CO is an operational system for near real-time coordination of reservoir operations and improved communications among operating entities during flood events. In contrast, FIRO is a research-based effort to enhance and inform reservoir decision making through improvements in weather and runoff forecasts. It provides a pathway and process for integrating the use of improved forecasts into operating procedures with an explicit goal of codifying forecast-informed operations into WCMs where FIRO is viable. F-CO is a system for coordinating operations within the Yuba-Feather watersheds. FIRO introduces improved observations and AR forecasts to anticipate when flood releases can be made in advance of a storm to reduce flooding or hold back water for the secondary benefit of water supply when forecasts indicate it is safe to do so. FIRO brings to F-CO better information on conditions outside the Yuba-Feather watersheds to inform how best to manage operations inside the system. Figure 2-3 shows the progression from the foundational F-CO to an overlay of FIRO, topped by the goal of revised WCMs that incorporate FIRO.

FIRO Benefits

- Improved forecasts inform decisions about releasing water in advance of flood events.
- FIRO operations can create additional space in reservoirs to capture peak flood flows and lower downstream peak flood stages.
- Opportunity for earlier spring refill for water supply when no precipitation is forecast.

2.4 Adapting Infrastructure at NBB to Maximize FIRO Benefits

To maximize the benefits of FIRO and the timing of WCM updates for NBB Reservoir, Yuba Water is designing a second spillway, the Atmospheric River Control (ARC) Spillway, at NBB Dam (see Figure 2-4).

The ARC Spillway is designed with gates that are 31.5 feet lower than the existing spillway gates, which will allow Yuba Water to release up to 35,000 cfs in advance of large, threatening storm events, when there is enough channel capacity to handle the flows. These releases will help evacuate space in the reservoir to capture peak flows when the biggest part of the storm arrives. The ARC Spillway operation gives Yuba Water the ability to activate an additional 117,000 ac-ft of reservoir space for flood mitigation purposes.

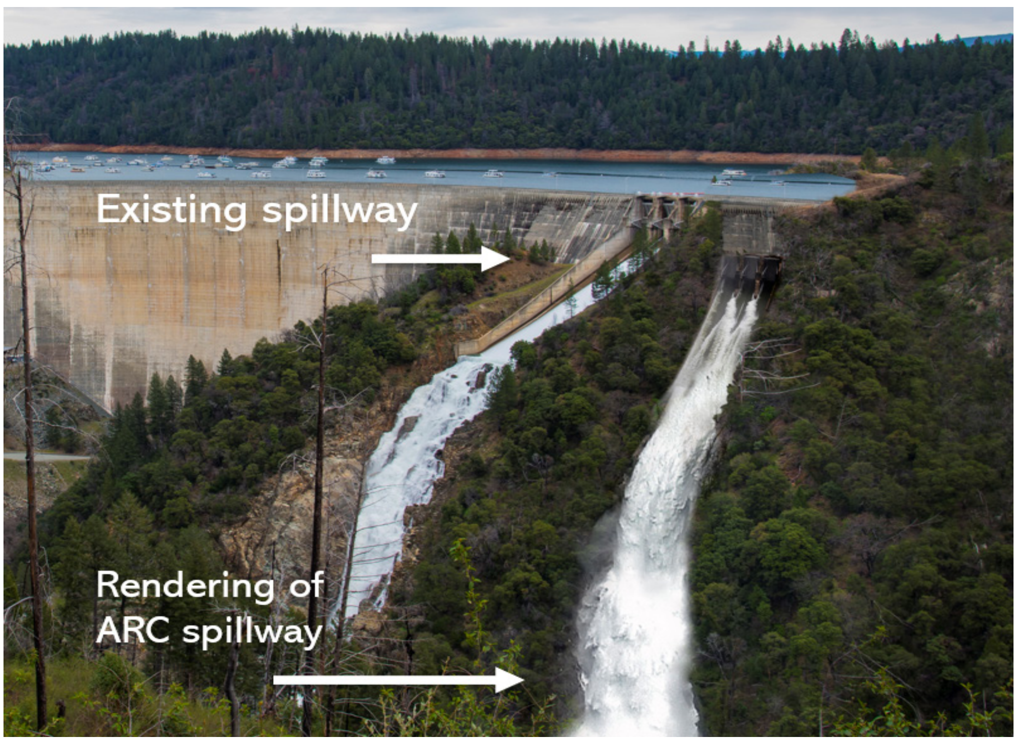


Figure 2-4. *The ARC Spillway will have the capacity to pass the flood of record (~50,000 cfs) without use of the primary spillway. Credit: Yuba Water Agency.*

The ARC Spillway will decrease flood risk for more than 160,000 residents in parts of Yuba and Sutter counties by improving the flexibility and control of releases from NBB Dam. This flexibility in turn has the potential to limit flood risk by reducing water levels on levees by 2 to 3 feet in a 100-year storm event like 1997, the region's storm of record. The spillway also adds a redundant release option, which could manage a storm of 1997's magnitude on its own to enhance dam safety.

Design of the ARC Spillway will be complete in fall 2022. Yuba Water is actively pursuing state and federal funding for the project.

2.5 Conclusion

The Yuba-Feather watersheds' characteristics, past flooding history, dominance of AR impacts, and past collaboration, including F-CO, make the region an ideal candidate for potential FIRO operations. The following sections of the PVA detail the work to date and the findings from that work, in addition to providing recommendations and a roadmap for transitioning from the PVA to the Final Viability Assessment.

2.6 References

Baek, S. H., & Lora, J. M. (2021). Counterbalancing influences of aerosols and greenhouse gases on atmospheric rivers. *Nature Climate Change.* https://doi.org/10.1038/s41558-021-01166-8

Berg, N., & Hall, A. (2017). Anthropogenic warming impacts on California snowpack during drought. *Geophysical Research Letters, 44,* 2511–2518, doi:10.1002/2016GL072104

Dettinger, M. (2016). Historical and future relations between large storms and droughts in California. *San Francisco Estuary and Watershed Science, 14*(2). Retrieved from https://escholarship.org/uc/item/1hq3504j

Florsheim, J., & Dettinger, M. (2015). Promoting atmospheric-river and snowmelt fueled biogeomorphic processes by restoring river-floodplain connectivity in California's Central Valley. In: Hudson, P., & Middelkoop, H. (eds.), Geomorphic approaches to integrated floodplain management of lowland fluvial systems in North America and Europe. *Springer*, 119–141. https://www.mdettinger.com/_files/ugd/3b5c57_ef17d141017c43f5b050a63e90366e8d.pdf

Gershunov, A., Shulinga, T., Ralph, F. M., Lavers, D. A., & Rutz, J. J. (2017). Assessing the climate-scale variability of atmospheric rivers affecting western North America. *Geophysical Research Letters, 44,* 7900–7908. https://doi.org/10.1002/2017GL074175

Gershunov, A., Shulgina, T., Clemesha, R. E., Guirguis, K., Pierce, D. W., Dettinger, M. D., ... & Ralph, F. M. (2019). Precipitation regime change in Western North America: the role of atmospheric rivers. Scientific reports, 9(1), 1-11.

Michaelis, A. C., Gershunov, A., Weyant, A., Fish, M. A., Shulgina, T., & Ralph, F. M. (2022). Atmospheric river precipitation enhanced by climate change: A case study of the storm that contributed to California's Oroville Dam crisis. *Earth's Future, 10*, e2021EF002537. https://doi.org/10.1029/2021EF002537

NOAA National Centers for Environmental Information. (2022). Climate at a glance: Statewide time series. Retrieved on April 14, 2022, from https://www.ncdc.noaa.gov/cag/

Section 3. FIRO and WCM Alignment

The previous FIRO pilot sites at Russian River and Prado Dam have undertaken the FIRO Viability Assessment process as a precursor to the U.S. Army Corps of Engineers (USACE) Water Control Manual (WCM) update process. Conducting these efforts sequentially can take many years before FIRO practices are regularly implemented at a viable site. The major deviation request process, in which USACE can approve temporary adjustments to its rule curve based on adequate justification, can be used to capture partial FIRO benefits at a reservoir before the WCM update is completed and implemented, but this also takes time and effort to secure. Additionally, there is significant overlap in the required analysis and modeling that needs to be conducted for these two processes and sequencing them without careful alignment can result in a duplication of effort.

Shortly after New Bullards Bar (NBB) and Lake Oroville (ORO) were selected to be studied as the next FIRO pilot sites in 2019, the USACE Sacramento District received funding to undertake the WCM update process for these sites. This funding presented an opportunity to conduct FIRO assessments and WCM updates in parallel for the first time. The concurrent alignment of FIRO and WCM updates is a groundbreaking innovation and a potential model for the future. If FIRO is to be applied at more sites operated by USACE, it will be necessary to streamline the FIRO Viability Assessment process and the WCM update process without losing the rigor required for each. Additionally, a current focus on modernizing WCMs across USACE presents an opportunity to explore FIRO at more sites. The Yuba-Feather project can provide a template for considering these two processes in parallel.

Recognizing the importance of developing and documenting the alignment of these two processes, a workgroup of water managers, researchers, engineers, and policymakers held three virtual one-day workshops for ORO and NBB. The tightly coupled timelines and interdependence of these processes necessitates strong communication between the FIRO and WCM update work teams. The workshop series, held in December 2020 and January 2021, served to educate members of each team on the requirements of the other, to identify connection points and synergies between the two processes, and to establish strong communication for the rest of the FIRO and WCM update project timelines. The detailed workshop agendas are included in Appendix B.

Key outcomes from the workshop series included:

- Defining clear goals and objectives for the FIRO and WCM update processes in relation to one another (see process crosswalk included in Appendix A).
- Improving understanding of projects by participants in both processes to enable more meaningful and effective collaboration.
- Aligning schedules, tasks, and common requirements to avoid duplicating efforts and ensure timely transmission of information.
- Establishing regular leadership meetings and integrating technical workgroups to collaborate, share analyses, monitor progress, and adapt as needed.
- Creating a model process for future FIRO-informed Water Control Manual updates.
- Tailoring research for operational requirements.

The workshop laid the groundwork for integration between a FIRO Preliminary Viability Assessment (PVA) and the WCM updates for ORO and NBB. A coordinated timeline of alignment steps is shown below in Figure 3-1.

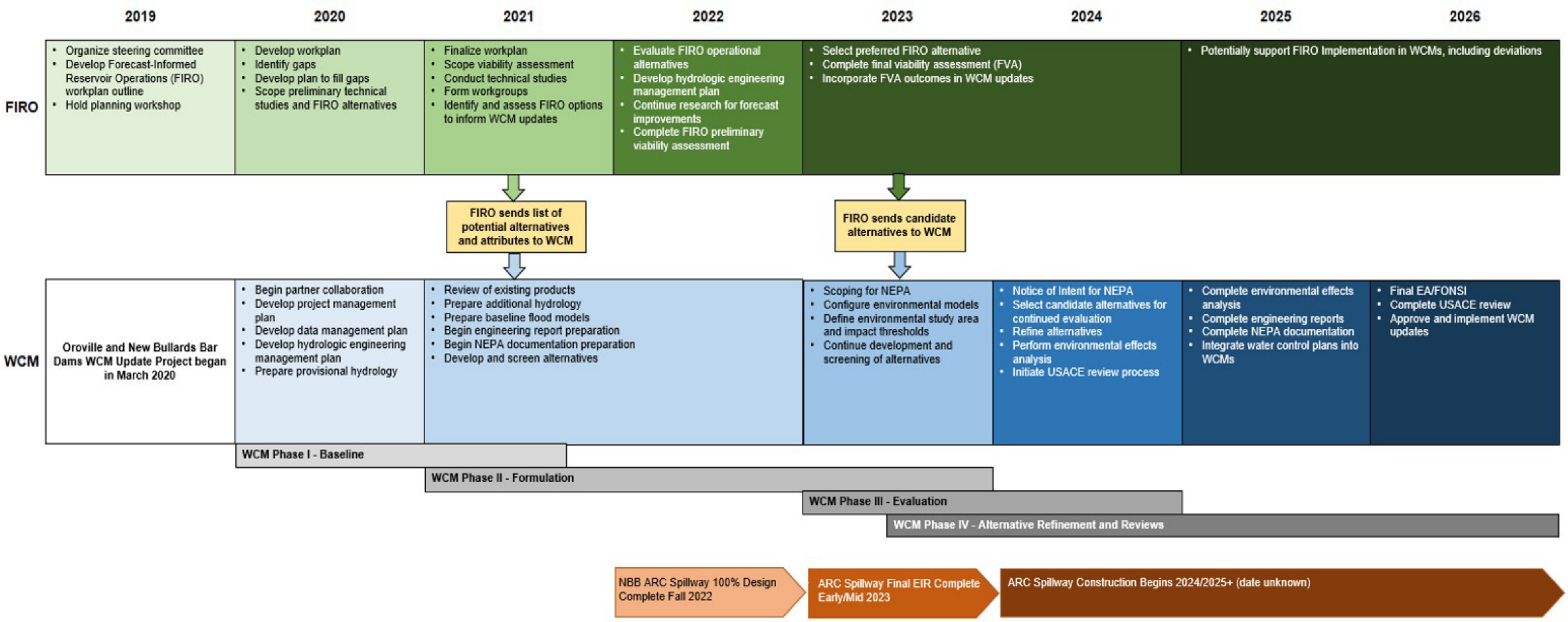


Figure 3-1. *FIRO PVA and WCM coordinated timeline as of September 2022.*

Based on discussions in the workshop series, nine teams were formed to address the tasks identified in the FIRO work plan. Each team includes members from the FIRO and WCM update teams to ensure a coordinated effort. Each team developed a charter to detail the focus, goals, and objectives of the team. The nine integrated teams are:

- Communication
- Forecast verification
- Observation
- Meteorology
- Hydrology
- Water resources engineering
- WCM alignment leadership
- Economics benefits
- Decision support tools

These teams served the PVA development process and are expected to remain intact for the work associated with the Final Viability Assessment (FVA). For the FVA, information will be gathered from each team to assess any lessons learned from the creation of the teams themselves and the execution of the team's workload. The FVA will address any recommended changes to team structure and execution for future projects where FIRO and WCM update alignment is necessary.

3.1 Communication Team

The communication team is composed of members from the California Department of Water Resources (DWR), Yuba Water, USACE, and the Center for Western Weather and Water Extremes (CW3E). The overarching goal for the Communication team is to coordinate timely and effective communication about the relevance and value of the Yuba-Feather FIRO initiative and related efforts to policymakers, decision makers, partners, and other stakeholders. The focus of the Communication team regarding the FIRO and WCM alignment is to ensure consistent messaging, to demonstrate a collaborative and cooperative process and the efficiencies gained by the alignment, and to work with USACE to align communication strategy.

3.2 Forecast Verification Team

The forecast verification team is composed of members from CW3E, University of Colorado Boulder, DWR, the California Nevada River Forecast Center (CNRFC) of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), the USACE Sacramento District (SPK), USACE's Engineer Research and Development Center (ERDC), and consultants. The focus is to assess the current weather and water forecast skills to understand reliability for release decision making and to establish a baseline from which improvements will be measured. The goal of the team is to develop and execute a systematic, comprehensive approach for evaluating forecasts as they relate to impacts that support, affect, or inform reservoir flood operations and/or water supply.

3.3 Observation Team

The observation team is composed of members from CW3E, Scripps Institute, DWR, Yuba Water, USACE's SPK and ERDC, NOAA, San Diego State University, and consultants. The focus is to determine if additional observational data are needed to increase the accuracy of precipitation and streamflow forecasts, especially from extreme events driven by atmospheric rivers (ARs), to support FIRO now and in the future. The goal of the Observation team includes ensuring observations are sufficient and available to achieve FIRO and WCM goals.

3.4 Meteorology Team

The meteorology team is composed of members from CW3E, DWR, Yuba Water, USACE's SPK and ERDC, NOAA, and consultants. The team focuses on the research and analysis needed to increase accuracy and reliability of meteorological forcings for hydrologic models (e.g., precipitation, snow level, temperature), especially associated with extreme events driven by ARs, to support FIRO now and in the future. The goal of the Meteorology team is to improve meteorological forecasts for the Yuba and Feather watersheds and their operational usability for Yuba Water, DWR, NWS, and USACE.

3.5 Hydrology Team

The hydrology team is composed of members from USACE's SPK and Hydrologic Engineering Center (HEC); the CNRFC; CW3E; Yuba Water; DWR; University of Nevada, Reno; San Diego State University; and consultants. The focus is to support development of hydrologic information needed to evaluate FIRO strategies and to determine what additional information and analysis is needed to increase the accuracy and reliability of runoff and streamflow forecasts to support FIRO.

3.6 Water Resources Engineering Team

The water resources engineering team consists of individuals from Yuba Water, DWR, USACE's SPK and HEC, the CNRFC, NOAA's National Marine Fisheries Service, CW3E, and consultants. The focus is to:

- Coordinate identifying operation objectives and considerations, performance metrics, existing conditions, the base reservoir operation model, the hydrology to be used, and FIRO operation strategies to be considered.
- Develop alternative attributes and strategies that are potentially viable for implementation in the updated WCMs.
- Ensure analysis methods, data, results, and documentation are useful for the WCM update process.
- Demonstrate that FIRO is viable for ORO and NBB from an operational perspective.

3.7 WCM Alignment Leadership Team

The WCM alignment leadership team is composed of members from CW3E, DWR, Yuba Water, and USACE's SPK and ERDC. The team focuses on how FIRO and the WCM updates can be effectively aligned and integrated (including the alignment of timing, studies, modeling, data needs, and analysis), what FIRO concepts can be applied toward an adaptive management approach as forecast skill improves, and how the process can work for triggering incremental improvements.

3.8 Economic Benefits Team

The economic benefits team is composed of members from CW3E, Yuba Water, DWR, USACE, and consultants. The focus is to identify and, if possible, quantify the economic benefits of FIRO and how other investments can be leveraged. The goal for the Economic Benefits team is to design the economic benefits assessment of FIRO for the FVA.

3.9 Decision Support Tools Team

The decision support tools team is composed of members from Yuba Water, DWR, USACE's SPK and ERDC, CW3E, and consultants. Decision support tools (DSTs) are the tools used to support NBB and ORO reservoir operations during the flood season where decisions are governed by USACE's Water Control Plans. The focus is to:

- Consider how Yuba-Feather FIRO strategies can be implemented in Yuba-Feather's Forecast-Coordinated Operations decision support system and USACE's Corps Water Management System in terms of forecast ingestion and processing, as well as reservoir operation modeling, including system operation.
- Consider integration with precipitation-runoff modeling, hydraulic routing, and consequence modeling, if needed.
- Consider how forecasts are currently represented in DSTs and how future forecast enhancements developed under Yuba-Feather FIRO can be integrated into DSTs.
- Consider the role of DSTs in WCM updates that allow flexibility for future enhancements.

The goal of the DST team is to review and document existing Yuba-Feather DSTs, identify potential gaps and opportunities for improvement, and develop strategies for integrating FIRO.

Section 4. How FIRO Viability Was Assessed

Viability of FIRO can be defined differently for different dams depending on the operational goals and authorized purposes. The central question that the Yuba-Feather FIRO Program seeks to answer is:

> Can current and improved forecasts of landfalling atmospheric rivers and associated precipitation and runoff be used to inform reservoir operations at New Bullards Bar and Oroville dams to enhance flood risk management and water supply reliability while supporting environmental needs?

The purpose of the PVA engineering study was to develop a proof of concept to answer this question and to inform the U.S. Army Corps of Engineers (USACE) Water Control Manual (WCM) updates for Oroville (ORO) and New Bullards Bar (NBB) dams. Subsequently, the Final Viability Assessment (FVA) will build on the PVA with a more detailed assessment and set of results. An explicit quantitative assessment of replacing the functional equivalent of the unconstructed Marysville Dam was not performed as a part of the PVA due to the broad uncertainties associated with how Marysville Dam might operate and integrate into system operations with ORO and NBB. A surrogate approach will be explored as a part of the FVA.

4.1 Approach

To assess FIRO viability, the water resources engineering (WRE) team developed and evaluated operation alternatives that explicitly include inflow forecasts in release decision making. As described in Section 3, the WRE team consisted of representatives from all partner agencies as well as consulting engineering firms supported by the partner agencies. Heavy coordination with the hydrology team, the Steering Committee, and the WCM update effort was supported throughout this work. The alternatives were modeled after FIRO alternatives developed in previous studies, namely the 2019 Folsom WCM Update (USACE 2019) and the Lake Mendocino FVA (FIRO Program 2020), described further in the next section.

The Yuba-Feather flood management system is complex, with the ORO and NBB dams operating for common downstream maximum flow objectives, a system of levees reducing flood risk to communities and agriculture downstream, and significant uncontrolled flow. In addition, both ORO and NBB are multi-purpose reservoirs, so tradeoffs between storage and release must be balanced. Dam safety must also be considered.

USACE Engineer Manual 1110-2-3600, *Management of Water Control Systems* (USACE 2017), describes the approach for developing flood regulation schedules for multi-reservoir systems: “General regulation schedules for an integrated system of projects are usually developed first for the tributary projects operating as separate units. The adjustment of the individual regulation schedules for coordinated regulation of the various tributary and main river projects are generally based on system analyses of the basin development, design floods, and historical floods of record.”

Accordingly, the WRE team divided this complex assessment into the components listed below.

Key Components of the Assessment

- **At-site analysis.** Develop operation alternatives at each dam that achieve performance objectives at the dam, absent downstream considerations. This component can be assessed by metrics such as pool elevation and outflow frequency.
- **System operation analysis.** Develop alternatives for coordinated release decision making for the dams, focusing on downstream considerations, including maximum objective flow limitations and balance of risk.
- **Combined alternative analysis.** Combine promising at-site and system operation components and assess performance against evaluation metrics.

4.2 Studies Informing the Evaluation Framework

To develop FIRO alternatives, the WRE team built on previous Yuba-Feather and FIRO studies. Foundational studies informing the PVA are listed in Table 4-1.

Table 4-1. *Foundational Yuba-Feather and FIRO studies that informed the PVA.*

ID	Study	Relevance	Reference
1	Oroville Dam Safety Comprehensive Needs Assessment	Preliminary development and assessment of forecast-based alternatives for ORO Dam.	DWR (2020)
2	New Bullards Bar Atmospheric River Control (ARC) Spillway evaluations	Preliminary development and assessment of forecast-based alternative for NBB Dam considering additional release capacity from ARC Spillway.	Yuba Water Agency (2020)
3	Lake Mendocino FIRO Program	Development and assessment of Ensemble Forecast Operation alternatives for Lake Mendocino. Operation strategy serves as an example for NBB and ORO dams.	Jasperse et al. (2020) Delaney et al. (2020)
4	Folsom Dam WCM Update	Development and assessment of forecast-based alternatives for Folsom Dam. Operation strategy serves as an example for Oroville and New Bullards Bar Dam.	USACE (2019)

ID	Study	Relevance	Reference
5	Yuba-Feather F-CO Program	Description of decision support system to facilitate coordinated releases for Oroville and New Bullards Bar dams.	David Ford Consulting Engineers (2008)

4.3 Evaluation Framework: The HEMP

Development of flood operation alternatives requires hydrologic engineering analyses. Following USACE protocol, the WRE team developed a hydrologic engineering management plan (HEMP) to guide those analyses. A HEMP is a technical outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem.

Engineer Pamphlet 1110-2-9, *Hydrologic Engineering Studies Design* (USACE 1994) describes the purpose of a HEMP: "Successful study completion requires management of time, money, and human resources to accomplish the necessary technical studies in an effective manner. Hydrologic engineering study products must satisfy study team and project sponsor needs. The technical studies must also be completed within available financial resources. It is important to plan the technical work at the beginning of the study to accomplish these requirements. Development of a hydrologic engineering management plan for the study is a crucial first step towards accomplishing these objectives."

The PVA HEMP defined the following:

- Statement of objective and overview of technical study process to provide information needed for the assessment.
- Identification of tasks to be completed for the technical analysis.
- General FIRO strategies to be analyzed.
- Specification of requirements for all FIRO alternatives that will be considered.
- Identification of hard criteria as well as project and systemwide considerations.
- Identification of initial tentative performance metrics for FIRO alternative evaluation.
- Identification of the project team members and their roles and responsibilities for conducting, reviewing, and approving of the hydrologic engineering study.
- Risks to the success of the study and mitigation actions.

The USACE Sacramento District (SPK) also developed a HEMP for the WCM updates. The WRE team and SPK team coordinated on definition of objectives, considerations, and performance metrics and alternative development and assessment strategies. The planning was designed so the PVA could inform the WCM updates assessment. The PVA HEMP is included as Appendix C (FIRO Program 2021a).

4.4 At-Site Water Control Plans

As described in Section 4.1, the first step of the assessment is to develop operation alternatives at each dam that achieve performance objectives at the dam, absent downstream considerations. Alternative attributes were defined by the WRE team and delivered to the Steering Committee as well as SPK in the form of a technical memo (Appendix D: FIRO Program 2021b). This preliminary analysis step builds to the development of a complete set of FIRO alternatives that consider system operation.

For the PVA, eight at-site alternatives were assessed, four for ORO and four for NBB, as shown in Table 4-2 below. The WRE team used two types of FIRO strategies that explicitly consider short-term inflow forecasts (less than 14 days) in release decision making:

- **Prescriptive.** The prescriptive strategies were based on elements from the updated WCM operation from Folsom Dam. These strategies are formulated with the question: Given the current storage and forecasted inflow, how much water from the reservoir needs to be evacuated below the maximum level, and at what rate, to meet desired objectives given estimated likelihoods of occurrence? The prescriptive strategy relies on predetermined target storage values (e.g., top of conservation elevation) and/or releases, both determined based on inflow forecast volume. The ensemble forecast processed to a single value (X percent non-exceedance probability value) or the deterministic forecast can be used to determine the top of conservation elevation and/or release magnitude.
- **Iterative.** The iterative strategies were based on elements from the Lake Mendocino FIRO Program alternatives. These strategies are formulated with the question: Given the current storage and forecasted inflow, how much storage must be released from the reservoir and at what rate to manage the forecasted uncertainty to meet the desired system objectives? The iterative strategy uses each member of the forecast ensemble to consider the full range of potential outcomes for a given release. If the range of ensemble forecasts exceed a prescribed tolerance of uncertainty above a given reservoir elevation, then a release schedule is formulated that releases the needed volume to mitigate this uncertainty given forecasted release constraints.

Table 4-2. *Initial eight at-site alternatives considered. Through the screening process, four at-site alternatives were identified as most promising (shown in gray).*

Dam	Strategy Type	Alt	Alt Description	Operation Principle
NBB	Prescriptive	FIRO Guide Curve	A forecast-based guide curve to specify drawdown in advance of flood events and conditional storage of water in the gross pool when forecast is dry.	• Evacuate volume above FIRO guide curve over less than one-day time window. • Increase storage utilization in the reservoir to mitigate high downstream flood releases.
NBB	Prescriptive	FIRO Release Schedule	A forecast-based release schedule to specify drawdown in advance of flood events. Flood control focus.	• Evacuate conservation space with increasing release steps to absorb forecast event, reducing peak releases and peak storage at NBB.
NBB	Iterative	Ensemble Forecast	Risk-based approach that uses the full reservoir pool and	• Flood control release decisions are formulated by managing forecasted uncertainty of exceeding a defined

Dam	Strategy Type	Alt	Alt Description	Operation Principle
		Operations (EFO)	ensemble streamflow predictions to manage forecast uncertainty.	storage threshold to a specified uncertainty tolerance level. • Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
NBB	Iterative	Hybrid EFO	Risk-based approach that uses a portion of the reservoir pool (FIRO Space) and ensemble streamflow predictions to manage forecast uncertainty.	• Same as EFO except that FIRO releases are restricted to a defined portion (FIRO Space) of the flood pool and conservation pool.
ORO	Prescriptive	PrescriptiveForecast_1 (EF008)	Use best-estimate forecast volumes to inform guide curve (top of conservation) computation and inflow-based releases.	• Relies on a guide curve (elevation based) based on forecasted inflow volumes. When in the flood control pool, evacuate the flow in a controlled manner to reduce downstream peak flows (not release inflow). Stepped releases are proposed.
ORO	Iterative	OROIterativeForecast_1	Iterative process using ensemble members to determine a reservoir release to maintain same dam risk profile as current operations.	• Identify a "minimally-changed release" through the flood event. This release (or release pattern) is identified as the maximum release needed to balance the use of the flood pool but not result in adverse dam safety concerns. Use the forecast information, and the uncertainty of that, to identify this release.
ORO	Iterative	EFO	Same as for NBB	• Same as for NBB
ORO	Iterative	Hybrid EFO	Same as for NBB	• Same as for NBB

Based on initial evaluations and refinement, the eight at-site alternatives were narrowed down to the four most-promising alternatives, two for each dam and two of each FIRO strategy type as highlighted in Table 4-2. Details of the individual alternatives can be found in appendices E, F, and G. Note that the NBB FIRO Guide Curve and Ensemble Forecast Operations (EFO) strategies both permit the release of conservation storage in anticipation of a large storm event. The FVA will examine the implications and magnitude of the available conservation storage for pre-releases.

4.5 System Operations

4.5.1 WCM Rules

ORO and NBB form a reservoir operating system because they are two reservoirs with dedicated flood storage reserves and joint flood operating rules. The ORO and NBB WCMs explicitly require coordinated operation of these two reservoirs to manage flows in the downstream river network. These reservoirs must meet downstream flow requirements, considering significant unregulated flows, while still operating to their individual, reservoir-specific flood management operating rules. These requirements necessitate a relatively sophisticated, coordinated operation to remain compliant and be effective.

A further complication is that the USACE joint operating rules assumed the addition of a third system reservoir, Marysville Dam, when they were developed 50 years ago. The reservoir operating rules for ORO and NBB also assumed that Marysville Dam would help NBB control flows on the Yuba River, adding 260,000 ac-ft of flood reserve (USACE 1970, 1971, 1972). Without Marysville Dam, NBB and ORO alone do not provide the anticipated flood management protection in the system. This burden has been recognized in the interim as ORO has been designated to surcharge to manage for the standard project flood (SPF) without Marysville Dam. Similarly, the NBB operating rule limiting releases to a challenging downstream flow threshold has been informally relaxed.

The Yuba-Feather watersheds are managed with a joint downstream flow constraint of 300 thousand cubic feet per second (kcfs) in the Feather River below the Yuba River. Both ORO and NBB are expected to constrain releases so that flows in the Feather River below Bear River do not exceed 320 kcfs. The existing WCMs for ORO and NBB also define downstream flow constraints specific to the Feather and Yuba Rivers at locations above the Feather and below the Yuba; these flow constraints are listed in Table 4-3.

Table 4-3. *Flow constraints defined in the NBB and ORO WCMs.*

Rule ID	Location	Flow Constraint (kcfs)	NBB	ORO
1	Feather River below Yuba River	300	✓	✓
2	Feather River below Bear River	320	✓	✓
3	Yuba River near Marysville	120 when Feather is “high”	✓	
		180 when Feather is “low”	✓	
4	Feather River at Yuba City	180		✓
5	Feather River downstream of ORO	150		✓

The text from the NBB Flood Control Diagram reads: “Water will not be released at such rates as will cause flows to exceed 120,000 cfs in Yuba River at Marysville when concurrent flows in Feather River are high. If necessary, however, releases may be increased when concurrent flows in Feather River are low; if flows in Yuba River at Marysville do not exceed 180,000 cfs”

(USACE 1972). This text was written assuming that Middle and South Yuba contributions to flow near Marysville would be managed through the proposed Marysville Dam. Because Marysville Dam was never constructed, much of the Yuba River watershed runoff remains unregulated, which places a larger burden on NBB to meet downstream flow constraints than was originally anticipated. Sensitivities to downstream flow constraint splits were assessed in Appendix H (MBK Engineers 2021c).

4.5.2 Forecast-Coordinated Operations

A formalized cooperating agreement between reservoir operators and regulatory agencies has been developed and implemented as a program that facilitates systematic, coordinated decision making in an environment of incongruent operating rules. This program is referred to as the Forecast-Coordinated Operation (F-CO) program. The program includes a common reservoir system operations model implemented within USACE Hydrologic Engineering Center (HEC) Reservoir System Simulation (ResSim). This model represents the flow constraints for the Yuba River near Marysville (Rule ID 3) and the Feather River at Yuba City (Rule ID 4) at 180 kcfs. A reservoir balance algorithm is used within the HEC-ResSim model to suggest releases from the two reservoirs to maintain the same percentage of flood space encroachment when other operating rules are otherwise in conflict. That model is part of the F-CO program's decision support system (DSS) (David Ford Consulting Engineers 2008), which both serves real-time forecasts and modeling results and facilitates their comprehension for operational participants. The F-CO program is described in Section 2.3.

4.5.3 Looking Ahead

The Yuba-Feather system operation is complex, and the development of new system operations strategies was beyond the scope of the PVA. As such, the system approach developed and implemented as a part of the F-CO program was used to demonstrate FIRO viability for the PVA.

The WRE team did, however, begin the process of scoping and exploring the foundational concepts of new systems approaches that may provide enhanced flood risk management benefits. These concepts will be further explored and potentially integrated as a part of the Yuba-Feather FVA work. The concepts are:

- **Risk balance.** A reservoir has two mechanisms to defend against a flood event's inflow. It can (1) store the inflow or (2) release it into the river below the dam. If too much water is stored instead of released, the reservoir's flood control reserve will be used up. This could jeopardize the safety of that reservoir's dam. If too much water is released into the downstream river system, the levees that contain that downstream flow could be at risk for failure. Therefore, a proper balance must be struck between the utilization of these two reservoirs defenses—storage and release—to effectively limit the risk of these two undesired outcomes. Both the balance in utilizing storage between ORO and NBB and their combined storage use versus utilizing downstream channel systems need to be considered in assessing alternatives (Appendix I: MBK Engineers 2021b, Appendix J: HDR 2020). As the new WCMs are being developed for NBB and ORO, explicit ways to measure system risk are needed to formalize and better understand these trade-offs in coordinated operations.
- **Need for coordination.** NBB and ORO's joint operating rules (Rule IDs 1 and 2) require operators of those two facilities to coordinate. However, the magnitude of the limits for

these rules—300 and 320 kcfs, respectively—are large enough that flows will not reach these levels frequently. An analysis (MBK Engineers 2021d) was performed to determine how often these two operating constraints would be realized. It showed that, in general, the Feather River below the Bear River constraint (Rule ID 2) is expected to be more frequently realized than the Feather River below the Yuba River constraint (Rule ID 1). Depending on the timing of the forecast and the actionable ensemble representation (e.g., 90 percent non-exceedance probability ensemble member) chosen by operators as the basis for forecast-informed releases, coordination would be required for events with frequencies of 1-in-10 to 1-in-100 years and rarer.

- **Balancing mainstem and tributary constraints.** Balancing mainstem (Rule IDs 1 and 2) and tributary (Rule IDs 3-5) flow constraints in the joint ORO and NBB operations is currently challenging. Operators are reliant on a model's algorithm to calculate coordinated releases when these sets of constraints come into conflict, which is typically the case during large flood events analyzed. This is not a desirable position since it is unnecessarily complicated and reduces the operators' ability to develop understanding and intuition for one of their essential job functions. Achieving rule clarity between the mainstem and tributary flow constraints through the ORO and NBB WCM updates is crucial. The frequency of F-CO activation was assessed and is provided in Appendix K (MBK Engineers 2021d).
- **Consideration for targeting lower downstream flows.** The current WCM rules for ORO and NBB have only two provisions for releasing water at rates less than the maximum prescribed downstream limits. One provision is the release schedule at ORO, which sets releases from ORO of 60 and 100 kcfs before reaching the ultimate 150 kcfs limit. The other provision is the 50 kcfs conditional release limit at NBB. Otherwise, these reservoirs are encouraged, through the WCM rules, to release water as rapidly as possible to limit flood space encroachment. For large enough events, flows reach the downstream flow constraint limits from the WCMs (i.e., full channel utilization).

SPK is currently engaged in updating the WCMs for NBB and ORO in consultation with Yuba Water and the California Department of Water Resources (DWR). The WCM alignment team has committed to reviewing and analyzing to see if the shared downstream 180/120 kcfs can be more clearly defined. This request to disambiguate the shared downstream 180/120 kcfs responsibility is listed on the considerations for the WCM updates. The WCM update provides an opportunity for an explicit rule to dictate how contributions to the Feather River below the Yuba River constraint are split between NBB and ORO.

4.5.4 Combining At-Site Alternatives with System Operation

Figure 4-1, below, shows how the prescriptive alternatives at ORO and at NBB were paired to form a combined alternative with the existing F-CO system operation (Alternative 2). An additional combined alternative was formed by pairing the iterative alternatives at ORO and NBB with the existing F-CO system operation (Alternative 3). These were compared with Alternative 1 (baseline), a pairing of the existing WCM operation at each dam and the existing F-CO system operation. All three alternatives considered the Atmospheric River Control (ARC) Spillway in place.

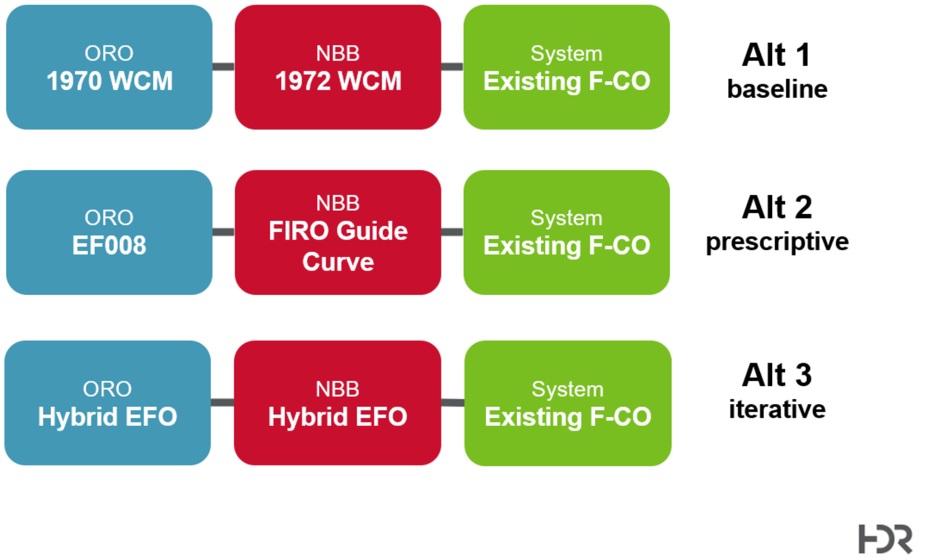


Figure 4-1. *The most promising alternatives were paired and combined with existing F-CO system operation.*

4.6 Simulation Plan

To evaluate the alternatives, a set of performance metrics was defined. As the goal of the PVA is a proof of concept, this set reflects a subset of metrics that will likely be used for the WCM updates. The metrics focus on flood risk management performance with a cursory evaluation of water supply impacts. In summary, the performance metrics include:

- Historical and scaled event-based routing results for max pool elevation; max outflow; max downstream flow at Yuba City, Marysville, the Feather-Yuba confluence, and Nicolaus; and end-of-event storage.
- Conditional annual maximum frequency curves for pool elevation, outflow, and downstream flow.
- Potential impacts on water supply, which were assessed by looking at the frequency of triggered pre-releases and the likelihood of significant over-forecast for Alternative 2 and a comparison of end-of-flood season storage for Alternative 3. This process is described further in Appendix L.

The WRE team evaluated FIRO alternative performance for two scenarios:

- **Perfect forecast runs.** How do alternatives perform when the forecast is correct? The Central Valley Hydrology Study (CVHS) hydrology, and scalings of the CVHS hydrology, were used for these runs.
- **Imperfect forecast runs.** How do alternatives perform when the forecast is uncertain (consistent with those currently available for operations)? GEFSv10-based hydrologic ensemble forecasts from the California Nevada River Forecast Center (CNRFC) were used for these runs.

The period of record, particularly the hindcast period of record, provides very limited opportunities to test and evaluate alternative strategies. To better challenge each strategy and provide for better comparison under extreme conditions, historical events were "scaled" (i.e., made larger). Scaling of the "perfect forecasts" using the CVHS hydrology was straightforward and accomplished by simply applying a consistent factor to the flows across the watersheds for selected historical flood events. For the "imperfect forecasts" provided through the HEFS hindcasts, a range of precipitation scaling factors were selected to provide the desired range of simulated inflows within the system for selected historical flood events using the CNRFC's Community Hydrologic Prediction System model. These simulations become the "observations." Scaled ensemble hindcasts were created by first multiplying the GEFSv10 hindcast precipitation by the same factor and processing the scaled ensemble precipitation hindcasts through the Community Hydrologic Prediction System model to create the scaled ensemble streamflow hindcasts for each node in the system.

The WRE team used HEC-ResSim, the USACE standard-of-practice reservoir operation modeling software to simulate reservoir operations of the alternatives where possible. For the hybrid EFO alternatives, a separate Python model of the reservoir system was used to compute releases. Those releases were entered as release overrides in HEC-ResSim so that a common routing model was used for all three alternatives. Figure 4-2 shows the HEC-ResSim model topology and network for the Yuba-Feather system.

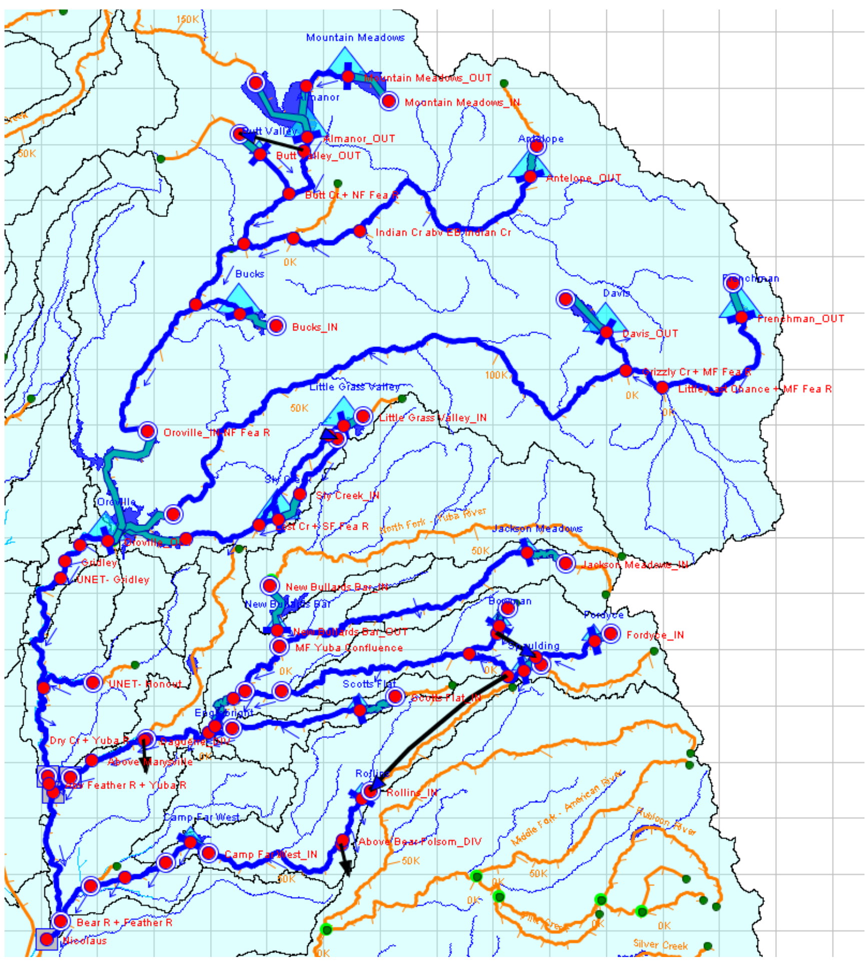


Figure 4-2. *HEC-ResSim topology and network for the Yuba-Feather system.*

Analysis details are included in the tables below. Table 4-4 lists the performance metrics and forecast input used for the assessment. Table 4-5 lists the scale factors used for specific event patterns. Table 4-6 describes the HEC-ResSim study model.

Table 4-4. *Performance metrics and forecast input for assessment. Alternatives should generally enhance flood risk management performance. Alternatives should maintain or enhance existing water supply impact performance.*

Row ID	Metric[a]	Forecast Input for Assessment[b]	
		Perfect Forecast Runs: How do alternatives perform when forecast is *correct*?	**Imperfect Forecast Runs:[c] How do alternatives perform when forecast is *incorrect*?**
1	1986 event pattern peak pool elevation, outflow, downstream flow, end-of-event storage	CVHS hydrology—all scalings	GEFS v10 hindcast hydrology—all scalings
2	1997 event pattern peak pool elevation and outflow, downstream flow, end-of-event storage	CVHS hydrology—all scalings	GEFS v10 hindcast hydrology—all scalings
3	2006 event peak pool elevation and outflow, downstream flow, end-of-event storage	CVHS hydrology—unscaled only	GEFS v10 hindcast hydrology—unscaled only
4	2017 event peak pool elevation and outflow, downstream flow, end-of-event storage	CVHS updated hydrology—unscaled only	Operational forecast ensemble hydrology—unscaled only
5	SPF peak pool elevation and outflow, downstream flow, end-of-event storage	Oroville WCM, Chart 32, SPF system routings 1 and 2, Feather and Yuba centerings. See Appendix D Attachment D-1. A. Research NBB WCM Chart 19, if needed]	N/A
6	Annual max conditional frequency curves: pool elevation, outflow, and downstream flow	CVHS hydrology. Use results from 1986 and 1997 event pattern routings to fit frequency curves. Assume three-day critical duration for all 1986 routings and one-day critical duration for all 1997 routings. Additionally, include 2006 and 2017 unscaled as points on the plot for reference (without influencing the curve fit). Assume critical duration of three days for both events.	GEFS v10 hindcast and operational forecast ensemble hydrology. Use same method as for perfect forecast runs.

a. Downstream locations to be assessed are Marysville, Yuba City, Yuba-Feather confluence, and Nicolaus.

b. Scale factors are shown in Table 4-5.

c. For imperfect forecast runs with prescriptive alternatives, the 75 percent non-exceedance probability volume at ORO was used for EF008, and the 75 percent non-exceedance probability volume at NBB was used for FIRO Guide Curve. Actual inflow hydrographs used were the CNRFC deterministic unscaled and scaled hydrographs from rainfall-runoff modeling. The imperfect forecast simulations with actual inflow represented by the rainfall-runoff hydrographs were used for frequency curve development. In addition, for the unscaled simulations, additional simulations were done using the CVHS or CVHS updated unscaled hydrology as the actual inflow hydrographs.

Table 4-5. *Scale factors used for assessment.*

Row ID	Hydrology	Event Pattern	Scale Factors
1	CVHS	1986 and 1997	0.20 to 0.60 at 0.20 increments 0.75 to 1.9 at 0.05 increments
2	Hindcast	1986	100% to 150% at 10% increments
3	Hindcast	1997	90% to 130% at 10% increments

Table 4-6. *Description of HEC-ResSim study models.*

Row ID	Element	Specification	Notes
1	Models and software version	Hindcast and CVHS/SPF starting point models, HEC-ResSim version 3.3.2.33	Available on the FIRO Google Drive. At NBB, ARC Spillway added as separate outlet structure, powerhouse configured separately, 50,000 cfs rule added to baseline. Both ORO and NBB include 320,000 cfs rule. See accompanying *READ ME* file for details.
2	Model network	Truncated Sacramento River Basin CVHS: Headwater reservoirs downstream to Nicolaus with and without ARC Spillway. See Figure 4-2.	For CVHS/SPF runs, headwater reservoir operation is included. For hindcast runs, although the headwater reservoirs are included in the model network, boundary condition inflows are input directly at ORO as a simplifying assumption.
3	Time step	Hourly	—
4	Hydrologic routing method	Muskingum-Cunge	—
5	Physical configuration of dam and outlets	ORO: VHS + updated rating curves NBB: CVHS NBB: CVHS + ARC Spillway No Marysville Dam	Flow out of Oroville River Valve Outlet System is configured as 0.

Row ID	Element	Specification	Notes
6	Baseline operation[a]	ORO 1970 WCM NBB 1972 WCM Existing F-CO system operation rule	—

a. Includes the 50,000 cfs inflow-based rule at NBB and the 320,000 cfs Feather River below Bear River maximum objective flow for both ORO and NBB. The existing F-CO system operation rule balances flood pool encroachment between ORO and NBB.

4.7 Recommendations

As expected, the PVA process for structuring the evaluation of Water Control Plan alternatives was a process for learning. Based on this experience, the WRE team offers the following recommendations for the FVA:

- Apply additional rigor to the consistent application of at-site and system constraints, data, hindcasts, and initial starting conditions as defined in the HEMP to ensure the evaluated alternatives can be objectively compared.
- More directly assess the potential impact (positive or negative) on water supply and an economic benefits assessment. (Full period-of-record simulations should be made for all alternatives.)
- Leverage hindcasts generated using the current GEFSv12 model.
- Consider using synthetically generated ensemble hindcasts to enhance the robustness testing of the alternatives under consideration.
- Investigate objective forecast-informed methods for dynamically coordinating releases to meet the downstream flow objectives at Yuba City and below the Bear River, including developing appropriate metrics for evaluation.
- Evaluate at-site and system performance with and without the ARC Spillway to address WCM update and/or planned deviation needs before construction of the spillway is complete (~2028).

4.8 References

CW3E. (2022). Yuba-Feather Forecast Informed Reservoir Operations. Development of Ensemble Forecast Operations alternatives for Lake Oroville and New Bullards Bar. April. *(PVA Appendix G)*

David Ford Consulting Engineers. (2008). Oroville–New Bullards Bar Forecast-Coordinated Operations: Decision support system technical documentation. Prepared for Yuba Water Agency. December 12.

Delaney, C. J., Hartman, R. K., Mendoza, J., Dettinger, M., Delle Monache, L., Jasperse, J., Ralph, F. M., Talbot, C., Brown, J., Reynolds, D., & Evett, S. (2020). Forecast Informed Reservoir Operations using ensemble streamflow prediction for a multipurpose reservoir in Northern California. *Water Resources Research, 56*(9), e2019WR026604. https://doi.org/10.1029/2019WR026604

DWR. (2020). *Oroville Dam safety comprehensive needs assessment—Task 2: Operations*. Prepared by HDR. July.

Jasperse, J., Ralph, F. M., Anderson, M., Brekke, L., Malasavage, N., Dettinger, M. D., Forbis, J., Fuller, J., Talbot, C., Webb, R., & Haynes, A. (2020). *Lake Mendocino Forecast Informed Reservoir Operations Final Viability Assessment.* Technical Report, UC San Diego. Retrieved from https://escholarship.org/uc/item/3b63q04n

FIRO Program. (2021a). Hydrologic Engineering Management Plan (HEMP) for the Yuba-Feather FIRO PVA evaluation of Water Control Plan alternatives. August.

FIRO Program. (2021b). Oroville and New Bullards Bar alternative attributes. Memorandum from Donna Lee, CFM; Nathan Pingel, PE; Rob Hartman; Ben Tustison, PE, to FIRO Steering Committee and SPK. August 25.

HDR. (2020). Yuba-Feather system storage balance. Memorandum from Aimee Kindel, PE; Mike Konieczki, PE; Nathan Pingel, PE; Donna Lee, CFM, to Yuba-Feather FIRO Team. June 17.

HDR. (2021). Development of Oroville Dam Forecast-informed Reservoir Operation Alternatives—At-site alternative EF008. Memorandum from Hongyu Deng, PE; Nathan Pingel, PE, D.WRE, PMP; Donna Lee, PMP; and Michael Konieczki, PE, D.WRE. November 3. *(PVA Appendix F)*

MBK Engineers. (2021a). Yuba-Feather system operations: Framework to depict system risk balance. Memorandum from Carissa Abraham, EIT; and Ben Tustison, PE. October 11. *(PVA Appendix H)*

MBK Engineers. (2021b). Preliminary Viability Assessment of at-site operations: Developing a FIRO guide curve for New Bullards Bar. Memorandum from Sophie Danielsen and Carly Narlesky, PE. November 11.

MBK Engineers. (2021c). Yuba-Feather system operations: Sensitivity to downstream flow constraint split. Memorandum from Carissa Abraham, EIT, and Carly Narlesky, PE. November 18.

MBK Engineers. (2021d). Forecast-Coordinated Operations activation frequency. Memorandum from Olivia Alexander, EIT, and Ben Tustison, PE. November 3.

USACE (1970). *Oroville Dam and Reservoir: Report on Reservoir Regulation for Flood Control.* SPK. August.

USACE. (1971). Marysville Reservoir, Yuba River, California: Hydrology.

USACE (1972). *New Bullards Bar Reservoir: Reservoir regulation for flood control.* SPK. June.

USACE. (1994). *Hydrologic engineering studies design.* EP 1110-2-9. Headquarters. July 31.

USACE. (2017). *Management of water control systems.* EM 1110-2-3600. October 10.

USACE. (2019). *Folsom Dam and Lake: Water Control Manual.* SPK. Published December 1987. Revised June 2019.

USACE. (2021). Hydrologic Engineering Management Plan: Oroville and New Bullards Bar Water Control Manual updates. SPK. Prepared by HDR. September 15. *(PVA Appendix C)*

Yuba Water Agency. (2020). New Bullards Bar secondary spillway: Evaluation of flood management performance for candidate secondary spillway outlets. Prepared by MBK Engineers. August 24.

Section 5. Water Control Plan Assessment Results

5.1 Introduction

As described in Section 4, the water resources engineering (WRE) team developed FIRO alternatives to examine whether FIRO is viable for Oroville (ORO) and New Bullards Bar (NBB) dams from an operational perspective. The Steering Committee defined viability specifically as: "Can current and improved forecasts of landfalling atmospheric rivers and associated precipitation and runoff be used to inform reservoir operations at New Bullards Bar (NBB) and Oroville (ORO) dams to enhance flood risk management and improved water supply while supporting environmental needs?" The purpose of the PVA was to develop a proof of concept to answer this question, especially to inform the U.S. Army Corps of Engineers (USACE) Water Control Manual (WCM) updates for ORO and NBB dams. Subsequently, the Final Viability Assessment (FVA) will build on the PVA with a more detailed assessment and set of results. It is important to recognize that the FIRO objective for this project is different from earlier efforts. At both Lake Mendocino and Prado Dam, the objective was to improve water resources outcomes without negatively impacting flood risk management and environmental objectives. Here, the objective is focused on improving the flood risk management outcomes with the existing physical infrastructure.

This section describes the PVA analysis results. The results demonstrate that FIRO has the potential to enhance flood risk management without impacting water supply. The frequency of exceeding key pool elevations, outflows, and downstream flows is generally reduced with the preliminary FIRO alternatives when compared to existing WCM operation (USACE 1970 and 1972). Some exceptions are described herein; however, these identify opportunities for alternative refinement, as described in Section 5.6. End-of-event storage, a cursory indication of water supply impacts, is generally increased. These results confirm that FIRO should be further studied under the FVA.

5.2 WCM Crosswalk

The PVA deliverables were designed to inform the WCM updates. These deliverables include:

- Definition and screening of FIRO at-site alternatives, including both prescriptive and iterative strategies.
- Identification of potential enhancements for system operation, focusing on the use of forward-looking metrics to compute coordinated releases that balance risk within the system. The computed release schedules can inform decision making between the Forecast-Coordinated Operations (F-CO) partner agencies.
- Preliminary analysis results for combined alternatives that include the most promising at-site alternatives and the existing F-CO system operation.
- A path forward to the FVA that focuses on providing additional information useful for the WCM updates, described in Section 5.6. This path includes refinement of alternatives and concepts to leverage future forecast skill in the Water Control Plan, known as "FIRO 2.0."

- Detailed documentation on the evaluation results, as shown in appendices C to L.

5.3 Alternative Water Control Plan Strategies

For the PVA, the WRE team evaluated three alternatives, including at-site and system operational rules, as described in Section 4 and summarized in Table 5-1 below. Alternative 1, WCM operation, represents the baseline condition to which the FIRO alternatives, 2 and 3, are compared. Alternative 2, the ensemble forecast model EF008, is a combination of prescriptive alternatives. Alternative 3, the Hybrid Ensemble Forecast Operations (EFO) model, is a combination of iterative alternatives. All alternatives consider the planned NBB Atmospheric River Control Spillway in place and include the existing F-CO system operation rule for joint downstream maximum objective flows. The existing F-CO system operation rule computes releases to balance encroachment of the reservoir flood control pools (David Ford Consulting Engineers 2008). The system rule is prioritized among the other operational rules included in the alternatives.

Potential enhancements that involve incorporating the use of forecasts into the F-CO system operation rule are described in Section 4.5 and appendices H, I, J, and K. This will be examined further under the FVA.

Table 5-1. *PVA combined alternatives, which are a combination of the most promising at-site alternatives and the existing F-CO operation.*

Alt ID	ORO At-Site	NBB At-Site	System Operation	Description
1	1970 WCM	1972 WCM	Existing F-CO	Existing WCM operation. Baseline to which alternatives are compared.
2	EF008	FIRO Guide Curve	Existing F-CO	Pairing of prescriptive alternatives at dams. The forecast ensemble is processed to a single inflow value (75 percent non-exceedance probability at dam) and is used to determine forecast-based top of conservation or guide curve and/or release magnitude based on pre-defined relationships. Considers forecast duration up to seven days.
3	Hybrid EFO	Hybrid EFO	Existing F-CO	Pairing of iterative alternatives at dams. A potential release from a dam is evaluated considering each forecast ensemble hydrograph. If the tolerable risk of a given outcome, such as exceeding a given reservoir elevation, is exceeded considering the full ensemble, a new release is evaluated. This process is repeated until the tolerable risk is not exceeded. Considers forecast duration up to 15 days.

5.4 Performance Metrics

To compare alternatives for the PVA, the WRE team used performance metrics that would inform the WCM updates. These include:

- Peak pool elevation, outflow, downstream flow, and end-of-event storage for the:
  - 1986 and 1997 unscaled and scaled events.
  - 2006 and 2017 unscaled events.
  - Standard project flood (SPF) system routings 1 and 2 from the ORO WCM, Chart 32 (USACE 1970).
- Annual maximum conditional frequency curves for pool elevation, outflow, and downstream flow at Yuba City, Marysville, the Feather-Yuba confluence, and Nicolaus.

The metrics focus on flood risk management performance. End-of-event storage is used as a cursory indication of water supply impacts, which will be examined further in the FVA.

The PVA examined both a perfect forecast and imperfect forecast scenarios. The perfect forecast scenarios examine how alternatives perform when the forecast is correct. The imperfect forecast scenarios examine how alternatives perform when the forecast has uncertainty.

For the PVA, an imperfect forecast scenario was examined using the ensemble hindcasts and actual inflow hydrographs from California Nevada River Forecast Center rainfall-runoff modeling. For the FVA, the WRE team will further consider additional robust testing of alternatives to imperfect forecasts.

5.5 Findings

A summary of findings for the perfect and imperfect forecast scenarios, comparing the FIRO alternatives (2 and 3) with existing WCM operation (1), is summarized below. Results, figures, and tables are presented at the end of the section. Additional results, including tables and operation plots, are included in Appendixes E, F, and G. All elevations are in reference to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Key Findings

- FIRO has the potential to enhance flood risk management without impacting water supply.
- Frequency of exceeding key pool elevations, outflows, and downstream flows is generally reduced with the preliminary FIRO alternatives when compared to existing WCM operation.
- End-of-event storage, a cursory indication of water supply reliability, is generally increased.

5.5.1 Perfect Forecast Scenario: Frequency Curves

Figure 5-1 and Figure 5-2, below, show the frequency curves for the perfect forecast scenario. A summary of these figures follows:

- **Elevation frequency-curves.** The difference in starting storage between the alternatives impacts the lower end of the elevation-frequency curves. Alt 1 is designed so the prescribed flood pool is not encroached during normal operation and is evacuated as quickly as possible during a flood event, given release limitations. Alt 2 and Alt 3 are designed to store water higher in the pool under normal operations, begin drawdown when an event is forecast, and then return to the original storage after the event. The FIRO Space at each dam as compared to maximum flood pool at ORO and NBB is shown in Table 5-2. For Alt 2 (NBB) and Alt 3 (NBB and ORO), the FIRO Space includes portions of both the conservation pool and the flood pool. These initial FIRO Space selections, made in consultation with the California State Water Project and the Yuba Water, are detailed in appendices D and E and will be refined in the FVA process. In particular, the inclusion of conservation space in the FIRO Space selection for ORO and the associated implications will be vetted in the FVA process. For Alt 1 simulations, the maximum flood pool is used at ORO, so no pre-event drawdown is required.

"FIRO Space" is a specified zone (or space) in a reservoir where water can be conditionally retained or released based on available forecast information and at the discretion of the dam operator. FIRO space can vary depending on several factors, including forecast lead time, release schedules, and reservoir storage required to meet authorized purposes.

Table 5-2. *Maximum range of winter FIRO Space designated for Alt 2 and Alt 3 compared to Alt 1 max flood space (total storage volume).*

Dam	Alt 1 Max Flood Space (per 1,000 ac-ft)	Alt 2 FIRO Space (per 1,000 ac-ft)	Alt 3 FIRO Space (per 1,000 ac-ft)
ORO	2,788 to 3,538	2,788 to 3,164	2,349 to 3,072
NBB	796 to 966	700 to 900	611 to 866

- **ORO elevation frequency-curve.** Both Alt 2 and Alt 3 decrease the frequency of exceeding 901 feet, the emergency spillway crest elevation.
- **NBB elevation frequency-curve**. Alt 3 reduces the frequency of exceeding 1,956 feet, the gross pool. Alt 2 maintains performance.
- **ORO outflow frequency-curve**. Alt 2 and Alt 3 can pass larger events without exceeding the maximum objective flow of 150,000 cfs.
- **NBB outflow-frequency curve**. Alt 3 can pass larger events without exceeding 50,000 cfs, a threshold flow identified by USACE in the 1972 WCM. Alt 2 passes smaller events at lower flows. With the constraint of 50,000 cfs maximum release, Alt 1 can pass larger events than Alt 2. However, 50,000 cfs is an intermediate limitation of the 1972 WCM based on inflow.
- **Feather River at Yuba City regulated flow-frequency curve.** Alt 2 and Alt 3 decrease the frequency of exceeding the maximum objective flow of 180,000 cfs. Alt 2 and Alt 3 can pass larger events without exceeding this objective.

- **Yuba River at Marysville regulated flow-frequency curve.** Alt 2 and Alt 3 decrease the frequency of exceeding the maximum objective flow of 180,000 cfs. The slope of the curves, absent a flat, regulated portion, demonstrate that the unregulated flow in the Yuba watershed is a major contributing factor in whether this criterion is met.
- **Feather-Yuba River confluence regulated flow-frequency curve.** Alt 3 reduces the frequency of exceeding the maximum objective flow of 300,000 cfs. Alt 2 slightly increases the frequency of exceeding this objective. This result may be attributable to the system operation for the 1997 unscaled event, which is discussed below. Enhancement of the system operation may improve this result.
- **Feather River at Nicolaus regulated flow-frequency curve.** Alt 2 and Alt 3 decrease the frequency of exceeding the maximum objective flow of 320,000 cfs. Alt 2 and Alt 3 can pass larger events without exceeding this objective.

5.5.2 Perfect Forecast Scenario: Unscaled Event Results

Table 5-3, below, shows the unscaled event routing results for the perfect forecast scenario. The unscaled events are among the largest on record. Results of the scaled events are also important for assessing performance and are included in Appendixes E, F, and G. A summary follows:

- **Unscaled historical events.** In general, Alt 2 and Alt 3 tend to decrease downstream flow and increase end-of-event storage with few exceptions. For the 1997 event, Alt 2 slightly exceeds system objective flows. This may be a result of refinement needed to the system operation rule to account for coordinated operation while releasing from the conservation pool. Currently, the rule focuses on balancing flood pools. For the 1997 event scaled by 1.05 and 1.1, the thresholds are not exceeded for Alt 2.
- **SPF routings.** All alternatives exceed some key thresholds for these design events. The system was designed to pass the SPFs with the addition of Marysville Dam, which was never built. The routings suggest that the preliminary FIRO alternatives alone do not overcome the storage capability of Marysville Dam. Further analysis of the SPF routings is required for the FVA. It must be noted, however, that the SPF routing assessment was done for historical context only, as USACE no longer uses this approach for assessing the capacity of the flood control system. Note also that this assessment is somewhat complicated by the lack of a Bear River flow component in the SPF hydrology, which affects interpretation of Table 5-3.

5.5.3 Imperfect Forecast Scenario: Unscaled Event Results

Table 5-4, below, shows the unscaled event routing results for the imperfect forecast scenario. Results of the scaled events are also important for assessing performance and are included in Appendixes E, F, and G. Note that the imperfect forecast scenario results are not directly comparable to the perfect forecast results because the hydrographs routed are from a different data set, as described in Section 4. Also, the SPFs are excluded for the imperfect forecast scenario because forecasts are not available for this design event. A summary of the results follows:

- **Unscaled historical events.** Results for Alt 2 and Alt 3 increase end-of-event storage and reduce downstream flows for some events. Alt 2 exceeds critical thresholds for the 1986 and 1997 event, and Alt 3 exceeds a critical threshold for the 1997 event. These exceedances highlight the need for further investigation of system operation. For the prescriptive alternatives, the processed value used for inflow forecast input should be examined.

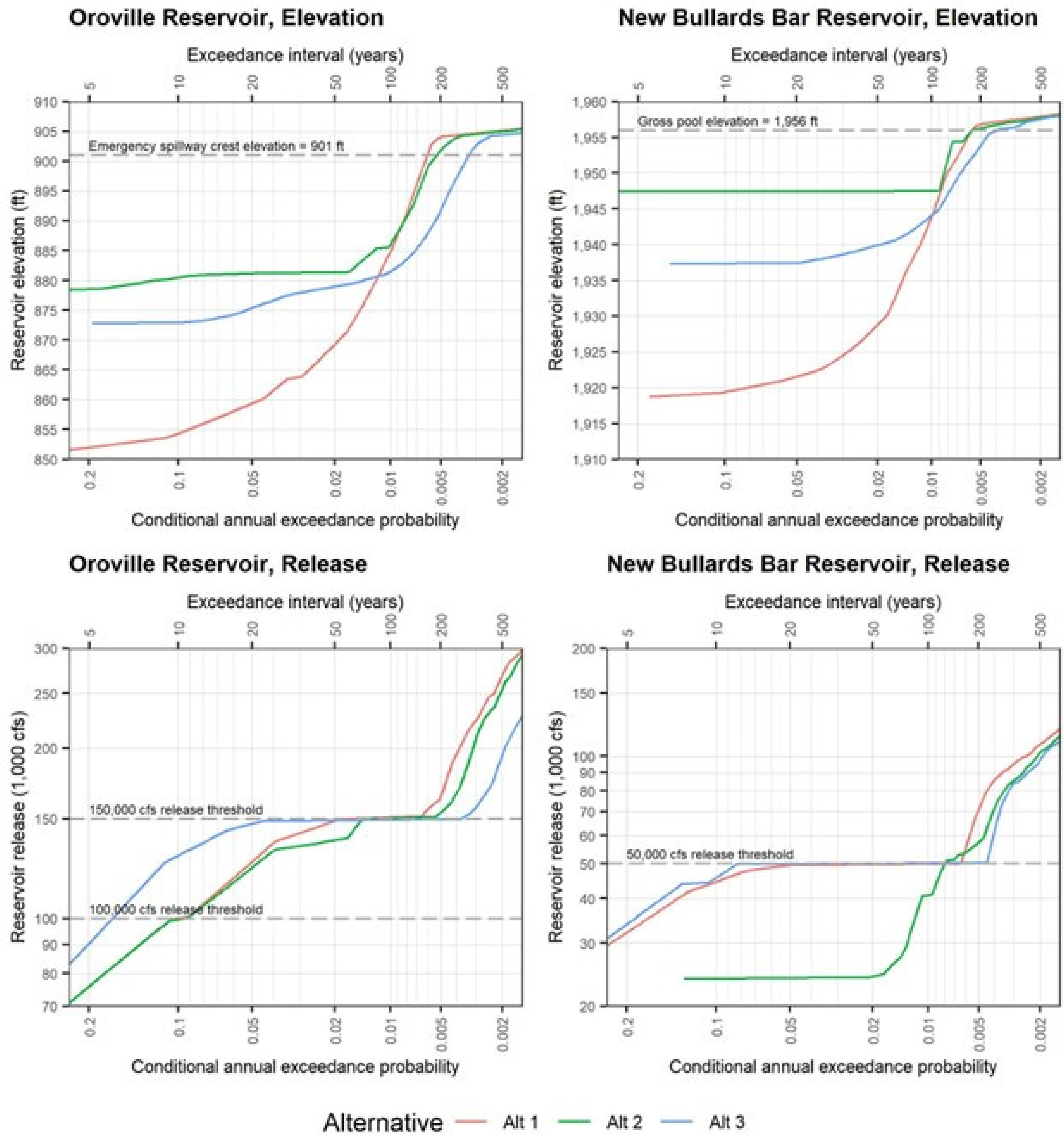


Figure 5-1. *Perfect forecast scenario: Comparison of FIRO alternative conditional frequency curves (Alt 2 and Alt 3) with baseline condition (Alt 1) for pool elevation-frequency and outflow-frequency curves at the reservoirs.*

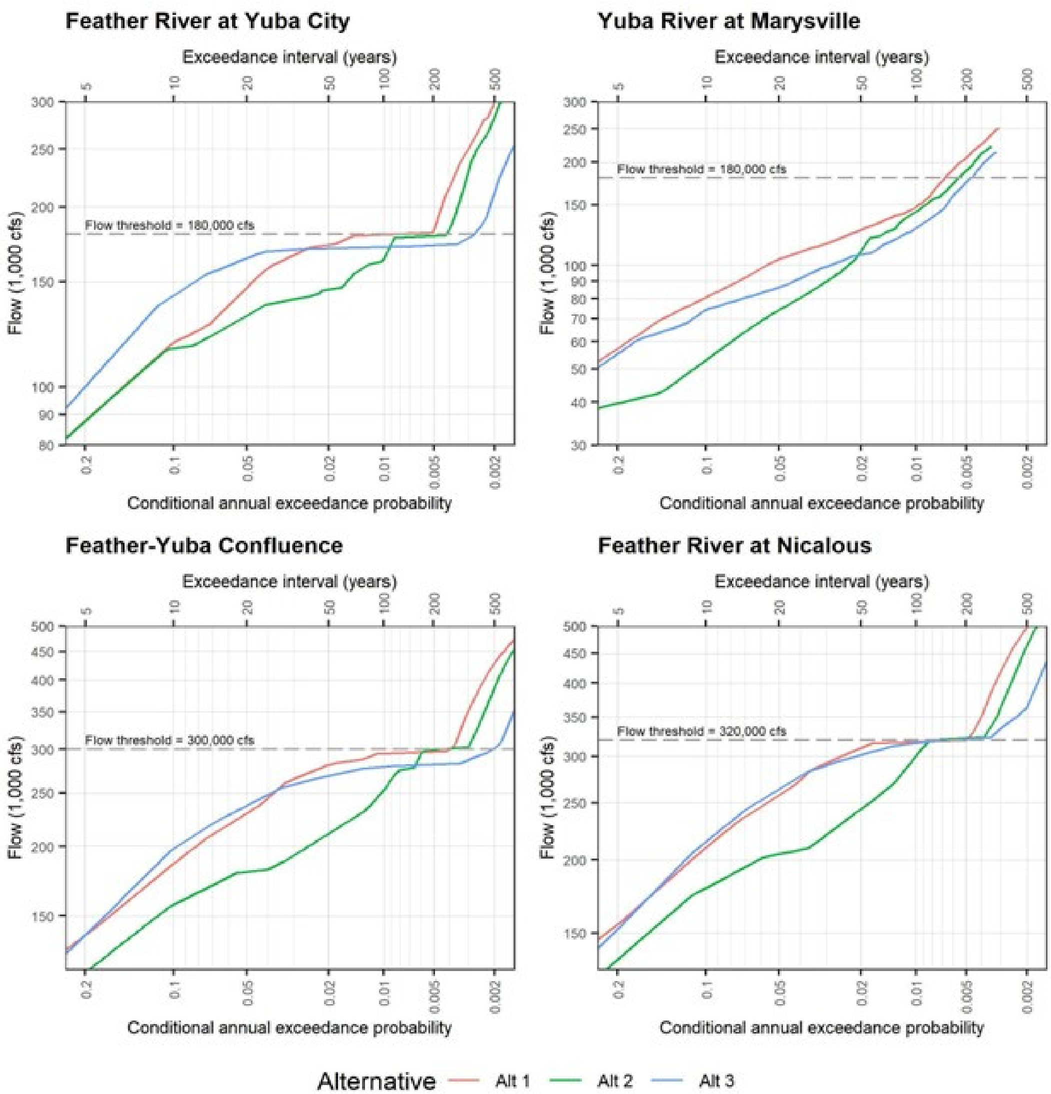


Figure 5-2. *Perfect forecast scenario: Comparison of FIRO alternative conditional frequency curves (Alt 2 and Alt 3) with baseline condition (Alt 1) for regulated flow-frequency curves at downstream locations.*

Table 5-3. *Perfect forecast scenario: Summary of unscaled event routing results for each alternative. Values that exceed key thresholds[a] are indicated in blue.*

		ORO Dam					NBB Dam					Englebright Dam	Max Flow by Location (cfs)			
Event	Alt	Start elev. (ft)	Max elev. (ft)	End elev. (ft)	Max inflow (cfs)	Max outflow (cfs)	Start elev. (ft)	Max elev. (ft)	End elev. (ft)	Max inflow (cfs)	Max outflow (cfs)	Max outflow (cfs)	Yuba City	Marysville	Feather-Yuba conf.	Nicolaus
1986	1	848.50	869.04	848.50	215,935	150,000	1,918.32	1,932.21	1,918.32	119,417	50,000	113,649	171,970	132,624	282,457	320,002
	2	875.40	880.81	875.40	215,935	133,211	1,941.89	1942.74	1941.84	119,417	37,016	100,253	143,426	118,690	249,836	289,631
	3	869.00	876.55	872.95	215,935	150,000	1,934.51	1938.14	1937.40	119,417	50,000	92,026	170,517	103,420	272,574	305,267
1997	1	848.50	890.87	848.50	320,472	150,000	1,918.32	1,953.01	1,918.32	104,480	50,000	130,436	177,797	139,230	291,692	319,484
	2	875.40	889.13	875.40	320,472	150,000	1,941.89	1952.26	1941.89	104,480	51,435	120,376	177,760	126,065	301,772	320,023
	3	869.00	884.71	869.00	320,472	150,000	1,934.51	1950.82	1934.51	104,480	50,000	121,922	168,444	124,804	278,768	319,890
2006	1	848.50	853.75	848.50	135,596	100,000	1,918.32	1,923.75	1,918.32	93,500	50,000	99,887	122,882	118,895	241,185	271,425
	2	875.40	880.24	875.40	135,596	100,000	1,941.89	1948.26	1941.89	93,500	18,064	52,143	122,432	71,533	193,795	223,396
	3	869.00	869.23	869.00	135,596	131,820	1,934.51	1941.38	1934.51	93,500	50,000	80,197	155,757	96,453	239,222	268,309
2017	1	848.50	870.56	848.50	155,635	112,398	1,918.32	1,918.97	1,918.32	40,571	40,571	79,140	120,090	94,634	204,890	227,661
	2	875.40	879.56	875.40	155,635	139,841	1,941.89	1945.20	1941.87	40,571	28,667	65,872	133,890	77,854	168,206	186,599
	3	869.00	870.75	869.00	155,635	150,000	1,934.51	1936.10	1934.51	40,571	48,938	72,331	158,511	81,016	237,690	259,172
SPF 1	1	848.50	903.79	898.68	443,820	172,555	1,918.32	1,950.99	1,927.16	89,775	50,000	50,489	180,476	146,158	309,972	308,307
	2	848.50	903.27	897.92	443,820	176,265	1915.30	1,946.03	1936.83	89,775	41,429	41,916	214,147	140,550	325,193	323,418
	3	848.5	899.53	897.30	444,000	150,000	1,918.32	1,956.60	1930.50	89,775	96,737	95,020	151,902	191,126	316,138	313,533
SPF 2	1	848.50	900.05	894.95	392,243	150,000	1,918.32	1,956.15	1,928.51	144,475	67,263	67,751	152,560	197,015	305,689	304,431
	2	848.50	896.62	891.83	392,244	150,000	1906.70	1,955.46	1941.12	144,475	36,512	36,999	177,154	156,263	313,780	309,175
	3	848.5	894.29	897.34	392,000	150,000	1,918.32	1,956.01	1930.17	144,475	50,952	51,442	153,173	182,463	306,191	304,032

a. Key thresholds are: 901 feet and 150,000 cfs outflow at ORO Dam; 1,956 feet and 50,000 cfs outflow at NBB Dam; 180,000 cfs at Yuba City; 180,000 cfs at Marysville; 300,000 cfs at the Feather-Yuba River confluence; and 320,000 cfs at Nicolaus.

Table 5-4. *Imperfect forecast: Summary of unscaled event routing results for each alternative. Values that exceed key thresholds[a] are indicated in blue. Elevations are in reference to NGVD 29.*

		ORO Dam					NBB Dam					Englebright Dam	Max flow by location (cfs)			
Event	Alt	Start elev. (ft)	Max elev. (ft)	End elev. (ft)	Max inflow (cfs)	Max outflow (cfs)	Start elev. (ft)	Max elev. (ft)	End elev. (ft)	Max inflow (cfs)	Max outflow (cfs)	Max outflow (cfs)	Yuba City	Marysville	Feather-Yuba conf.	Nicolaus
1986	1	848.50	889.06	848.50	292,112	150,000	1,918.32	1,939.41	1,918.32	74,576	50,000	109,543	164,641	119,118	274,651	312,528
	2	875.40	903.04	875.40	292,112	167,598	1,941.89	1,941.89	1,941.89	74,576	44,297	113,516	173,863	128,444	246,835	287,796
	3	869.00	880.33	868.04	292,112	150,000	1,934.51	1,934.76	1,934.60	74,576	44,226	100,840	168,470	114,144	282,416	319,478
1997	1	848.50	887.80	848.87	326,487	150,000	1,918.32	1,952.95	1,918.32	126,312	50,000	139,324	162,972	152,308	266,904	297,467
	2	875.40	896.95	875.40	326,487	150,000	1,941.89	1,955.49	1,941.89	126,312	37,927	130,546	160,516	145,486	291,774	321,971
	3	869.00	876.29	869.00	326,487	150,000	1,934.51	1,942.71	1,934.51	126,312	50,000	136,033	164,741	155,080	295,452	325,442
2006	1	848.50	853.75	848.50	135,596	100,000	1,918.32	1,923.75	1,918.32	93,500	50,000	99,887	122,882	118,895	241,185	271,425
	2	875.40	876.96	875.40	135,596	87,063	1,941.89	1,943.00	1,941.89	93,500	24,794	74,481	109,505	93,531	196,170	230,272
	3	869.00	869.00	866.10	131,435	76,474	1,934.51	1,934.54	1,934.51	93,500	36,588	52,035	77,831	64,659	141,273	174,886
2017	1	875.40	870.56	848.50	155,635	112,398	1,941.89	1,918.97	1,918.32	40,571	40,571	79,140	120,090	94,634	204,890	227,661
	2	875.40	901.15	875.40	155,635	100,786	1.941.89	1.943.25	1.941.87	40,571	34,926	70,038	102,472	83,117	173,195	189,592
	3	869.00	871.11	869.00	146,269	150,000	1.934.51	1.936.10	1.934.51	40,571	58,050	80,454	161,566	79,469	236,539	262,467

a. Key thresholds are: 901 feet and 150,000 cfs outflow at ORO Dam; 1,956 feet and 50,000 cfs outflow at NBB Dam; 180,000 cfs at Yuba City; 180,000 cfs at Marysville; 300,000 cfs at the Feather-Yuba River confluence; and 320,000 cfs at Nicolaus.

Alternatives 2 and 3 represent a range of potential FIRO strategies that demonstrated how FIRO could be implemented within the Yuba-Feather watersheds. Both strategies have shown value, and both need further refinement. The analysis completed for the PVA has helped inform the next steps of development by the WRE team in the FVA.

Note that the two alternatives represent different FIRO paradigms, but each also has different respective parameters, such as the specified range of FIRO Space at each reservoir and length of lead time used for initiating FIRO releases. These types of parameters can be modified for the FVA. Moving to the FVA, considerations for parameterizing alternatives include:

- What is the preferred range of pre-release volumes and lead-times at each reservoir?
- Is the operation constrained by operational delays or limitations in gate changes?
- What are the maximum bounds for FIRO Space at NBB; how does this transition into spring refill space?
- What size of event can necessitate the use of an enhanced flood pool? An event greater than SPF?
- What intermediate flow targets should/can be practically integrated into the FIRO release strategy? (Informed by WCM workshop series.)
- Does an advanced release limited by physical capacity raise any concerns?

5.6 Recommendations

The following next steps are recommended for the FVA:

- Further develop concepts for refining system operation. As demonstrated in the PVA results, refinement of the system operation may enhance flood risk management performance.
- Define the FIRO Space for each dam. In the PVA analysis, FIRO Space was delineated differently among the alternatives. The PVA results can inform specification of FIRO Space.
- Enhance consideration of uncertainty in forecasts of unregulated flows for FIRO alternatives. The routing results showed the significance of the uncontrolled flows below the reservoirs and their impact on reservoir releases. Both volume and timing should be considered. Forecast improvement efforts should focus on both inflow to the reservoirs and uncontrolled local flows.
- Continue to coordinate with USACE Sacramento District and integrate information from the WCM update projects. This information may include specification of intermediate release thresholds, fall drawdown and spring refill curves, emergency spillway release diagram alternatives, and updated hydrology.
- Use updated GEFSv12 hindcasts for evaluations, if available.
- Conduct additional water supply impact evaluations.
- Consider further refining forecast uncertainty.
- Consider including resiliency to climate change as an evaluation metric.
- Assess additional considerations for alternatives such as practicality for real-time use, including runtime, ability to backcheck model computations, emergency operation, and need for integration into F-CO and Corps Water Management System decision support systems.
- Develop ideas for describing FIRO Space and FIRO 2.0 in the WCMs.

5.7 References

David Ford Consulting Engineers. (2008). Oroville–New Bullards Bar Forecast-Coordinated Operations: Decision Support System Technical Documentation. Prepared for Yuba Water. Dec. 12.

USACE. (1970). *Oroville Dam and Reservoir: Report on reservoir regulation for flood control.* SPK. August.

USACE. (1972). *New Bullards Bar Reservoir: Reservoir regulation for flood control.* SPK. June.

Section 6. Studies and Research in Support of PVA

The Yuba-Feather PVA stands on a foundation of extensive scientific research on meteorology, hydrology, observational capabilities, and forecast skill assessment capabilities. This work has focused on the atmospheric river (AR) storms that produce most of the Yuba-Feather watersheds' precipitation—rain and snow—driving both beneficial water supply and flood risk.

The research discussed in this section centers on improving forecasts and their use in decision making by combining the rigor of established engineering testing protocols with the strengths of scientific studies and peer review. At the core of this research lie a well-established, successful operational framework, created by the California Nevada River Forecast Center (CNRFC) at the National Weather Service (NWS), financial, human capital, and political support for scientific advancement, and a willingness to collaborate.

This foundation of research benefits from a collaborative research and operations partnership (RAOP) approach among scientists, engineers, and water managers. Figure 6-1 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 research and operations 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 Lake Oroville (ORO) and North Bullards Bar (NBB).

FIRO links hydrologic prediction to its meteorological drivers, grounded by model forcings derived from observations and knowledge of the quality of the forecast information, addressing both quantitative and qualitative pathways for operational forecast improvement. Understanding the physical processes and quantifying the predictability of extreme events in the Yuba-Feather watersheds will better inform meteorological situational awareness and confidence in hydrometeorological forecasts for improved decision support for reservoir management. Sections 6.1 through 6.4 provide details about these efforts and other relevant advances.

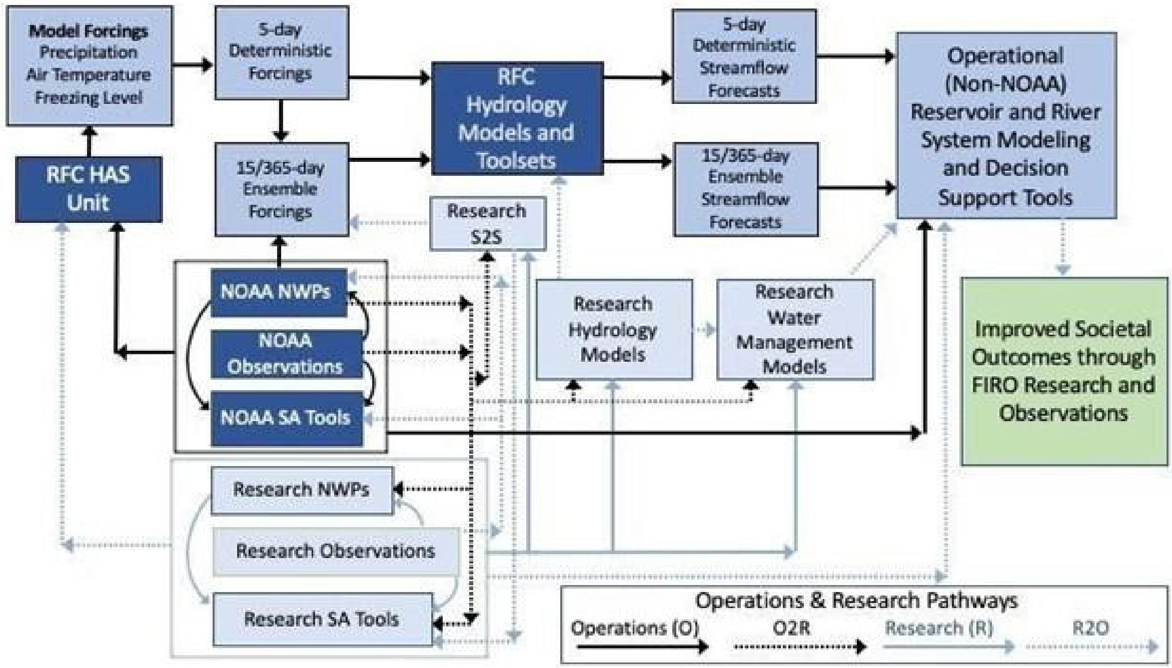


__Figure 6-1.__ Operations and research pathways concept as applied to Yuba-Feather FIRO.

6.1 Meteorological Analysis, Assessment, and Research

Meteorology analysis, assessment, and research characterized the watershed precipitation over the Upper Yuba and Feather River watersheds and its association with landfalling ARs. Characteristics of landfalling ARs—such as integrated water vapor transport (IVT) magnitude; direction; intensity; duration; and mesoscale features such as the presence of mesoscale frontal waves, barrier jets, narrow cold frontal rainbands, or variable freezing levels used in demarking rain versus snow—were investigated to identify features that strongly influence precipitation and streamflow extremes and predictability within the watersheds. Case studies and numerical modeling of individual events and collections of events reveal common sources of uncertainty that span the mesoscale to the synoptic scale at lead times of two to seven days before high-impact events and show that uncertainty varies by event type, lead time, and location. Modeling initiatives using the Center for Western Weather and Water Extremes (CW3E) West-WRF model and development of forecast tools have leveraged these analyses, this assessment, and this research for decision support and situational awareness for FIRO.

Meteorological research tasks pursued through the PVA in support of FIRO include:

- Development of a climatology of watershed precipitation and IVT magnitude and direction that best correlates with precipitation over the Yuba-Feather watersheds (as in Ricciotti and Cordeira 2022).
- Investigation of AR intensity and duration on the non-linear increase in precipitation and reservoir inflows in the Yuba-Feather region.

- Investigation of the synoptic and mesoscale processes related to the ARs and the large-scale flow to describe the conditional dependency of precipitation forecasts with lead time.
- Identification of essential atmospheric structures during AR Recon activities (2021 and 2022) associated with forecast uncertainty in landfalling ARs (Wilson et al. 2022), including features that span mesoscale to synoptic scales over the North Pacific basin.
- Expansion of West-WRF's modeling capabilities and implementation of a 200-member ensemble to improve the forecast characterization of extremes in landfalling ARs and their potential impacts.
- Design and implementation of multi-model, ensemble-derived, and watershed-centric forecast tools at CW3E to improve situational awareness and decision support of the FIRO process.
- Investigation of the probabilistic prediction of IVT with deep learning (as in Chapman et al. 2022).

6.1.1 AR Characteristics and Precipitation Mechanisms

Water resources in the western United States are highly dependent upon precipitation that varies greatly on daily, monthly, and annual timescales (Dettinger et al. 2011). Each year, about half of the precipitation in the Yuba-Feather watersheds falls over 85–100 hours (Lamjiri et al. 2018) on about 15 calendar days (Dettinger et al. 2011).

How much annual precipitation in the Yuba-Feather watersheds is associated with ARs?

According to Dettinger et al. (2011), landfalling ARs are the source of about 40 percent of the region's total annual precipitation and about 30–40 percent of the region's total annual streamflow. An updated climatology by Ricciotti and Cordeira (2022) using Oregon State's PRISM precipitation dataset for HUC-8 mean areal precipitation (MAP) produced similar statistics for the Yuba-Feather watersheds (Table 6-1), with more than 60 percent of annual precipitation falling on days with landfalling ARs.

Table 6-1. *Watershed mean annual precipitation summary for Yuba-Feather watersheds. Table adapted from Ricciotti and Cordeira (2022).*

Watershed	Precipitation Characteristics				Correlation (r^2) Between IVT/Water Vapor and Precipitation			
	Average Annual MAP	Percent of Precip. from Extremes (Top 5%)	# Days to Receive 50% of Annual	Percent on AR Days (~28 Days per Year)	IVT Magnitude and Precip.	Projected IVT Magnitude and Precip.	Projected 850-hPa Water Vapor Flux and Precip.	Projected 925-hPa Water Flux and Precip.
Upper Yuba	1619mm (63.7″)	36%	16	63%	0.44	0.60	0.65	0.66
North Fork Feather	1394mm (54.9″)	34%	16	66%	0.46	0.61	0.65	0.65
Middle Fork Feather	1174mm (46.2″)	37%	16	64%	0.43	0.60	0.64	0.65
EB North Fork Feather	842mm (33.1″)	36%	16	65%	0.38	0.54	0.56	0.57

How do ARs influence extreme precipitation events?

More than 80 percent of long-duration and high-intensity precipitation events in California, including over the Yuba-Feather watersheds, are associated with ARs (Figure 5 of Lamjiri et al. 2017) and almost all three-day precipitation events exceeding 300 mm (~12 inches) in Northern California are also associated with ARs (Figure 6 of Lamjiri et al. 2020). Drawing on that information and the Ralph et al. (2019) AR scale, Lamjiri et al. (2020) identified that more than 60 percent of three-day precipitation events over 200 mm (~8 inches) were associated with weak-to-moderate AR1–2 events, whereas about 60 percent of three-day precipitation events over 300 mm (~12 inches) were associated with strong-to-exceptional AR3–5 events. The three-day precipitation threshold is widely used in studies seeking to quantify the probable maximum precipitation (WMO 2009) and also correlates best with unregulated river discharge over West Coast basins (Warner et al. 2012). In other words, larger three-day precipitation events are associated with more intense and longer-duration landfalling ARs, and subsequently larger river discharges.

Why do some ARs produce extreme precipitation events while others do not?

The precipitation in a landfalling AR is maximized where the AR path is perpendicular to terrain. The daily IVT magnitudes associated with landfalling ARs in California only explain about 45 percent of the variance in daily watershed MAP in the Yuba-Feather watersheds (Table 6-1; Ricciotti and Cordeira 2022). When the direction of the IVT magnitude is also taken into account, this value increases to about 60 percent for landfalling ARs near the San Francisco Bay Area with southwesterly IVT (Table 6-1) and close to 70 percent during the cool season only (not shown). In other words, the water vapor flux magnitude and direction associated with landfalling ARs is a crucial ingredient that explains a large majority of the variance in daily precipitation in the Yuba-Feather watersheds.

Storm intensity and duration also affect AR-related precipitation. The PVA meteorology team conducted a revised analysis originally based on the work of Cunningham and Cordeira (2019) that investigated the IVT associated with landfalling ARs of different intensities and durations following the Ralph et al. (2019) scale. The study used IVT data in the North-Central Valley at 39°N, 121.875°W (west-southwest of Yuba City) and cross-referenced AR start times with hourly precipitation at Brush Creek, California, within the Feather River watershed and California Data Exchange Center (CDEC) hourly derived inflow into ORO for water years (WYs) 1998–2017. Whereas average five-day time-integrated IVT magnitudes were 51 percent larger for AR3–events than AR1–2 events, the average five-day time-integrated precipitation and inflow volumes were 145 and 173 percent larger, respectively (Figure 6-2). The latter five-day average accumulated inflow volume into ORO was about 98,050 acre-feet (ac-ft) associated with AR1–2 events and 268,071 ac-ft associated with AR3–5 events, affirming that more intense and longer-duration ARs following the Ralph et al. (2019) AR scale produce significantly more precipitation and larger reservoir inflows than less intense, shorter-duration ARs in the Yuba-Feather region of California.

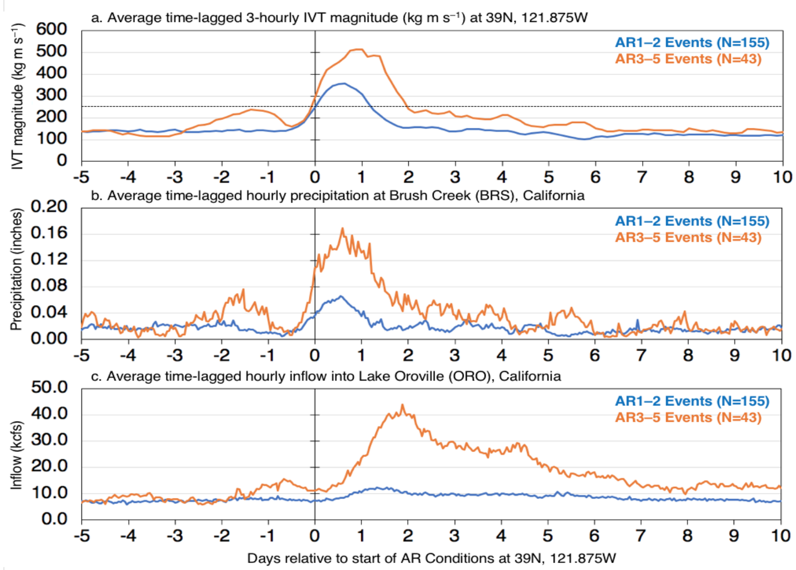


Figure 6-2. *Time-lagged average time series of (a) three-hourly IVT magnitude; (b) hourly precipitation at Brush Creek, California; and (c) hourly inflow into Lake Oroville, California, for AR1–2 events (blue) and AR3–5 events (orange) lagged relative to the start date of AR conditions at 39°N, 121.875°W.*

What other factors influence precipitation and streamflow during a landfalling AR?

In addition to IVT magnitude and direction, precipitation and streamflow in a landfalling AR in the Yuba-Feather watersheds may be influenced by several meteorological processes that vary from one event to the next (and are themselves affected by other mesoscale and microphysical processes). Among these processes are:

- Water vapor flux altitude (Ralph et al. 2013; Hecht and Cordeira 2017; Ricciotti and Cordeira 2022).
- Precipitation shadowing from the upstream topography of the Coast Ranges and precipitation enhancement due to water vapor flux through terrain gaps (e.g., Neiman et al. 2004).

- Development of a mesoscale frontal wave (e.g., Martin et al. 2019; Michaelis et al. 2021) or successive AR events (e.g., AR families; Fish et al. 2022).
- Development of a Sierra Barrier Jet (e.g., Ralph et al. 2003; Neiman et al. 2002, 2013; Hughes et al. 2014; Rutz et al. 2014; White et al. 2015; Lamjiri et al. 2018).
- Development of a narrow cold frontal rainband, or NCFR (e.g., Ralph et al. 2011; Cannon et al. 2020) or regions of enhanced convergence that can lead to intense precipitation within a landfalling AR.
- Variability in the altitude of the freezing level and rain/snow transition (Henn et al. 2020; Sumargo et al. 2020).
- Variability in cloud microphysics, such as the seeding of orographic precipitation from higher-altitude precipitation (e.g., Browning 1980; Hill 1983; Neiman et al. 2002; Ralph et al. 2003; Creamean et al. 2013).

Appendix M provides more details on these processes. Table 6-2 highlights how some of them have been involved in six recent landfalling ARs that affected the Yuba-Feather watersheds.

Table 6-2. *Summary of meteorological and hydrometeorological characteristics of six recent landfalling ARs to affect the Yuba-Feather watersheds.*

Event	Coastal AR Scale	Upper Yuba Mean Areal Precip	Narrow Cold-Frontal Rainband	Mesoscale Frontal Wave	Sierra Barrier Jet	Lowest Freezing Level	Highest Freezing Level	Yuba River @ Marysville Peak Stage
Source/units:	ERA5	Inches	Composite Radar	NCEP GFS Analyses	Chico/Oro Profilers	kft	kft	ft
7–9 Jan 2017	5	8.3	✗	✓	✓	8.5	9.5	85
7–12 Feb 2017	5	12.5	✗	✓	✓	8.5	9.5	85
13–15 Feb 2019	4	7.2	✓	✓	✓	4.0	9.5	75
26–29 Feb 2019	3	7.5	✗	✓	✓	4.0	7.0	74
26–29 Jan 2021	2	4.7	✓	✓	✓	1.5	2.5	62
23–25 Oct 2021	5	11.6	✗	✗	✓	7.0	11.0	70

6.1.2 Case Studies Illustrating AR Characteristics and Predictability

Of practical importance is whether landfalling ARs' characteristics are predictable at lead times that will make it possible to provide enhanced situational awareness, or actionable quantifiable information, for FIRO. Several studies have quantified the ability of numerical models to predict landfalling ARs, while others have focused on the large-scale processes that influenced forecast uncertainty in the subsequent AR landfall characteristics (e.g., orientation, intensity, duration) or mesoscale-to-microphysical processes that influenced the forecast uncertainty in associated precipitation. This section describes some of these studies; Section 6.4, below, provides an overview of verification statistics.

6.1.2.1 February 2019 “Valentine’s Day” AR

The February 15–15, 2019, “Valentine’s Day” AR ranked as an AR3 on the Ralph et al. (2019) scale along most of the California coast and reached AR4 intensity in Southern California. The long duration and dynamically favorable characteristics of the AR produced heavy precipitation and disruptive snowfall (Hatchett et al. 2020). Multiple synoptic-to-mesoscale features interacted to promote the formation, evolution, and intensity of the AR, including:

- **Synoptic-scale:** A northern-stream amplifying 500-hectopascal (hPa) trough interacted with a quasi-stationary southern-stream cyclone and tropical moisture export over the northeast Pacific to promote the initial formation of the AR and direct it toward California.
- **Mesoscale:** The development and intensification of a mesoscale frontal wave and secondary cyclone along the northeastern flank of the AR promoting the intensification and lengthening of the duration of AR conditions.

Hecht et al. (2022) examined the ensemble forecasts of these key features that contributed to uncertainty in the AR itself and downstream impacts using the global ensemble prediction systems of the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) and European Centre for Medium-Range Weather Forecasts (ECMWF) models (i.e., GEFS and EPS, respectively). Ensemble forecasts of AR landfall were both sensitive to the structure and evolution of the 500-hPa trough over the northeast Pacific: forecasts that accurately predicted the development of the trough were the first forecasts to also increase the likelihood of subsequent AR landfall. Similarly, neither GEFS or EPS accurately predicted the development and intensification of the mesoscale frontal wave, and therefore failed to predict an earlier AR landfall, longer duration of AR conditions, more intense AR at landfall, and 200–300 percent higher watershed precipitation totals over the Upper Yuba watershed at lead times over two days. Accurate precipitation forecasts at lead times over two days were highly dependent upon a combination of both synoptic and mesoscale processes related to the AR and the large-scale flow. A graphical summary of the results of Hecht et al. (2022) is provided in Appendix M.

6.1.2.2 January 2021 AR

The January 26–28, 2021, AR ranked as an AR2 on the Ralph et al. (2019) scale and produced heavy rain and snow throughout much of California. The stalling of the AR along the coast focused upslope moisture flux in central California where the Upper Yuba watershed received 4.6 inches of MAP in a 72-hour period and over 4 feet of high-elevation snow. The landfalling AR also contained an NCFR that led to destructive flooding and debris flows in Monterey County and was associated with large multi-model forecast uncertainty at lead times of more than five days. The large forecast uncertainty may be summarized as follows:

- At lead times of two to three weeks, CW3E’s Week-3 AR activity forecast derived from NCEP ensemble data initialized on January 11, 2021, illustrated a far-above-normal potential for AR activity over central California from January 26 to February 1; the forecast derived from ECMWF ensemble data illustrated a much lower potential.
- At lead times of about six to eight days, CW3E’s AR Landfall Tool illustrated an over-80-percent likelihood of a landfalling AR over central California on January 26–28 using NCEP ensemble data initialized on January 20. Using ECMWF ensemble data, the same tool illustrated a probability below 25 percent.

- At lead times of seven days, IVT magnitude forecasts derived from the NCEP deterministic model initialized on January 21 nearly matched verification in magnitude and position, while the forecasts derived from the ECMWF deterministic model failed to even resolve a landfalling AR.

The stalling and pivoting of the AR over central California prolonged precipitation duration and was a source of ensemble uncertainty (R. Torn, personal communication, 2021).

The associated differences in forecasted IVT and AR characteristics contributed to large differences in forecasted precipitation; forecasts initialized on January 21 by ECMWF were far too low as compared to GFS forecasts and verification. Discussions of this event during AR Recon suggested the forecast uncertainty was derived from the interaction of synoptic-scale features over the western and central North Pacific more than one week before the AR formed. Accurate precipitation forecasts at lead times of two to seven days before this case were highly dependent upon synoptic-scale processes over the central and northeast Pacific related to the large-scale flow and mesoscale processes at landfalling related to the stalling and pivoting of the AR.

This event shows how AR Recon can improve prediction skill through better observation of key features upstream over the North Pacific, as well as the importance of using multi-model ensembles in the FIRO process. A graphical summary of the results is provided in Appendix M.

6.1.2.3 October 2021 AR

A series of three landfalling ARs between October 19 and 26, 2021, culminated with a landfalling AR in central and Northern California that ranked as an AR5 on the Ralph et al. (2019) scale; it was the strongest October AR in 40 years at San Francisco and, overall, the strongest since January 2017. Portions of Northern California received more than 15 inches of total precipitation from the three storms. Intense rainfall on October 24 caused flooding in the Bay Area, triggered multiple landslides in Northern California, and set a daily rainfall record in the Northern Sierra 8-Station Index. Consistent with Ralph et al. (2016), this extreme daily precipitation event occurred in association with a landfalling AR and the formation of a strong south-southeasterly Sierra Barrier Jet over 70 knots. Although there was heavy rain, reservoirs only saw small increases in storage due to dry antecedent conditions; ORO storage only increased by 176,000 ac-ft (about 5 percent of capacity).

While many of the storms described above are associated with short- and longer-lead-time forecast uncertainty, the third and strongest AR in this series was well forecasted out to three days' lead time, with the presence of the AR well forecasted out to six days. Similarly, mesoscale characteristics of the AR such as landfall location and freezing level were forecasted particularly well. CNRFC forecasts generally captured a rapid drop in the height of the freezing level up to four days prior across the Yuba-Feather watersheds (Figure 2-3). The magnitude and rate of change in freezing levels were accurately predicted at lead times of one to four days at ORO, with small biases during periods of warm air advection at the onset of the storm. The results of this case study demonstrate the importance of antecedent conditions on AR-related precipitation impacts and highlights the types of prediction skill and lead times that are possible for well-forecasted events.

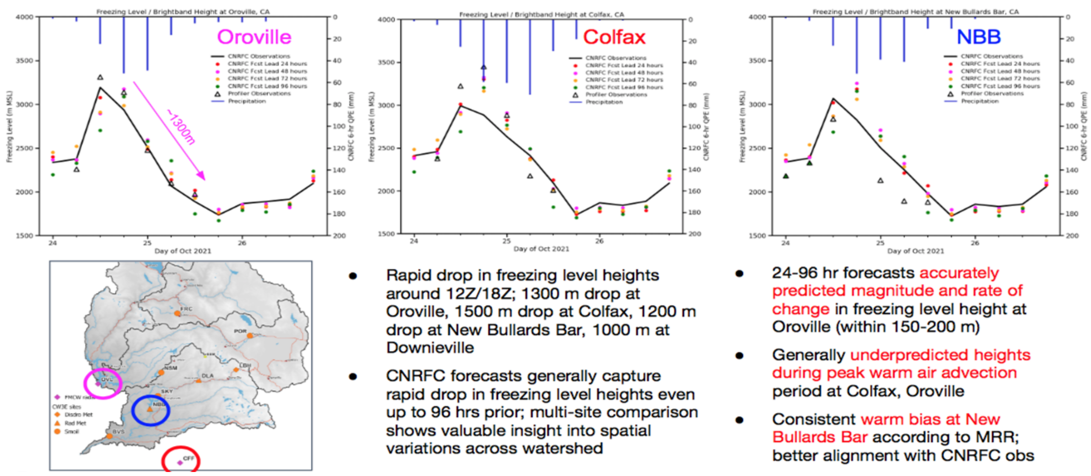


Figure 6-3. *Verification statistics for CNRFC freezing level forecasts during the October 2021 landfalling AR event at ORO, Colfax, and NBB with annotations by CW3E.*

6.1.2.4 Landfalling ARs During Winter 2017 and 2019

The record wet 2017 and 2019 WYs were evaluated by Cannon et al. (in review) using hindcast forecasts based on the 64-member West-WRF ensemble forecast model. To establish sources of forecast uncertainty, the ensemble's representation of the meteorology of landfalling ARs and precipitation was compared to field campaign observations and operational quantitative precipitation estimates Analyses of multiple impactful flooding events within the study period demonstrated that, *on average:*

- The representation of orographic forcing was a primary error source at longer lead times.
- At shorter leads when AR characteristics were often well represented, challenges in simulating orographic precipitation efficiency dominated model bias.

Importantly, the influence of individual sources of uncertainty varied by event type, lead time, and location. Cannon et al. (in review) underscore the need to identify conditional dependence in order to better understand sources of uncertainty. In other words, are there specific storm characteristics of some landfalling ARs that may lead to better or worse predictability than others?

6.1.3 Forecast Diagnostics and Sources of Uncertainty (AR Recon)

CW3E leads AR Recon to address sources of uncertainty within ARs over the northeast Pacific. The overall goal of AR Recon is to support water management decisions and flood forecasting by using targeted airborne and buoy observations over the northeast Pacific to improve analysis and forecasts of landfalling ARs and their impacts on the U.S. West Coast at lead times of zero to five days (see Appendix M for more background). With the knowledge gained via AR Recon and capacity provided by FIRO, CW3E can interpret, analyze, and develop new diagnostics to evaluate the dynamics, forecasts, and uncertainty of landfalling ARs that are of particular interest to reservoir operations in the Yuba-Feather watersheds. In WY 2022, AR Recon conducted 32 flights over 25 Intensive Observing Periods, releasing a total of 687 dropsondes.

50 drifting buoys with surface pressure instruments were added to the northeast Pacific. This effort also included a weather briefing and post-event summary presentation with FIRO partners in advance of the high-impact landfalling AR in October 2021, at which CW3E highlighted many AR-related and precipitation-related forecast diagnostics spanning global and regional numerical weather prediction (NWP) models and a special run of the CW3E West-WRF model. Examples of these diagnostics included thermodynamic and kinematic forecasts illustrating the Sierra Barrier Jet during AR landfall and IVT forecasts illustrating the extreme intensity of the storm (Figure 6-4).

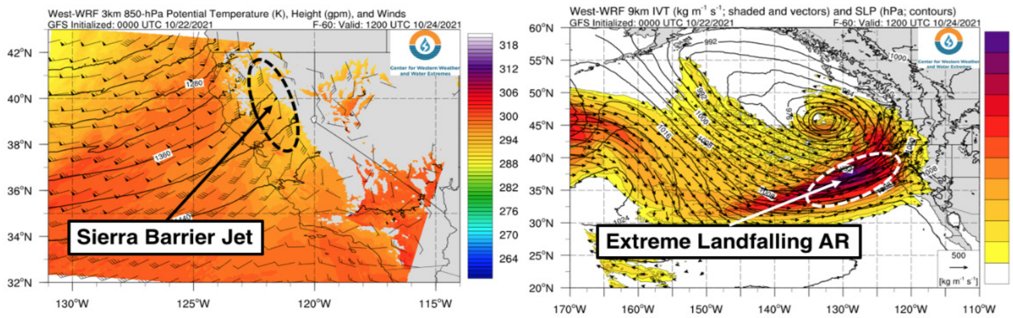


Figure 6-4. West-WRF forecasts initialized at 0000 UTC on October 22, 2021, valid at 1200 UTC October 24, 2021, illustrating (a) the Sierra Barrier Jet in the 850-hPa wind field and (b) the extreme intensity of the landfalling AR in the sea-level pressure and IVT field.

6.1.4 West-WRF Improvements

CW3E has developed an optimized version of the Weather Research and Forecasting model (Skamarock et al. 2008; Powers et al. 2017), named West-WRF, that is run in near real-time (NRT) forecast mode in support of FIRO and scientific research of extreme weather events over the western United States (Ralph et al. 2016; Cordeira et al. 2017). The 2021–2022 (WY2022) NRT features several additions and improvements upon previous NRT simulations, for both technical and scientific purposes:

- Four sets of West-WRF NRT simulations run on the Comet supercomputer at the San Diego Supercomputer Center. These simulations include four WRF simulations: two based on the NCEP GFS (one on a version from 2020 frozen for machine learning purposes, another based on a new version from 2022), one based on the ECMWF HRES, and one that leverages the GFS and ECMWF ensemble forecasts for a 200-member ensemble.
- An expanded 3-km domain, now including all of the U.S. West Coast for WY2022 (Figure 6-5), to both capture the precipitation field from ARs making landfall in Northern California and be less subject to domain boundary interference as ARs propagate north to south.
- Increased vertical resolution from 60 to 100 levels to better capture the lower troposphere where key AR-related physical processes such as the Sierra Barrier Jet occur (Figure M-1).
- Improved snowpack initialization by ingesting a daily 4-km snow product from the University of Arizona (Broxton et al. 2016; Zeng et al. 2018; Broxton et al. 2019).
- Adjustments to the West-WRF parameterization schemes, including the Thompson microphysics scheme (Thompson et al. 2008) focusing on cloud droplet concentration and

auto conversion parameters for better representation of West Coast orographic precipitation and precipitation efficiency.

- Expanded ensemble size from 48 members in WY2021 to 200 members in WY2022. This led to better statistical sampling of the key sources of uncertainty that negatively impact NWP (e.g., initial conditions and physics parameterizations). The larger ensemble also resulted in improved forecast skill for the ensemble mean and a greater likelihood of predicting the timing and magnitude of extreme AR events that lead to flooding and debris flows.

Appendix M describes these additions and improvements in more detail.

6.1.5 Refinement of Decision Support System Visualizations

In 2020–2022, several numerical advances within the meteorological community, and at CW3E, led to a refinement of existing tools and development of new forecast tools in support of decision support services and FIRO:

- Global deterministic and ensemble models were expanded to higher resolutions (e.g., below 25 km) and ensemble members were added.
- ECMWF deterministic and ensemble data became available and were acquired through a research and operations partnership.
- CW3E gained access to and took operational control of the COMET supercomputer.
- CW3E developed and implemented a 200-member high-resolution West-WRF ensemble.

Through collaboration and coordination with the Yuba Water, the California Department of Water Resources, and the NWS California-Nevada River Forecast Center, several tools were developed, modified, or expanded to better serve decision making in the Yuba-Feather watersheds:

- The AR Landfall Tool was expanded to contain more GFS ensemble members, ECMWF-derived and West-WRF-derived forecast information, and a "Sierra foothills transect."
- Deterministic and ensemble-based forecast products were expanded to include the ECMWF model and multi-model comparisons. This included creation/expansion of AR-scale tools, time series, and probabilistic quantitative precipitation forecasts (QPFs) for point and watershed locations within California and the western United States to leverage the GFS, ECMWF, and West-WRF forecasts.

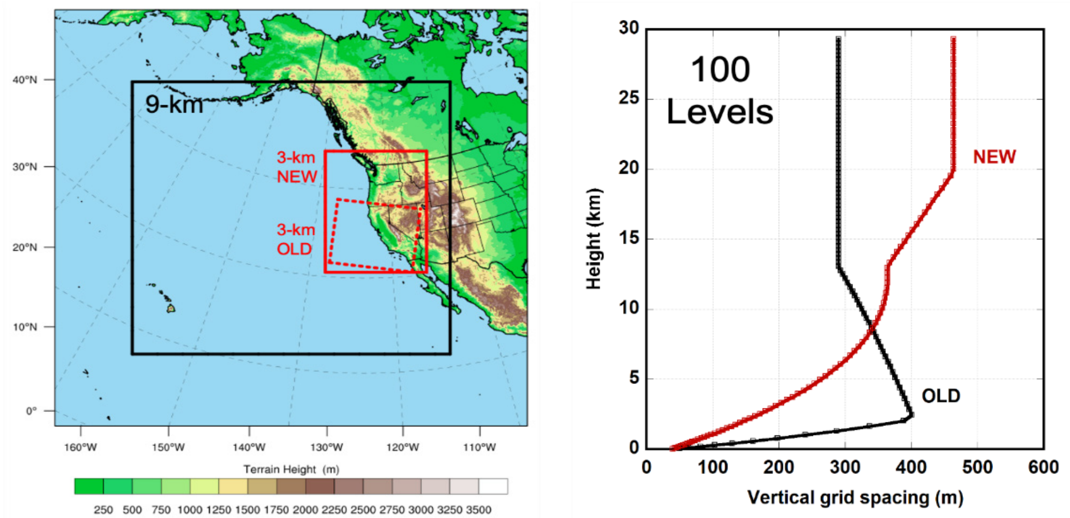


Figure 6-5. *Left: West-WRF NRT WY2021–2022 domains, with terrain height (shaded, m) and vertical level grid spacing as a function of height (red) compared to the previous configuration (black). Right: old versus new vertical grid spacing as a function of altitude.*

6.1.6 Machine Learning Predictive Capabilities

CW3E is focused on developing creative, novel approaches for skillful forecasts to support FIRO at the Yuba-Feather watersheds. One such avenue is applying machine learning algorithms to develop predictive models and decision support tools. The most recent phase of this effort (relevant to FIRO) focuses on probabilistic predictions of IVT, short-range prediction of precipitation using innovative deep learning techniques, and convolutional neural networks to capture spatial precipitation patterns:

- Chapman et al. (2022) studied deep learning post-processing methods to obtain reliable, accurate probabilistic forecasts of IVT in ARs. Results show that these methods compete with or outperform the calibrated GEFS system at lead times out to five days.
- Hayatbini et al. (2022) focused on post-processing NWP predictions to improve the accuracy of short-range rainfall prediction.
- Badrinath et al. (2022) proposed to identify and reduce biases affecting predictions of a dynamical model using a machine learning method based on spatial convolution to capture complex spatial precipitation patterns. Results yield a reduction in root-mean-square error (RMSE) of about 15 percent and about a 3 percent improvement in Pearson correlation over West-WRF for lead times of one to four days; the latter effectively adds more than a day of predictive skill when compared to West-WRF.

See Appendix M for more details.

6.1.7 Findings

Meteorology analysis, assessment, and research on landfalling ARs and watershed precipitation in the Yuba-Feather watersheds have identified several key characteristics of ARs that may lead to hydrometeorological forecast uncertainty spanning lead times from two days to more than seven. Many of these key characteristics, such as upstream interactions among the synoptic-scale flow, landfalling IVT magnitude and direction, and mesoscale features such as the Sierra Barrier Jet or NCFRs, (1) were explored via case studies, (2) provided a locus for NWP modeling studies and forecast tool development, and (3) were identified as essential atmospheric structures during AR Recon. The results of Cannon et al. (in review) importantly demonstrate that the influence of individual sources of uncertainty in precipitation forecasts varied by event type, lead time, and location and underscore the need to further identify conditional dependence to better understand sources of uncertainty.

A comprehensive list of key findings is provided in the box below.

Key Findings

- Extreme events are responsible for a large majority of the interannual variability in precipitation over the Yuba-Feather watersheds.
- More than 80 percent of long-duration and high-intensity precipitation events in the Yuba-Feather watersheds are associated with ARs.
- More intense and longer-duration ARs following the Ralph et al. (2019) AR scale produce a ~150 percent larger increase in precipitation and reservoir inflows than less intense and shorter-duration ARs in the Yuba-Feather watersheds.
- Water vapor flux magnitude and direction explain a large majority of the variance in daily precipitation in the Yuba-Feather watersheds.
- The Sierra Barrier Jet modulates precipitation across the west slope of the Sierra Nevada, including the Yuba-Feather watersheds, during a majority of landfalling ARs that produce the region’s most extreme precipitation.
- Landfalling ARs often contain variable freezing levels and/or large forecast errors in the height of the freezing level that can lead to errors in precipitation and streamflow forecasts.
- Case studies and AR Recon activities demonstrate that accurate precipitation forecasts at lead times over two days are highly dependent on a combination of both synoptic and mesoscale processes related to the AR and the large-scale flow; uncertainty varies by event type, lead time, and location. Information from offshore reconnaissance helps address these dependencies in ways that lead directly to immediate and event-specific forecast improvements.
- A 200-member West-WRF ensemble improves representation of the probability distribution of precipitation and precipitation extremes during landfalling ARs.
- Deep learning methods compete with or outperform the calibrated Global Ensemble Forecast System at lead times out to five days for landfalling ARs, generating reliable and skillful probabilistic forecasts (Chapman et al. 2022).
- A modified U-Net convolutional neural network (CNN) that post-processed daily accumulated precipitation over the U.S. West Coast added more than a day of predictive skill compared to the West-WRF model. The CNN outperforms other existing methods for the prediction of extreme events, highlighting a promising path forward for improving precipitation forecasts (Badrinath et al. 2022).

6.1.8 Recommendations

Following the recommendations below will enhance the benefits of FIRO by improving inflow volume/streamflow forecast accuracy and lead-time specific operations for ORO and NBB:

- Develop an extended catalog of landfalling AR and precipitation characteristics affecting the Yuba-Feather watersheds to identify systematic sources of forecast uncertainty as a function of lead time and physical processes.
- Analyze the resolution and skill of mesoscale and microphysical processes in NWP (such as the Sierra Barrier Jet or precipitation efficiency).
- Investigate forecast characteristics of landfalling ARs that lead to systematic sources of precipitation forecast biases (e.g., cold bias in freezing level).
- Keep AR Recon in place each year, with continued focus on improvements in flight targeting techniques, evaluation of different forecast sensitivity metrics, assimilation methodologies, and innovative data collection. The Final Viability Assessment (FVA) should assess its impact on forecasts of precipitation in the Yuba-Feather watersheds.
- Review lead-time predictability of landfalling ARs specifically for the Yuba-Feather watersheds, including lead-time prediction of specific events.
- Continue to evaluate the effectiveness of the West-WRF ensemble in probabilistic and extreme precipitation forecasts over the Yuba-Feather watersheds.
- Leverage reforecast or hindcast datasets (e.g., West-WRF) to improve precipitation forecasts over the Yuba-Feather watersheds.
- Incorporate forecast information from West-WRF into new forecast tools such as watershed precipitation (Yuba-Feather catchments), freezing level, and barrier jet.
- Continue to explore and develop novel AI/machine learning methods to improve AR, ridge, precipitation, and freezing-level forecasts and help improve AR forecast lead times.
- Explore methodologies to investigate the influence of climate change on FIRO at ORO and NBB.

6.1.9 References

Badrinath, A., Delle Monache, L., Hayatbini, N., Chapman, W., Cannon, F., & Ralph, F. M. (2022). *Improving precipitation forecasts with convolutional neural networks* [Manuscript submitted for publication].

Browning, K. A. (1980). Structure, mechanism, and prediction of orographically enhanced rain in Britain. In R. Hide & P. W. White (Eds.), *Orographic effects in planetary flows* (pp. 85–114). World Meteorological Organization, International Council of Scientific Unions.

Broxton, P. D., N. Dawson, & X. Zeng. (2016). Linking snowfall and snow accumulation to generate spatial maps of SWE and snow depth. *Earth and Space Science, 3*(6), 246–256. https://doi.org/10.1002/2016EA000174

Broxton, P. D., X. Zeng, & Dawson, N. (2019). *Daily 4 km gridded SWE and snow depth from assimilated in-situ and modeled data over the conterminous US, version 1* (NSIDC-0719) [Dataset]. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/0GGPB220EX6A

Cannon, F., Oakley, N. S., Hecht, C. W., Michaelis, A., Cordeira, J. M., Kawzenuk, B., Demirdjian, R., Weihs, R., Fish, M. A., Wilson, A. M., & Ralph, F. M. (2020). Observations and predictability of a high-impact narrow cold-frontal rainband in over Southern California on 2 February 2019. *Weather and Forecasting, 35*(5), 2083–2097. https://doi.org/10.1175/WAF-D-20-0012.1

Cannon, F., et al. (in review). Precipitation hindcast skill, error, and uncertainty over California's watersheds in a high-resolution ensemble. *Monthly Weather Review.*

Chapman, W. E., Delle Monache, L., Alessandrini, S., Subramanian, A. C., Ralph, F. M., Xie, S., Lerch, S., & Hayatbini, N. (2022). Probabilistic predictions from deterministic atmospheric river forecasts with deep learning. *Monthly Weather Review, 150*(1), 215–234.

Cordeira, J. M., Ralph, F. M., Martin, A., Gaggini, N., Spackman, R., Neiman, P. J., Rutz, J., & Pierce, R. (2017). Forecasting atmospheric rivers during CalWater 2015. *Bulletin of the American Meteorological Society, 98*(3), 449–459.

Creaman, J. M., Suski, K. J., Rosenfeld, D., Cazorla, A., Demott, P. J., Sullivan, R. C., White, A. B., Ralph, F. M., Minnis, P., Comstock, J. M., Tomlinson, J. M., & Prather, K. A. (2013). Dust and biological aerosols from the Sahara and Asia influence precipitation in the western U.S. *Science, 339*(6127), 1572–1578. https://doi.org/10.1126/science.1227279

Cunningham, J., & Cordeira, J. (2019). *Freezing levels and atmospheric rivers over the California Feather River watershed* [Paper presentation]. 18th Annual American Meteorological Society Student Conference (held jointly with the 99th American Meteorological Society Annual Meeting), Phoenix, AZ.
https://ams.confex.com/ams/2019Annual/webprogram/Paper356303.html

Dettinger, M. D., Ralph, F. M., Das, T., Neiman, P. J., & Cayan, D. R. (2011). Atmospheric rivers, floods, and the water resources of California. *Water, 3,* 445–478.

Fish, M. A., Done, J. M., Swain, D. L., Wilson, A. M., Michaelis, A. C., Gibson, P. B., & Ralph, F. M. (2022). Large-scale environments of successive atmospheric river events leading to compound precipitation extremes in California. *Journal of Climate, 35*(5), 1515–1536.
https://doi.org/10.1175/JCLI-D-21-0168.1

Hatchett, B. J., Cao, Q., Dawson, P. B., Ellis, C. J., Hecht, C. W., Kawzenuk, B., Lancaster, J. T., Osborne, T. C., Wilson, A. M., Anderson, M. L., Dettinger, M. D., Kalansky, J. F., Kaplan, M. L., Lettenmaier, D. P., Oakley, N. S., Ralph, F. M., Reynolds, D. W., White, A. B., Sierks, M., & Sumargo, E. (2020). Observations of an extreme atmospheric river storm with a diverse sensor network. *Earth and Space Science, 7*(8), e2020EA001129.
https://doi.org/10.1029/2020EA001129

Hayatbini, N., et al. (2022). *A dual-branch deep learning framework to improve short range rainfall forecasts* [Manuscript submitted for publication].

Hecht, C. W., & Cordeira, J. M. (2017). Characterizing the influence of atmospheric river orientation and intensity on precipitation distributions over North Coastal California. *Geophysical Research Letters, 44*(17): 9048–9058. https://doi.org/10.1002/2017GL074179

Hecht, C. W., Michaelis, A. C., Martin, A. C., Cordeira, J. M., Cannon, F., & Ralph, F. M. (2022). Illustrating ensemble predictability across scales associated with the 13–15 February 2019 atmospheric river event. *Bulletin of the American Meteorological Society, 103*(3), E911–E922.
https://doi.org/10.1175/BAMS-D-20-0292.1

Henn, B., Weihs, R., Martin, A. C., Ralph, F. M., & Osborne, T. (2020). Skill of rain–snow level forecasts for landfalling atmospheric rivers: A multi-model model assessment using California's network of vertically profiling radars. *Journal of Hydrometeorology, 21*(4): 751–771. https://doi.org/10.1175/JHM-D-18-0212.1

Hill, F. F. (1983). The use of average annual rainfall to derive estimates of orographic enhancement of frontal rain over England and Wales for different wind directions. *Journal of Climatology, 3*(2), 113–129. https://doi.org/10.1002/joc.3370030202

Hughes, M., Mahoney, K. M., Neiman, P. J., Moore, B. J., Alexander, M. & Ralph, F. M. (2014). The landfall and inland penetration of a flood-producing atmospheric river in Arizona. Part II: Sensitivity of modeled precipitation to terrain height and atmospheric river orientation. *Journal of Hydrometeorology, 15,* 1954–1974.

Lamjiri, M. A., Dettinger, M. D., Ralph, F. M., & Guan, B. (2017). Hourly storm characteristics along the U.S. West Coast: Role of atmospheric rivers in extreme precipitation. *Geophysical Research Letters, 44*(13), 7020–7028. https://doi.org/10.1002/2017GL074193

Lamjiri M. A., Dettinger, M. D., Ralph, F. M., Oakley, N. S., & Rutz, J. J. (2018). Hourly analyses of the large storms and atmospheric rivers that provide most of California's precipitation in only 10 to 100 hours per year. *San Francisco Estuary and Watershed Science, 16*(4). https://doi.org/10.15447/sfews.2018v16iss4art1

Lamjiri, M. A., Ralph, F. M., & Dettinger, M. D. (2020). Recent changes in United States extreme 3-day precipitation using the R-CAT scale. *Journal of Hydrometeorology, 21*(6), 1207–1221. https://doi.org/10.1175/JHM-D-19-0171.1

Martin, A. C., Ralph, F. M., Wilson, A., DeHaan, L., & Kawzenuk, B. (2019). Rapid cyclogenesis from a mesoscale frontal wave on an atmospheric river: Impacts on forecast skill and predictability during atmospheric river landfall. *Journal of Hydrometeorology, 20*(9), 1779–1794. https://doi.org/10.1175/JHM-D-18-0239.1

Michaelis, A., Martin, A. C., Fish, M. A., Hecht, C., & Ralph, F. M. (2021). Modulation of atmospheric rivers by mesoscale frontal waves and latent heating: Comparison of two U.S. West Coast events. *Monthly Weather Review, 149*(8), 2755–2776.

Neiman P. J., Ralph, F. M., White, A. B., Kingsmill, D. E., & Persson, P. O. G. (2002). The statistical relationship between upslope flow and rainfall in California's coastal mountains: Observations during CALJET. *Monthly Weather Review, 130,* 1468–1492.

Neiman, P. J., Ralph, F. M., Persson, P. O. G., White, A. B., Jorgensen, D. P., & Kingsmill, D. E. (2004). Modification of fronts and precipitation by coastal blocking during an intense landfalling winter storm in southern California: Observations during CALJET. *Monthly Weather Review*, *132*(1), 242–273. https://doi.org/10.1175/1520-0493(2004)132%3C0242:MOFAPB%3E2.0.CO;2

Neiman P. J., M. Hughes, B. J. Moore, F. M. Ralph, & E. M. Sukovich, 2013: Sierra barrier jets, atmospheric rivers, and precipitation characteristics in Northern California: A composite perspective based on a network of wind profilers. *Monthly Weather Review, 141,* 4211–4233.

Powers, J. G., Klemp, J. B., Skamarock, W. C., Davis, C. A., Dudhia, J., Gill, D. O., Coen, J. L., Gochis, D. J., Ahmadov, R., Peckham, S. E., Grell, G. A., Michalakes, J., Trahan, S., Benjamin, S. G., Alexander, C. R., Dimego, G. J., Wang, W., Schwartz, C. S., Romine, G. S.,…Duda, M. G. (2017). The Weather Research and Forecasting model: Overview, system efforts, and future directions. *Bulletin of the American Meteorological Society, 98*(8), 1717–1737. https://doi.org/10.1175/BAMS-D-15-00308.1

Ralph, F. M., Neiman, P. J., Kingsmill, D. E., Persson, P. O. G., White, A. B., Strem, E. T., Andrews, E. D., & Antweiler, R. C. (2003). The impact of a prominent rain shadow on flooding in California's Santa Cruz mountains: A CALJET case study and sensitivity to the ENSO cycle. *Journal of Hydrometeorology, 4*(6), 1243–1264. https://doi.org/10.1175/1525-7541(2003)004%3C1243:TIOAPR%3E2.0.CO;2

Ralph F. M., Neiman, P. J., Kiladis, G. N., & Weickmann, K. (2011). A multiscale observational case study of a Pacific atmospheric river exhibiting tropical-extratropical connections and a mesoscale frontal wave. *Monthly Weather Review, 139,* 1169–1189.

Ralph, F. M., Coleman, T., Neiman, P. J., Zamora, R. J., & Dettinger, M. D. (2013). Observed impacts of duration and seasonality of atmospheric-river landfalls on soil moisture and runoff in coastal Northern California. *Journal of Hydrometeorology*, *14,* 443–459.

Ralph F. M., Cordeira, J. M., Neiman, P. J., & Hughes, M. (2016). Landfalling atmospheric rivers, the Sierra Barrier Jet, and extreme precipitation in northern California's Upper Sacramento River watershed. *Journal of Hydrometeorology*, *17,* 1905–1914.

Ralph F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., Schick, L. J., & Smallcomb, C. (2019). A scale to characterize the strength and impacts of atmospheric rivers. *Bulletin of the American Meteorological Society, 100,* 269–289.

Ricciotti, J. A., & Cordeira, J. M. (2022). Summarizing Relationships Among Landfalling Atmospheric Rivers, Integrated Water Vapor Transport, and California Watershed Precipitation 1982–2019. *Journal of Hydrometeorology*.

Rutz J. J., Steenburgh, W. J., & Ralph, F. M. (2014). Climatological characteristics of atmospheric rivers and their inland penetration over the western United States. *Monthly Weather Review*, *142*(2), 905–921. https://doi.org/10.1175/MWR-D-13-00168.1

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X.-Y., Wang, W., & Powers, J. G. (2008). *A description of the Advanced Research WRF version 3.* https://doi.org/10.5065/D68S4MVH

Sumargo, E., Cannon, F., Ralph, F. M., & Henn, B. (2020). Freezing level forecast error can consume reservoir flood control storage: Potentials for Lake Oroville and New Bullards Bar reservoirs in California. *Water Resources Research, 56*(8), e2020WR027072. https://doi.org/10.1029/2020WR027072

Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Monthly Weather Review,* 136, 5095–5115. https://doi:10.1175/2008MWR2387.1

Warner, M. D., Mass, C. F., & Salathé, E. P. (2012). Wintertime extreme precipitation events along the Pacific Northwest coast: Climatology and synoptic evolution. *Monthly Weather Review, 140,* 2021–2043.

White, A. B., Neiman, P. J., Creamean, J. M., Coleman, T., Ralph, F. M., & Prather, K. A. (2015). The impacts of California's San Francisco Bay Area Gap on precipitation observed in the Sierra Nevada during HMT and CalWater. *Journal of Hydrometeorology, 16*(3), 1048–1069. https://doi.org/10.1175/JHM-D-14-0160.1

Wilson, A. M., Cobb, A., Ralph, F. M., Tallapragada, V., Davis, C., Doyle, J., Delle Monache, L., Pappenberger, F., Reynolds, C., Subramanian, A., Cannon, F., Cordeira, J., Haase, J., Hecht, C., Lavers, D., Rutz, J. J., & Zheng, M. (2022). Atmospheric River Reconnaissance Workshop promotes research and operations partnership. *Bulletin of the American Meteorological Society, 103,* E810–E816.

[WMO] World Meteorological Organization. (2009). *Manual on estimation of probable maximum precipitation (PMP).* WMO-1045. https://library.wmo.int/doc_num.php?explnum_id=7706.

Zeng, X., Broxton, P., & Dawson, N. (2018). Snowpack change from 1982 to 2016 over conterminous United States. *Geophysical Research Letters, 45*(3), 12,940–12,947. https://doi.org/10.1029/2018GL079621

6.2 Hydrology

The PVA hydrology work consists of a two-part analysis that generates (1) ensemble and deterministic streamflow hindcasts, including scaled events, and (2) flow frequency analysis. Both provide the baseline data support for assessing FIRO viability by helping to understand the forecast uncertainties (especially extreme events), developing and testing operation strategies, and assessing management goals like flood protection and water supply. For the first analysis, the CNRFC uses the NWS Hydrologic Ensemble Forecasting System (HEFS) tool to compute current and future streamflows at a series of flow points in the Yuba-Feather watersheds. These ensembles were used as the basis for the Yuba-Feather PVA assessment of FIRO Water Control Plan alternatives. In the second analysis, the U.S. Army Corps of Engineers (USACE) updates the flow frequency curves and expands the analysis to additional locations based on the data and methodology developed from several existing studies. The data and methodology are also needed to update the Water Control Manuals (WCMs) for ORO and NBB.

Hydrological research tasks pursued through the PVA in support of FIRO include:

- Developing ensemble streamflow hindcasts spanning 1985–2010 and scaled events based on GEFSv10.
- Collaborating on the flow frequency analysis being conducted concurrently by USACE as part of the WCM updates for ORO and NBB.
- Providing scaled historical hindcast events for evaluation by the water resources engineering (WRE) team.
- Coordinating on deterministic and probabilistic forecast verification of inflows at NBB and ORO within the verification task.

The development of ensemble and deterministic streamflow hindcasts and flow frequency analysis provided the baseline for other studies and research areas in support of the PVA (e.g., water resource engineering, forecast verification). As such, the findings associated with analysis of these baseline data are reported below.

6.2.1 HEFS Background

A single-value or "deterministic" forecast comprises a single estimate of each forecast variable at each time and location. An HEFS hydrologic forecast, on the other hand, is an ensemble—a set of possible values of the forecast variables (precipitation and temperature). This means that HEFS generates hydrologic forecasts that provide information about forecast uncertainty.

HEFS translates an ensemble of meteorological inputs through hydrologic models to provide an ensemble of outputs (e.g., streamflow). In this case, the hydrologic model is a coupled snow model (SNOW-17) and a soil model (SAC-SMA).

HEFS relies on a combination of physically based and statistical models. The hydrologic models mentioned above are physically based, and the meteorological forecast uncertainties are produced through statistical modeling. MEFP is the statistical model in which meteorological ensembles are generated. It relies on historical observations to determine forecast errors. This requires statistical modeling of the relationship between the past forecasts and observations. If this relationship is relatively constant or "stationary" in time, past forecasting errors provide a statistical guide to future forecasting errors. The main input forecast sources to the MEFP used at the CNRFC are the RFC precipitation forecasts and the mean GEFSv10 temperature and precipitation forecasts.

The MEFP is conducted in two parts. First, the parameter estimator (MEFPPE) is used to calculate the parameters of each statistical model. The parameters must be estimated from a long and consistent record of paired predictions and observations. This is necessary to minimize sampling uncertainty. For the PVA, the MEFP parameters were based on the 1985–2010 GEFSv10 hindcast datasets (precipitation and temperature) and the corresponding observations. The observations are MAP and temperature estimates created from historical gauge networks. This is the same observed dataset used to calibrate the hydrologic models. This is important because the meteorological observational inputs to the MEFPPE statistical models should be as consistent as possible with the source used to parameterize the hydrologic models to reduce bias. Secondly, the estimated parameters from MEFPPE are applied in real time to the "raw" operational forecasts (GEFS) to create equally likely meteorological ensemble time series. Outputs from the MEFP are fed as inputs through the physically based hydrologic models one ensemble pair at a time. Figure 6-6 shows the overall flow of the HEFS from parameter estimation to the final streamflow ensemble output.

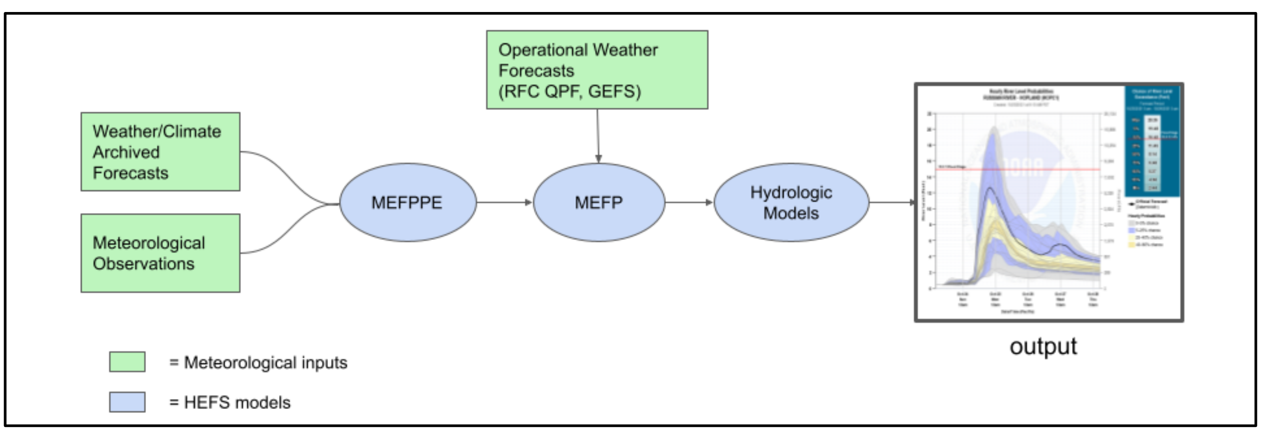


Figure 6-6. *Flow of the HEFS from parameter estimation to the final streamflow ensemble output.*

6.2.2 Hindcast Methodology

In current CNRFC operational forecasting, the HEFS model runs are processed using current issuances of meteorological forecast sources (GEFS and RFC) and run through the hydrologic models using current basin states. These hydrology models and watershed states are identical to what is used in the production of the CNRFC deterministic forecasts (see Hydrology Appendix N for further detail). The inputs to the MEFP are GEFSv12 mean temperature, RFC QPF, and GEFSv12 mean QPF. The RFC QPF is used as the single source input to MEFP for the first three days of forecast lead time, and the GEFSv12 is used for days 4-15. The GEFSv12 mean temperature forecast is used as the single source input to MEFP for all lead times. Note that GEFSv10 is no longer run operationally by NCEP and therefore GEFSv12 is used for current operations. An assessment of forecast skill for the two versions of the model suggest they are essentially the same.

The hindcast process follows the general flow of operational HEFS forecasting: single source meteorological forecasts are fed to the MEFP, and ensemble forcings from the MEFP statistical models are processed through the hydrology models initiated with antecedent conditions reflective of the hindcast forecast time. The end result is a set of equally likely streamflow ensemble forecasts reflective of the watershed conditions at that time. For the Feather-Yuba hindcasts, GEFSv10 was used as the single source for both temperature and precipitation. The RFC precipitation forecasts were not used due to limited record length. The GEFSv10 hindcast dataset (also used in MEFPPE) covers the 1985–2010 period. Naturally, this is also the period that covers the Feather-Yuba HEFS hindcast effort.

To generate hindcasts, the first step is to create antecedent watershed conditions for every day during the hindcast period. To do this, historical hydrologic model simulations are run using archived observed forcings (precipitation and temperature). The snow and soil model states are saved for every day during the historical model simulation. This spanned the 1983–2010 period for the Feather-Yuba hindcasts. The historical simulation period starts earlier than the actual hindcast period in order for the hydrology models to “warm up” from the assumed initial conditions and reduce error due to initial condition assumptions.

Once historical basin states have been saved, the HEFS hindcasts are processed one day at a time. Starting at the beginning of the hindcast period, 1985, GEFSv10 mean hindcast precipitation and temperatures are processed through the MEFP, resulting in forcing ensembles for that day. The hydrology models are initiated using the appropriate antecedent conditions, and then the MEFP ensembles are processed through the hydrology models, resulting in streamflow ensemble hindcasts for that particular day. This process is followed one day at a time until the end of the hindcast period (September 2010). The output from this hindcast process is a large collection of ensemble streamflow forecasts using consistent meteorological inputs and hydrology models spanning 25 years.

6.2.3 Events

To evaluate the performance of alternative reservoir management strategies for extreme events, a set of ensemble streamflow hindcasts greater than what has been observed in the historical record was needed. To support this need, HEFS hindcasts were generated using scaled versions of large historical events in the hindcast period of record. To create a scaled hindcast, the antecedent watershed conditions need to be altered as well as the meteorological inputs. As with the period-of-record hindcasts, the first step of the scaled hindcast is to create antecedent watershed conditions reflective of the event. To do this, the historical precipitation values were scaled uniformly across all watersheds, the historical hydrology models were run using these scaled inputs, and then the watershed conditions were saved for every day covering the scaled event time window. This process was done for every scaling increment and every historical event selected for scaling. The GEFSv10 was used as the forecast source, and the MEFP output meteorological time series were scaled by the same factor used to create the scaled watershed states, resulting in scaled ensemble streamflow hindcasts after processing through the hydrology models.

The three largest historical events in the hindcast period—February 1986, December 1996/January 1997, and December 2005/January 2006—were selected as the basis for the scaled events. Scaled events were created at different increments for the three historical patterns due to the varying size of these historical events. The maximum five-day observed precipitation during these three periods was used as the precipitation scaling window. The scaling windows along with the scale factors are listed in Appendix N.

6.2.4 Frequency Analysis

Flow frequency analysis assigns likelihood to peak flows and volumes resulting from flows over selected durations (e.g., three days). For the purposes of FIRO, the analysis focuses on the largest annual flows on the Feather and Yuba Rivers resulting primarily from precipitation events. The determination of these flood frequencies at various index locations provides the basic information for scaling hindcasts (Section 6.2.3) and the assessment of candidate reservoir operation sets.

Unregulated flow frequency estimates will be generated for the following locations:

1. Feather River at ORO Dam
2. Feather River below Honcut Creek
3. Feather River above Yuba City
4. Feather River at Yuba River
5. Feather River at Bear River
6. North Fork Yuba River at NBB Dam
7. Yuba River at Englebright Dam
8. Yuba River above Marysville

Previous estimates of system flow frequencies for locations 1–6 and 8 were made as part of the Sacramento–San Joaquin Comprehensive Study (USACE & DWR 2002), the Central Valley Hydrology Study (USACE & David Ford Consulting Engineers 2015), and the Comprehensive Needs Assessment (DWR 2018) conducted after the ORO Dam spillway incident. Estimates of inflow frequency for NBB Dam and Englebright Dam add needed information about the upper portion of the Yuba River watershed.

The frequency update used for the Yuba-Feather FIRO FVA is being performed as part of the concurrent update to the WCMs for ORO and NBB. USACE is leading that effort and coordinating regularly with the FIRO teams.

6.2.5 Recommendations

The following next steps are recommended:

- Generate streamflow hindcasts using the newer GEFSv12 weather model as the meteorological input with a hindcast period of 1990–2019 plus February 1986.
- Investigate the capacity to generate MEFP snow level ensembles to improve hydrologic modeling and forecasting/hindcasting.
- Generate hindcast data related to seasonal spring runoff forecast volumes (e.g., April–July volume) to assist in the development of spring refill strategies.
- Consider synthetically generated ensemble forecasts for more rigorous evaluation of candidate FIRO Water Control Plan alternatives.
- Analyze flood and refill potential for the spring months to help establish dates between which the maximum flood control space could transition to a maximum conservation space without increasing risk to the projects or downstream communities.

6.2.6 References

[USACE & DWR] U.S. Army Corps of Engineers & California Department of Water Resources. (2002). *Sacramento and San Joaquin River Basins comprehensive study: Technical studies documentation.* https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/usace_2002.pdf

[USACE] U.S. Army Corps of Engineers & David Ford Consulting Engineers. (2015). *Central Valley hydrology study.* https://www.hdrinc.com/sites/default/files/inline-files/hdr-central-valley-hydrology-study-report.pdf

[DWR] California Department of Water Resources. (2018). *Comprehensive Needs Assessment: Technical report.* https://water.ca.gov/Programs/State-Water-Project/SWP-Facilities/Oroville/Oroville-Dam-Safety-Comprehensive-Needs-Assessment

6.3 Observation Efforts and Results

Current monitoring in the Yuba and Feather watersheds is essential to supporting forecast improvements and understanding the impacts of extreme precipitation events. Precipitation impacts are modulated by antecedent watershed conditions, in particular the state of snowpack, streamflow, and soil moisture. Observations are necessary to validate models (see Section 6.1) and are key to informing process-based understanding of watershed hydrology. Network enhancements made in support of the Yuba-Feather FIRO project objectives build on the existing monitoring networks in the watersheds, including additions made by Forecast-Coordinated Operations (F-CO), to identify and fill gaps spatially, temporally, and in particular data types. Evolving network needs will be identified via an annual evaluation of the observation network on key criteria including spatial and temporal gaps in existing networks, data quality and reliability, and data dissemination and visualization. Note that this section is not covering airborne reconnaissance, which is a critical component of FIRO. Advances made because of the airborne campaigns over the northeast Pacific, and recommendations for future plans, can be found in Section 6.1. In future, the network evaluation for the Yuba and Feather watersheds may include requirements for airborne observations over the Central Valley and coastal mountain ranges to maximize FIRO utility: many processes important to precipitation over the Yuba and Feather watersheds occur over these areas (e.g., White et al. 2015; Ralph et al. 2016).

The tasks undertaken to improve hydrometeorological observations through the PVA in support of FIRO include:

- Pursue a high-spatial-resolution precipitation dataset to support research and a better understanding of physical processes in complex terrain.
- Establish NRT data accessibility through the Geostationary Operational Environmental Satellite (GOES) and/or the California Data Exchange Center.
- Assess data transmission reliability, especially during significant storm events.
- Pursue enhancements to the observational network including, but not limited to, all-weather precipitation gages; soil moisture; snow water equivalent, or SWE (including the Airborne Snow Observatory, or ASO); snow density; and instrumentation to aid in assessing and modeling the snowpack's energy budget.

Requirements for the observations component of FIRO are contingent on the results of the network evaluation plan (Appendix O) and coordination with the recommendations from other sections of the PVA.

6.3.1 High-Resolution Precipitation Dataset

The nature of weather and climate processes in the region creates unique challenges in accurately quantifying the precipitation amount at fine spatial and temporal scales. Many widely used measurement techniques like weather radar and satellites are insufficient for high-resolution forecast verification and process diagnostics due to biases and noise. It is thus critical to gather as much information as possible from in situ networks and integrate it reliably and consistently.

The Analysis of Record for Calibration, developed by the NWS Office of Water Prediction, is a national-scale gridded dataset that includes hourly precipitation (1979–2019; ~1 km scale) and uses RFC quantitative precipitation estimation (QPE) since 2004. This dataset's utility has been investigated by the hydrology and verification PVA authors. Due to NRT data needs, the CNRFC Mountain Mapper tool is preferred. We recommend continued development and implementation of the CNRFC Mountain Mapper tool for the FVA in order to best leverage the precipitation (and ancillary) data collected from existing and newly deployed sensor networks. Due to the importance of other quantities including SWE, temperature, and humidity, the FVA process should consider whether similar high-spatial-resolution datasets should be constructed for these other parameters.

6.3.2 Remote Sensing

Remotely sensed data offer higher spatial coverage of snow and soil data in difficult-to-monitor, complex terrain. This year, for the first time, data from ASO are available for the Yuba and Feather watersheds; however, several satellite-based datasets also provide valuable information about snow coverage, available snow water, and soil moisture. In WY2022, ASO has collected snow data during three flights over the Yuba and four flights over the Feather. These data include SWE, snow depth, and albedo derived from lidar altimetry and a snow density model

(Painter et al. 2016) and are available on ASO's online data portal. ASO data fill spatial gaps in SWE and snow depth data and can be used in conjunction with other, higher-temporal-resolution remote sensing data such as the Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover and SWE (calculated retrospectively; Schneider and Molotch 2016) to validate estimates of available snow water in models and forecasts. In WY2023, four flights are planned over both the Feather and Yuba watersheds.

Ground-based remotely sensed data include integrated water vapor (IWV), calculated from GPS data, snow level calculated from vertically pointing radars, and hydrometeor profiles observed by vertically pointing radars (measured at CW3E stations; see Figure 6-7). IWV data from GPS are point-based, but they offer higher temporal resolution than radiosondes and can be used in conjunction with radiosondes for decision support and model validation. In addition, since condensation of vapor can be a major mechanism for heat transfer from the air to the snowpack during warm winter storms (Marks et al. 1998), GPS IWV may be useful to evaluate more widely available humidity measurements. The snow level data have already been used for model validation and might be used to help understand the physical drivers of the spatial variability of snow level within the watersheds. The hydrometeor profiles have potential utility for process-based modeling studies and model validation. Further exploration of the utility of these datasets is recommended for the FVA.

6.3.3 Network Evaluation Plan

The objective of the network evaluation plan is to regularly assess the adequacy of the existing observation network to achieve FIRO goals. This assessment is proposed on an annual basis, in perpetuity for the life of the network, and will cover variables of interest: precipitation (amount and phase), soil moisture, streamflow, temperature, snow (SWE, snow level, and albedo). (Note that this list of variables may be amended as needed.) This PVA presents the initial evaluation plan; the FVA will follow on the execution of the recommendations from the assessment. Table 6-3, below, outlines the plan's methods for addressing higher-level issues (see Appendix O for the full evaluation plan). Analyses are to be completed as part of the FVA.

Table 6-3. *Methods for evaluating issues in the network evaluation plan.*

Higher-Level Issue	Method
Spatial gaps in data	• Identify spatial coverage and representativeness (of watershed characteristics) of key observation types: precipitation, SWE, streamflow, soil moisture, snow level, precipitation phase, and snow albedo • Pay particular attention to coverage with respect to forecast/model error in collaboration with the meteorology and verification teams
Temporal gaps in data	• Identify frequency of station reporting, with particular attention to spatial coverage of higher-time-resolution data
Data reliability	• Determine frequency of station outages, particularly during ARs • Identify availability of all-weather precipitation, particularly above the rain-snow transition

Data quality control	• Survey major operators' quality control methods, with attention to timing of quality control relative to receipt of data and emphasis on precipitation, SWE, streamflow, soil moisture, snow level, and precipitation phase
Data availability (CDEC, CW3E website)	• Survey network operators to determine availability of data on online platforms, particularly on CDEC or via GOES telemetry • Survey beneficial data types currently unavailable on CDEC • Survey data visualization needs of stakeholders and operators

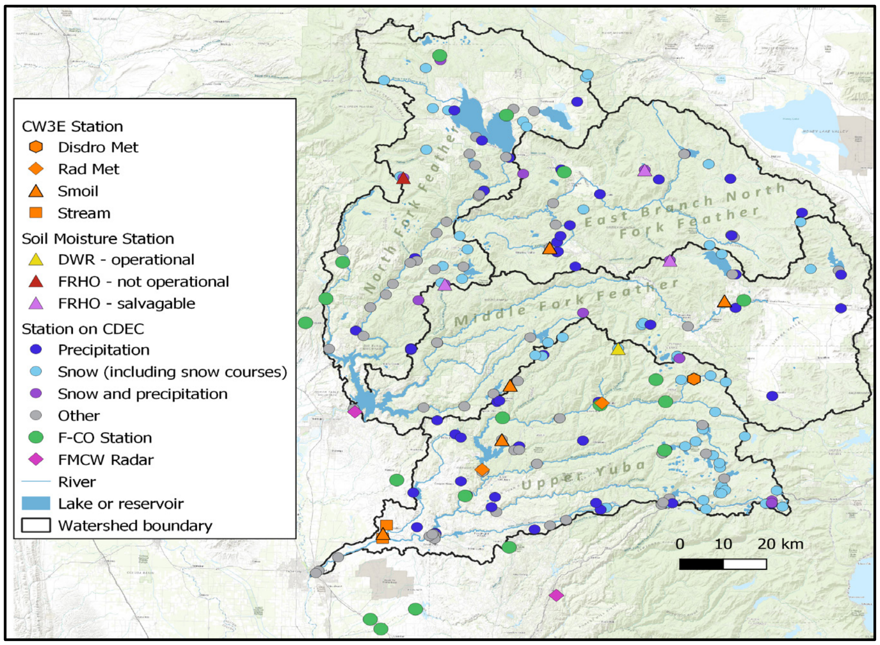


Figure 6-7. *Map of all observation locations in the Yuba and Feather watersheds available via CW3E or CDEC (as of April 2022). Basemap: Esri topographic map.*

6.3.4 Enhancement to the Observational Network

CW3E has added 10 stations thus far to the observation network, as well as a radiosonde launch site (see Appendix O for station information). FIRO station types include streamflow measurements, surface meteorology with soil moisture (SMOIL), surface meteorology with micro rain radars (snow level), disdrometers (precipitation phase), and GPS (IWV) (Radar Met, or Rad Met hereafter). Additionally, FIRO's highest elevation site in the Yuba watershed (LBH, at 1,680 m/5,512 feet) has a disdrometer installed (Disdro Met hereafter) to target phase changes within storm events to help identify the rain-snow transition as called for in the work plan. All SMOILs and Rad Mets have precipitation measurements, and three stations have all-weather precipitation via heated tipping buckets. The heated tipping buckets were installed at sites above 2,000 feet elevation with proper power accommodations; the all-weather precipitation data extend the utility of the gauges as called for in the work plan.

All six SMOIL stations have soil moisture and temperature at six depths, up to 1 meter deep or as deep bedrock (one station as of 2022; see Appendix O, Table O-1, for details). Most SMOIL and Rad Met sites are telemetered in NRT and are available on CDEC, and all sites of all types are planned to be telemetered. Radiosondes are sent directly to the Global Telecommunications

System upon completion of data collection. Future enhancements to FIRO include additional soil moisture stations and snow measurements at higher-elevation stations. The station types and their utility to FIRO are outlined below in Table 6-4. One major use of the observations overall is—in collaboration with the meteorology, hydrology, and verification teams—to create and update estimates of forecast skill for these observations. The observations will allow for more local forecast evaluations in the complex terrain of the Yuba and Feather watersheds.

CW3E has also absorbed the Feather River Hydrologic Observatory (Malek et al. 2017; Avanzi et al. 2018), a wireless sensor network of soil moisture, snow depth, incoming solar radiation, and air temperature measurements. In support of FIRO objectives, following DWR's permitting timeline with the U.S. Forest Service, CW3E plans to maintain a reduced version of the existing node network and continue the valuable period of record of these measurements.

Table 6-4. *Station types deployed by CW3E and their utility to FIRO.*

Station Type	Utility to FIRO
Streamflow	Ancillary streamflow data from Dry Creek to support Yuba River streamflow data
SMOIL	Monitoring surface meteorology (air temperature, relative humidity, incoming solar radiation, air pressure, wind speed, and precipitation) as well as soil moisture for decision makers
Disdro Met	SMOIL with the addition of monitoring precipitation phase to support development of precipitation diagnostic for decision makers
Rad Met	Monitoring surface meteorology as well as snow level, precipitation phase, and IWV data to support development of precipitation diagnostics for decision makers
Radiosonde	Data are assimilated into models; aids development of WWRF; real-time decision support

6.3.5 Findings

Key findings of the PVA include:

Key Findings

- Soil moisture data are lacking and many existing observations are not available in NRT. The soil moisture stations added by FIRO have increased the spatial and temporal coverage of soil moisture data available in NRT, but some landscape characteristics are still not well-represented. Soil moisture data need a long period of record to be useful (three to six years minimum; Ford et al. 2016) and are currently most useful for situational awareness and model validation.
- Precipitation stations have good spatial and temporal coverage and represent key identified landscape characteristics. Precipitation is also most useful and most readily integrable into runoff forecasts.
- The high-spatial-resolution precipitation dataset should be completed for the FVA, and similar datasets covering SWE and temperature should be considered.
- All-weather precipitation gages (especially above about 5,000 feet elevation) have the best accuracy for determining precipitation totals regardless of precipitation phase. Metadata are lacking for identifying gage types at high elevations.
- Current precipitation data quality at high elevation should be further investigated with regards to high QPF error in those regions.
- Point measurements of precipitation phase at mid-elevations (about 5,000 feet) can validate freezing level forecasts by identifying the rain-snow transition elevation. More of these data would be useful in validation efforts.
- Snow level data, used for adjusting forecasts (nowcasting) and validating gridded datasets, would benefit from additional point measurements to add granularity.
- Precipitation phase and snow level data from CW3E stations had very little to no missing data during ARs. Further examination of outages is required to quantify error across other observation types during ARs.
- Data quality and reliability are a priority for many variables (SWE, snowpack albedo, snow density, temperature, humidity) for understanding snowmelt timing and magnitude.

6.3.6 Recommendations

In support of FIRO objectives, CW3E has expanded soil moisture observations in the Yuba and Feather watersheds significantly and supplemented the existing precipitation observations to develop higher resolution spatial and temporal coverage of data in the region. The observation types of interest are the focus of the network evaluation plan to be completed annually and assess data availability, reliability, and utility. Ongoing work on the network evaluation plan and coordination with other sections will inform the recommendations to be executed by the FVA.

The following recommendations will enhance the benefits of FIRO, contingent on further investigation via the network evaluation:

- Develop and implement the CNRFC Mountain Mapper tool to best leverage the precipitation (and ancillary) data collected from existing and newly deployed sensor networks. Use the Mountain Mapper tool to create a high-resolution precipitation dataset. Consider using Mountain Mapper or similar tools to create high-resolution datasets for SWE and temperature.
- Confirm and exhibit the utility of newly available observation types (e.g., snow albedo, ASO, Rad Met data including GPS IWV, snow level, and hydrometeor profiles) to inform/validate forecasts in case studies. Define a clear scope for this work, which may include incorporating other datasets (e.g., snow reanalyses) or conventional observation types such as temperature and humidity.
- Determine which hydrometeorological monitoring stations exist offline and work with operators to make data available in NRT and more readily integrated into forecast, verification, and decision support tools.
- Investigate the data quality of high-elevation precipitation further and identify the all-weather gages available to improve QPE representation and QPF errors.
- In close collaboration with the meteorology, hydrology, and forecast verification teams, ensure the observations are useful for understanding and verifying the model representation of local-scale processes.
- Conduct and refine the network evaluation plan annually to accommodate partner recommendations and needs.
- Plan network installation/enhancement to fill gaps as they are identified.

6.3.7 References

Avanzi, F., Maurer, T. P., Malek, S. A., Glaser, S. D., Bales, R. C., & Conklin, M. H. (2018). *Feather River Hydrologic Observatory: Improving snowpack forecasting for hydropower generation using intelligent information systems.* California Energy Commission.

Ford, T. W., Wang, Q., & Quiring, S. M. (2016). The observation record length necessary to generate robust soil moisture percentiles. *Journal of Applied Meteorology and Climatology*, *55*(10), 2131–2149. https://doi.org/10.1175/JAMC-D-16-0143.1

Malek, S. A., Avanzi, F., Brun-Laguna, K., Maurer, T., Oroza, C. A., Hartsough, P. C., Glaser, S. D. (2017). Real-time alpine measurement system using wireless sensor networks. *Sensors, 17*(11), 30. https://doi.org/10.3390/s17112583

Marks, D., Kimball, J., Tingey, D., & Link, T. (1998). The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, *12*(10-11), 1569–1587. https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11%3C1569::AID-HYP682%3E3.0.CO;2-L

Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., Hedrick, A., Joyce, M., Laidlaw, R., Marks, D., Mattmann, C., McGurk, B., Ramirez, P., Richardson, M., Skiles, S. M., Seidel, F. C., & Winstral, A. (2016). The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment, 184,* 139–152. https://doi.org/10.1016/j.rse.2016.06.018

Ralph, F. M., Prather, K., Cayan, D., Spackman, J. R., Demott, P., Dettinger, M., Fairall, C., Leung, R., Rosenfeld, D., Rutledge, S., Waliser, D., White, A., Cordeira, J., Martin, A., Helly, J., & Intieri, J. (2016). CalWater field studies designed to quantify the roles of atmospheric rivers and aerosols in modulating U.S. West Coast precipitation in a changing climate. *Bulletin of the American Meteorological Society, 97*(7), 1209–1228. https://doi.org/10.1175/BAMS-D-14-00043.1

Schneider, D., & Molotch, N. P. (2016). Real-time estimation of snow water equivalent in the Upper Colorado River Basin using MODIS-based SWE reconstructions and SNOTEL data. *Water Resources Research, 52,* 7892–7910. https://doi.org/10.1002/2016WR019067

White, A. B., Neiman, P. J., Creamean, J. M., Coleman, T., Ralph, F. M., & Prather, K. A. (2015). The impacts of California's San Francisco Bay Area Gap on precipitation observed in the Sierra Nevada during HMT and CalWater. *Journal of Hydrometeorology, 16*(3), 1048–1069. https://doi.org/10.1175/JHM-D-14-0160.1

6.4 Weather and Water Forecast Verification

The Yuba-Feather FIRO project is grounded in the idea that using high-quality forecast information can lead to better decisions about water storage and releases at ORO and NBB reservoirs. Therefore, gaining a thorough knowledge of the quality of the forecast information affecting runoff generation and inflows into the reservoirs is a critical step for potential FIRO implementation.

This section describes the forecast evaluation and verification of AR-related atmospheric and hydrologic characteristics relevant for FIRO in the Yuba-Feather watersheds. For this effort, we evaluated forecasts over available periods of record for each model and observation source, using a verification framework that considered the datasets, time scales, metrics, and tools appropriate for describing baseline forecast skill under AR conditions. The baseline forecast skill describes the long-term predictability of AR and hydrologic characteristics aggregated over relevant time scales.

This section also presents examples of events or cases from which research directions for the FVA could be derived. (See Appendix P for more details.)

Forecast verification tasks pursued through the PVA include:

- Development of a verification framework and identification of key meteorological and hydrologic characteristics.
- 34-year assessment of landfall error for ARs only affecting the Yuba-Feather region.
- 28-year evaluation of 72-hour precipitation forecasts from global and high-resolution models at different lead times in the Yuba and Feather watersheds.
- Identification of the 10 largest forecast errors of 72-hour precipitation in the Yuba and Feather watersheds.
- Eight-year evaluation of freezing level forecast error.
- 25-year evaluation of probabilistic inflow forecasts and 17-year evaluation of deterministic inflow forecasts at ORO and NBB.

6.4.1 AR Landfall Error

Landfall position of an AR is a key indication for the onset and location of extreme precipitation in California. Landfall represents the "first stage" of forecast error as the AR plume propagates onshore and is one of the measures used to describe the large (synoptic) scale forecast predictability. Landfall error was evaluated using IVT from 34 years (1985–2018) of West-WRF 9 km reforecasts. (West-WRF reforecasts are used here as a reflection of a current, state-of-the-art forecast system with high resolution, a long period of record, and a static model configuration.) The one- to five-day lead time forecasts were compared to the ECMWF v5 reanalysis throughout the cold season (December through March). ARs are defined as contiguous areas ("objects") of IVT above a given threshold using the Method for Object-based Diagnostic Evaluation, or MODE (Davis et al. 2009). Landfall is defined as occurring when any part of the AR object is within a quarter degree of the coastline; the landfall position is defined as the latitude with the highest IVT (i.e., the core of the AR). To focus on ARs that affect the Yuba-Feather water basin, the metrics presented here only consider ARs that make landfall between 35.5° and 38.5° north (Ricciotti and Cordeira 2022).

Figure 6-8, below, shows a performance diagram (Roebber 2009) for forecasted landfalling ARs, where a "hit" is defined as an instance where both the forecast and the reanalysis have landfalling AR "objects." The probability of detection for landfalling ARs at the 250 kg/m/s threshold and 24-hour lead time is over 0.95: that is, 95 percent of the observed IVT objects were correctly matched to a forecasted AR object at the time of landfall. The success ratio, or the ratio of correctly matched AR objects at the time of landfall to the total number of forecasted objects at 24-hour lead time, is approximately 0.9 (i.e., the false alarm ratio is 0.1). Both metrics steadily fall with increasing lead time to a probability of detection of 0.65 and a success ratio of 0.8 at 168 hours. The metrics for ARs with IVT over the 500 kg/m/s threshold are lower than those defined with a threshold of 250 kg/m/s threshold at every lead time. The critical success index is greater than 50 percent for all lead times using a threshold of 250 kg/m/s, whereas the critical success index for the 500 kg/m/s threshold is 50 percent or greater only up to 96 hours' lead time. This likely means that higher-intensity ARs are contributing to a greater degradation in hit rate, given the overlap of 500 kg/m/s objects within the 250 kg/m/s threshold. At a 24-hour lead time over the 34-year record, there are 186 landfalling ARs at the 250 kg/m/s threshold, while there are only 30 landfalling ARs at the 500 kg/m/s threshold in the selected latitude band. At 168-hour lead time, the number of landfalling ARs at 500 kg/m/s is only 16. This suggests higher-intensity ARs are under-forecasted (i.e., missed) at long lead times.

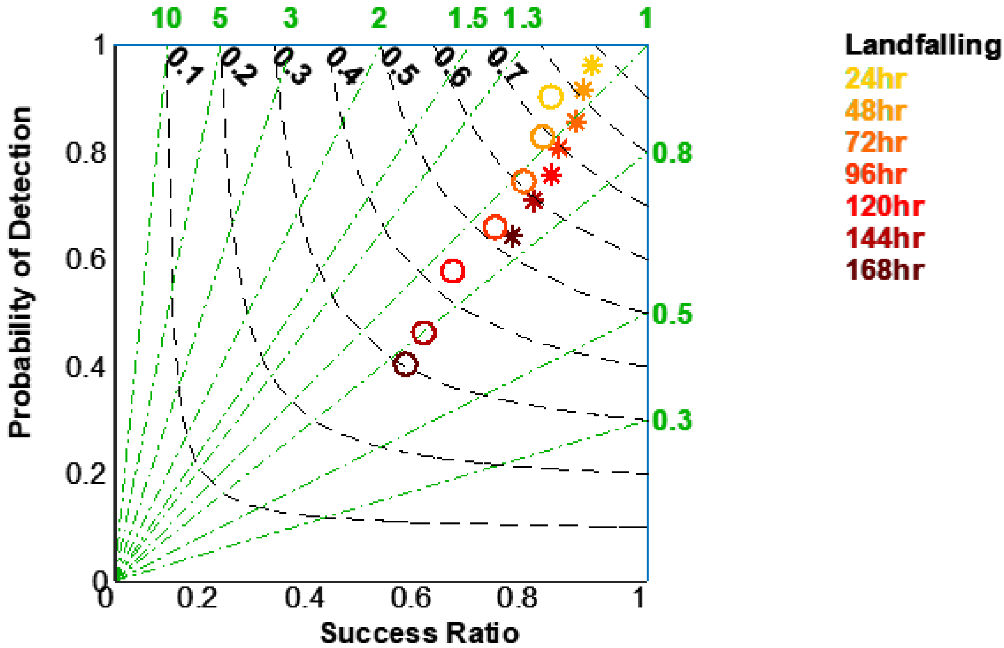


__Figure 6-8.__ Performance diagram for existence of landfalling ARs for the 250 kg/m/s threshold (asterisks) and the 500 kg/m/s threshold (circles) at lead times from 24 hours to 168 hours. The green radial lines are the frequency bias, and the curved black lines are the threat score. Points closer to the upper right corner of the diagram indicate better model performance.

When ARs are correctly matched at the time of landfall, the average position error for the ARs with a 250 kg/m/s threshold at a 24-hour lead time is 160 km, while the average error for the ARs with a 500 kg/m/s threshold at the same lead is 125 km (Figure 6-9). At 144-hour lead time, the average errors have increased to 435 km and 345 km. As noted above, there are fewer ARs at the higher threshold, which leads to the larger confidence interval, shown in the shading. Although the difference between the two thresholds is not statistically significant (except for 168-hour forecasts), there is a tendency for ARs defined by 500 units to have a smaller landfall error. The difference between the contingency table metrics (shown in Figure 6-13) and the landfall position error suggests that while the forecast is less likely to predict the existence of a stronger landfalling AR, if it does predict the existence of a stronger AR, it is more likely to correctly position that AR.

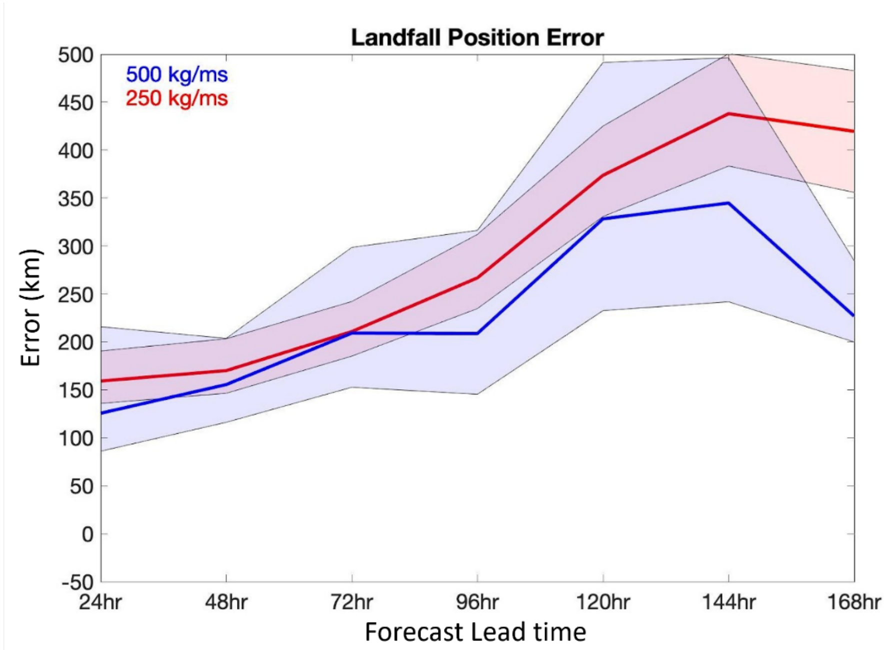


Figure 6-9. *Average landfall position error for ARs at the 250 (red) and 500 (blue) kg/m/s thresholds. The shading indicates the 90 percent confidence interval computed with bootstrapping.*

6.4.2 72-Hour MAP Error

The 72-hour deterministic MAP forecasts are assessed from three forecast models to provide lead times at which a multi-model system can adequately provide skill. The accumulation period of 72 hours encapsulates the mean AR duration in Northern California—and therefore adequately represents event total precipitation—and is consistent with Central Valley hydrology (USACE & David Ford Consulting Engineers 2015) for hydrologic-time-scale impacts from precipitation. We compared the MAP as a method to understand the hydrologic implications in the mountainous Yuba and Feather watersheds. Precipitation forecasts from GEFSv10, GEFSv12, and the West-WRF 3-km reforecast (hereafter WWRF) are compared and skill is assessed between December and March for WYs 1990–2017. Forecasted precipitation was compared to the CNRFC QPE. For the GEFS models, the ensemble mean is used as the predictor of the basin MAP. The methodology aligns with the approach described by Brown et al. (2014) for providing input skill assessments that go into MEFP to force a set of hydrologic ensembles used in HEFS. These hydrologic ensemble predictions are input to the Ensemble Forecast Operations (EFO) model (Delaney et al. 2020) for FIRO decision support. MAP is estimated either by the 1° grid point centered nearest or distributed within the individual watersheds (for GEFS) or averaged within the watershed boundaries (WWRF and CNRFC QPE). The individual six-hour forecasts available for each model (20 for WWRF and 64 for the GEFS runs) were combined into three-day MAP forecasts for days 1–3 to days 14–16 for the GEFS, and days 1–3 to days 3–5 for WWRF (note that the WWRF forecast horizon is five days).

Figure 6-10 shows the performance of the three models in the Yuba watershed using the coefficient of determination (R^2), RMSE, and bias for the GEFSv12 (blue), WWRF (red), and GEFSv10 (green) models with 95 percent confidence intervals shown. Using an $R^2 \geq 0.5$ as a threshold for reasonable association (Murphy 1995), GEFSv10 and GEFSv12 explain at least 50 percent of the variance in observed three-day MAP out to the six- to eight-day lead time. WWRF also shows skill in the Yuba watershed through its five-day forecast and a modest improvement in variance captured for a one- to three-day lead time compared to both GEFS models. Overall, the differences in the two versions of GEFS are not statistically significant in either watershed, except for the bias. In the Yuba watershed, GEFSv10 shows a dry bias and GEFSv12 shows a wet bias throughout the one- to 16-day lead time. In the Feather watershed (not shown), GEFSv10 shows a wet bias for one- to six-day lead times, then a dry bias for seven- to 16-day lead times. WWRF also has a wet bias for one- to five-day lead times—a larger one than GEFSv12. This difference in bias is most likely a result of the resolution differences between GEFSv10 (~111 km), GEFSv12 (~50 km), and WWRF (3 km). Finally, WWRF and GEFSv10 have similar (not statistically significant) RMSE between 0.6 and 0.8 inches from days 1–5, but GEFSv12 appears to have a lower (statistically significant) RMSE than WWRF. The Feather and Yuba watersheds are some of the wettest in the Sierra Nevada, and these results are consistent with other studies showing that higher-resolution numerical guidance overestimates precipitation in the Sierra Nevada (Caldwell et al. 2009; Hughes et al. 2020).

Figure 6-11 shows the results for the more extreme rainfall events that exceed the 90th percentile of three-day observed MAPs for December–March 1989–2017 in the Feather watershed. The three-day total threshold value was 2 inches for the Feather, which generated 367 observed events in the analysis. The symmetric extremal dependence index (SEDI) better conveys the skill of rare events by logarithmic scaling of contingency table metrics (e.g., hit rate). Heidke skill score, which describes the proportion of correct forecasts compared to chance, was also used. The SEDI score is above 0 for all lead times out to six to eight days for GEFS versions, whereas the Heidke skill score(see Appendix P) is above 0.5 through a five- to seven-day lead time. WWRF tends to perform better than GEFSv10 in the Feather watershed through lead times of one to three days (two to four days using the SEDI score). GEFSv12 tends to have a better Heidke skill score in the Yuba watershed (see Appendix P) than WWRF and GEFSv10, but not to a statistically significant degree. Overall, this analysis suggests that the global and regional forecasts can capture the observed 72-hour precipit ation (better than a random forecast), including larger events, out to five to eight days' lead time and that each forecast model has systematic biases that could be addressed to better estimate hydrologic responses within the watersheds.

Note that the long accumulation time and smoothing (aerial averaging) of the precipitation within the watershed broaden the target for precipitation skill. Intra-watershed variability in precipitation distributions, especially in places of complex networks of flows, can play an important role in decision making for FIRO. Additional analysis, including shorter aggregation times, may better highlight benefits and/or differences across the models that could provide added value for FIRO viability. Conversely, little separation between models could provide enhanced confidence for forecasts used in decision making.

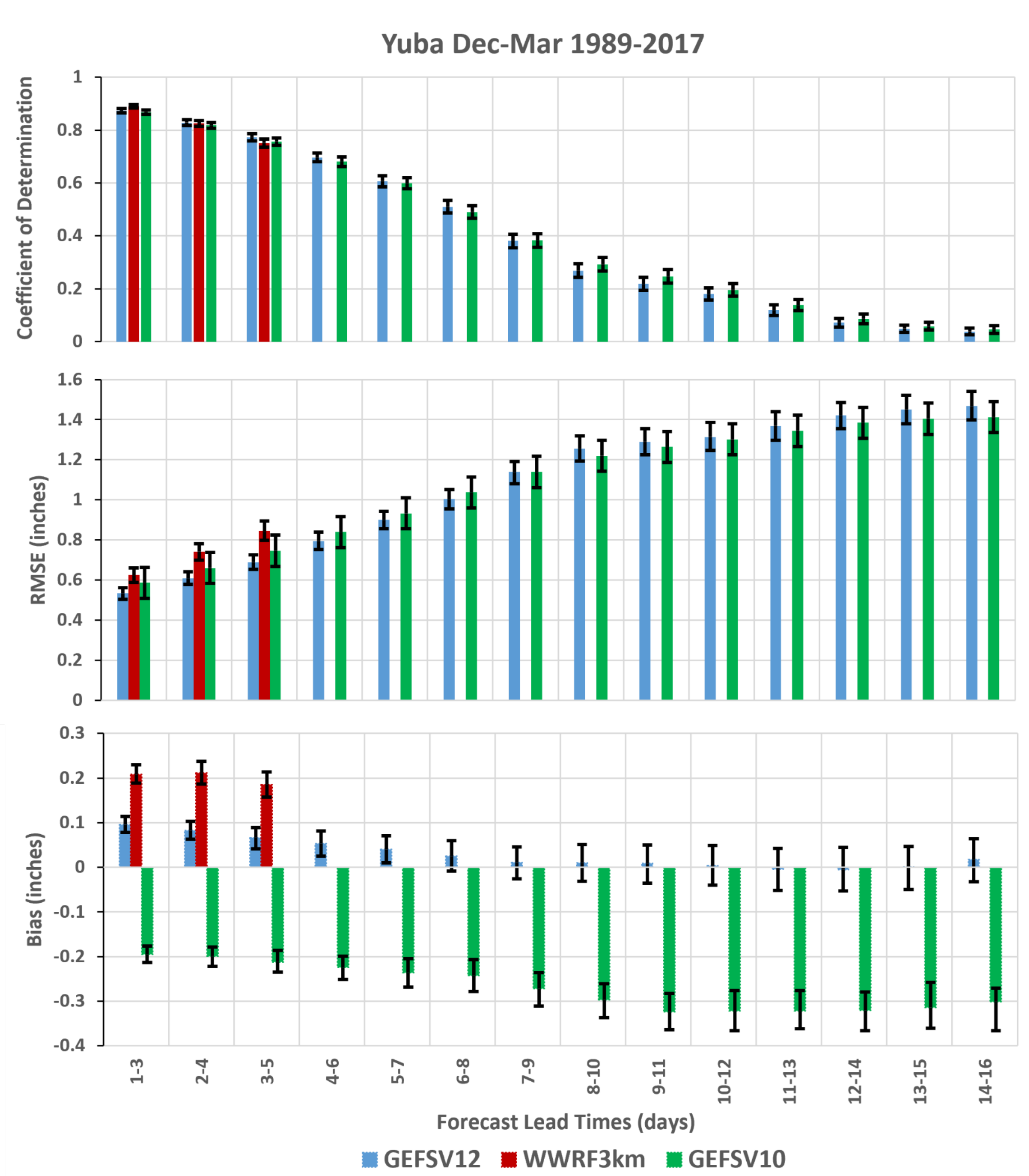


Figure 6-10. *R^2, RMSE (inches), and bias (inches) for 72-hour MAP for the GEFSv12 ensemble mean, WWRF 3-km, and GEFSv10 ensemble mean for the Yuba watershed for December through March 1989–2017. Error bars denote 95 percent confidence intervals.*

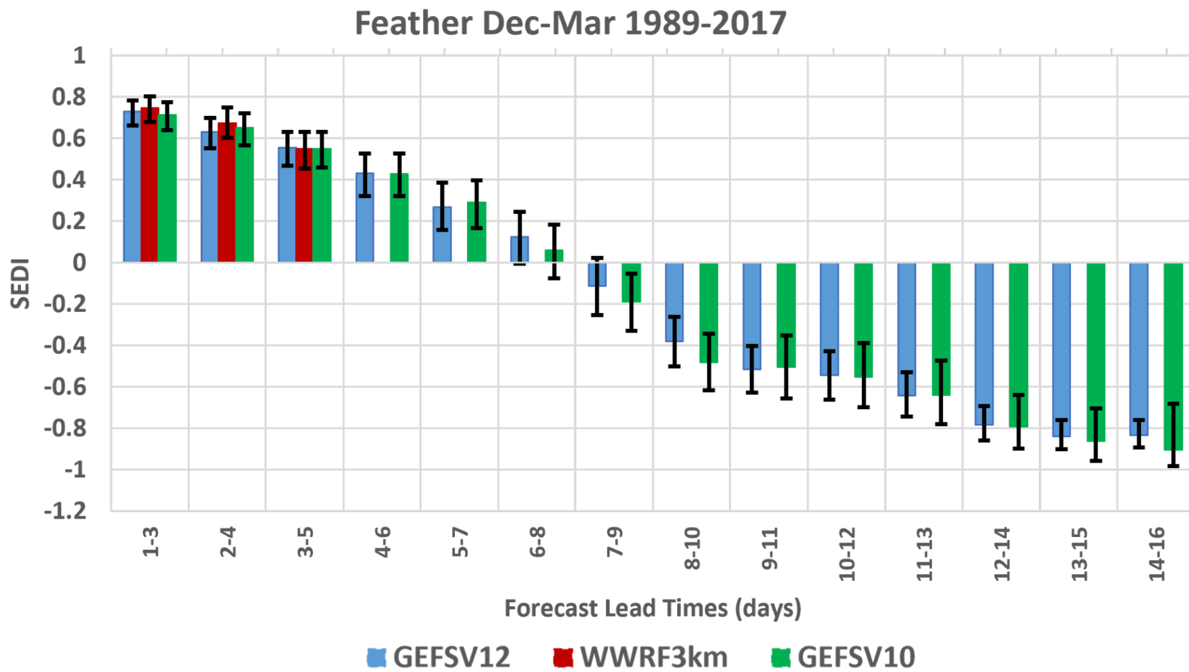


Figure 6-11. *SEDI for the 90th percentile three-day observed MAP for the Feather basin. Error bars denote 95 percent confidence intervals.*

Table 6-5 shows the bias and percent error of GEFSv12 and WWRF QPF at a lead time of three to five days for the 10 largest observed (non-overlapping) 72-hour precipitation periods in the Yuba watershed during the analysis period. Overall, both the GEFSv12 ensemble mean and WWRF deterministic forecasts performed reasonably well for these upper-right tail events. The average 72-hour QPF bias was -1.2 inches for the GEFSv12 ensemble mean and 0.9 inches for WWRF, suggesting that GEFSv12 tends to underestimate the most extreme events in the Yuba watershed and WWRF tends to overestimate them. The average forecast error for these 10 events was 23 percent for the GEFSv12 ensemble mean and 20 percent for WWRF. Most GEFSv12 and WWRF forecasts were within 30 percent of the observed values, and only one WWRF forecast exceeded a percent error of 50 percent. Smaller forecast errors were found in the Feather watershed, especially for the WWRF forecasts (see Appendix P). These results suggest that, on the watershed scale, both GEFSv12 and WWRF can produce realistic forecasts of the most extreme 72-hour precipitation events in the Yuba and Feather watersheds at lead times of three to five days.

Note that the initial conditions used to force the GEFSv12 forecasts were modified around 1999, and thus are not consistent through the study period. In the Feather watershed, for example, R^2 is statistically higher in the 2000–2017 period than the 1989–1999 period at lead times of two to four, three to five, four to six, and five to seven days. The RMSE is consistently lower during the second period than during the first, with a statistically significant difference at lead times up to five to seven days (see Appendix P for more details). Although the sample sizes between the two periods are different, it is important to recognize improved skill as models continue to improve over time.

Table 6-5. *Largest non-overlapping observed three-day MAP in the Yuba watershed during the entire analysis period and the corresponding GEFSv12 and WWRF QPF bias and percent error at a lead time of three to five days.*

Valid Date	QPE	GEFSv12 Bias	GEFSv12 Percent Error	WWRF Bias	WWRF Percent Error
January 3, 1997	11.75	-1.49	12.68%	0.28	2.38%
January 11, 2017	10.19	-3.71	36.41%	0.49	4.81%
March 12, 1995	9.22	1.98	21.48%	0.33	3.58%
February 10, 2017	8.73	-1.26	14.43%	2.99	34.25%
January 11, 1995	8.62	1.58	18.33%	2.08	24.13%
March 5, 1991	8.17	-2.14	26.19%	-0.16	1.96%
December 14, 1995	7.82	-0.18	2.30%	-1.43	18.29%
February 11, 2014	7.76	-2.51	32.35%	1.97	25.39%
March 17, 2012	7.54	-2.29	30.37%	4.59	60.88%
December 17, 2002	7.37	-2.28	30.94%	-2.05	27.82%
Mean		**-1.23**	**22.55%**	**0.91**	**20.35%**

6.4.3 Freezing Level Error

The Sierra Nevada Mountains lie within an elevation range that commonly fluctuates between above- and below-freezing temperatures during winter storms. Freezing level height (Z_{FL}) forecast error can influence the distribution and phase of precipitation over the watersheds and influence the resulting hydrologic impacts. Using an average ±350 m Z_{FL} forecast error at one- to three-day lead times for the Sierra (Henn et al. 2020), Sumargo et al. (2020) developed a simplified approach that found inflow volume uncertainties of under 10 percent to over 50 percent of the flood pool storages at the ORO and NBB, depending on the Z_{FL}, antecedent moisture condition, and precipitation event magnitude. This result emphasizes the significant impact small Z_{FL} forecast errors may have and the critical need for Z_{FL} forecast accuracy for reservoir and flood control operations in the Yuba and Feather watersheds.

Baseline Z_{FL} forecast skill metrics are evaluated at ORO (OVL, 114 m elevation), and Colfax (CFF, 644 m elevation) using archived real-time forecasts from the CNRFC and existing field campaign observations. The CNRFC Z_{FL} forecast data were evaluated over eight cool seasons (November through April) between WY2013 and WY2021. Freezing level forecasts from the CNRFC are available from their data archive website (https://www.cnrfc.noaa.gov/arc_search.php) and are initialized daily at 12:00 Coordinated

Universal Time. Existing field campaign observations include Frequency-Modulated Continuous Wave (FMCW) snow level radar (Johnston et al. 2017) at CFF and OVL. Field observations from the FMCW at CFF and OVL were downloaded from https://psl.noaa.gov/data/obs/datadisplay/. The FMCW data are collected at 10-minute intervals. We resampled the observations by finding the mean FMCW value of a 50-minute window, centered on each valid time. This gave us 161 total window pairs at CFF and 160 at OVL. The Z_{FL} forecast data were evaluated with matched observations and forecasts valid at 12:00 Coordinated Universal Time at four 24-hour interval lead times. For each period of record, R^2, RMSE, and bias were calculated.

Figure 6-12 shows the baseline skill metrics for the CNRFC Z_{FL} forecasts at CFF and OVL. R^2 ranges between 0.5 and 0.75 (i.e., forecast captures 50 to 75 percent of the variance of observations) within a 24-hour lead time at CFF and OVL, respectively, and decreases to 0.4 at a 96-hour lead time. RMSEs are twice as large or more than the average bias, which might indicate that the CNRFC forecasts suffer from large random errors. Overall, OVL has less skill than CFF. The two sites are separated by about 70 km and differ in elevation by about 530 m. This result might suggest that local thermodynamic effects, observation quality, and/or timing of AR conditions on scales of over 100 km have some impact on forecast accuracy.

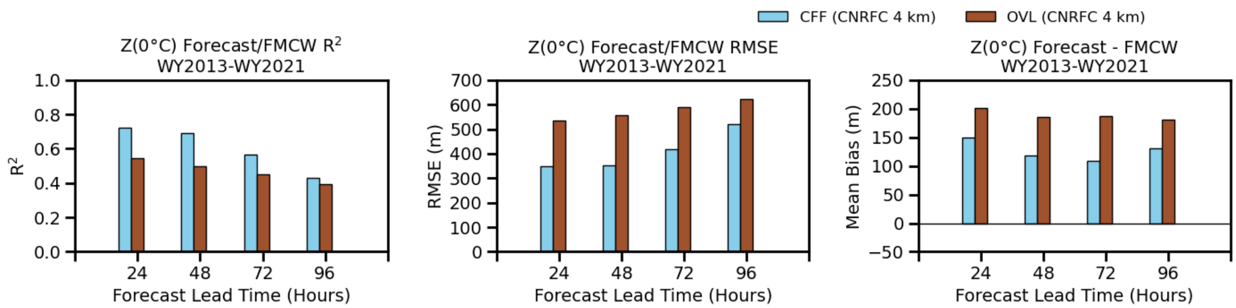
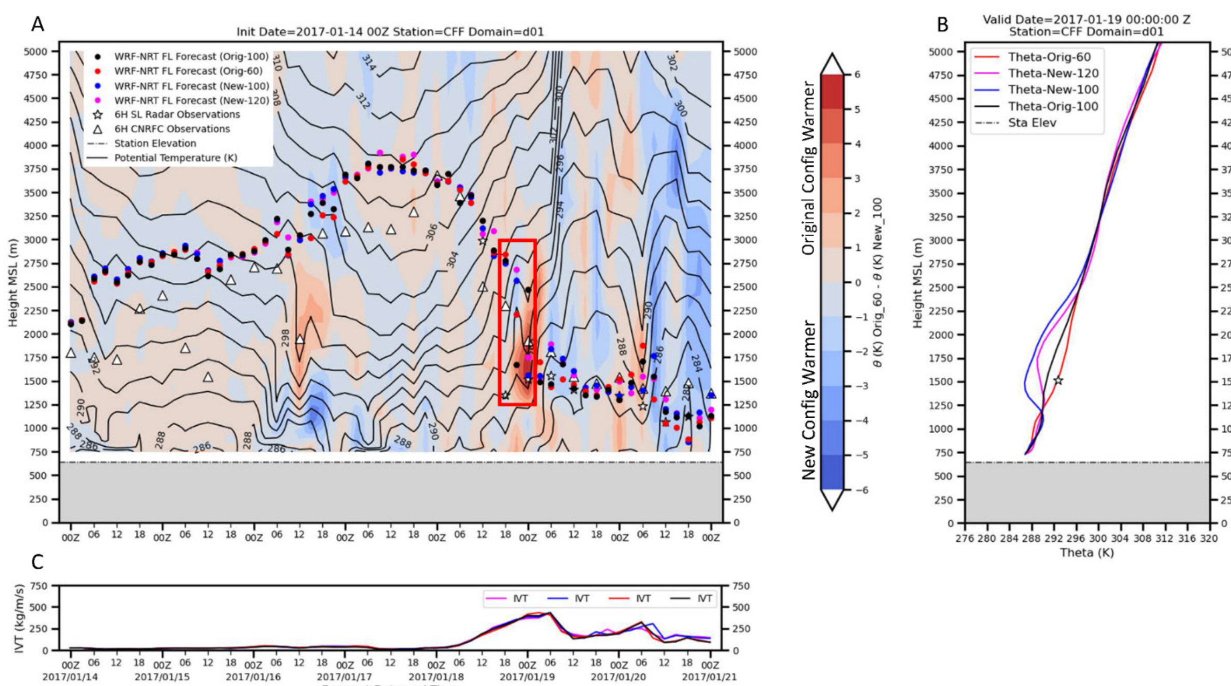


Figure 6-12. *CNRFC freezing level forecast R- (left), RMSE (middle), and mean bias (right) at Colfax (CFF, blue) and Oroville (OVL, brown) as a function of forecast lead time. Forecasts were evaluated for the cool seasons of WY2013 through WY2021.*

There are several challenges in association with adequately observing freezing level. The brightband height, or the altitude of the maximum radar reflectivity from the FMCW, represents the layer in which the hydrometeors change phase (White et al. 2002). The 0°C isotherm is assumed to be above this layer to compensate for the time/depth of melt to occur and subsequent hydrometer breakup. Henn et al. (2020) previously found the depth of the hydrometeor melt level to be on the order of 138–236 m. This depth can also play a role in accurately forecasting the freezing level, where the cooling effects from evaporating/melting hydrometeors within the melt layer can, in certain environments, lead to an expansion of the isothermal melt layer, helping to lower the Z_{FL} (Kain et al. 2000). Forecast models may not detect the depth of these isothermal layers, since it is highly dependent upon the precipitation rate. Isothermal layers are a source of uncertainty, as assumptions are needed to possibly account for thaw and refreeze processes (N. Patrick, personal communication, March 2022). All of these factors are also affected by the precision of the FMCW radar return, which limits the degree to which forecast errors can be minimized (in this case, the FMCW resolution at OVL and CLF is 40 m). Finally, the profiler network throughout California is spatially limited and may not be situated correctly to capture locally generated differences in the Z_{FL} due to processes such as downward bending of the melt level near the foothills of the Sierra (Minder & Kingsmill 2013).

Similar challenges exist when calculating freezing levels from high-resolution forecasts. In addition to differences between the brightband height and the 0°C isotherm, comparisons of forecasts to observations can be affected by, e.g., the vertical resolution of the model. Figure 6-13 shows the comparison of the freezing level between four different configurations of the West-WRF NRT model from an event beginning January 14, 2017. The simulations differ in the total number of levels and the distribution of levels within the lowest 5 km. The profiles marked *orig* represent configurations in which the default WRF model stacking structure is used, whereas the profiles marked *new* represent stacking structure that mimics (i.e., is interpolated from) the ECMWF model in the lowest 5 km. The total model levels span between 60 and 120 vertical levels. The dots in Figure 6-13A represent the calculated Z_{FL} from each WWRF configuration and show a clear trend in the Z_{FL} over time. At most times, Z_{FL} differences are 250 m or less. However, there are timesteps where the difference is over 1,000 m (e.g., January 19, 2017 at 0:00 Coordinated Universal Time, just after the onset of possible AR conditions; see Figure 6-13C). At this time step, there is a large difference in potential temperature (on the order of 5–6°C) between the original 60-level configuration and the new 100-level configuration. Figure 6-13B shows that all four WWRF configurations have different potential temperatures between 1,200 and 2,600 m in height, with the new 100 WWRF configuration showing a large temperature inversion. It should also be noted that the forecasted Z_{FL}s across all configurations in the previous timestep are greater than the observed Z_{FL}s by 1 km. After the mean Z_{FL} bias was calculated over all start dates, stations, and WWRF domains, the new 100-level configuration was shown to have the most skill. However, the sample size from this study is quite small (222 pairs), and more robust analyses must be performed. More research should be done to identify and attempt to account for these major sources of forecast and



observational Z_{FL} error.

Figure 6-13. *(A) Vertical profile time series plot at CFF, beginning January 14, 2017, using the 9 km domain, of θ from the default 60-level WWRF configuration (black contours), difference in θ between the original 60 and new 100 WWRF configurations (shading), calculated Z_{FL} from each WWRF configuration (dots; colors represent each WWRF configuration), FMCW observations (stars), and CNRFC observations (triangles). (B)*

Vertical profile of θ from each WWRF configuration on January 19, 2017, at 0:00 Coordinated Universal Time. The star is the FMCW observation from (A) at the same time. (C) Time series of IVT beginning January 14, 2017.

6.4.4 72-Hour Inflow Error

Forecasts of 72-hour inflow to NBB and ORO Reservoirs are evaluated with potential science goals of (1) providing baseline meteorological/hydrological forecast skill in order to assess future model improvements, (2) understanding the priority forecast skills for FIRO needs, and (3) determining relationships between event characteristics and model skill. The CNRFC's deterministic forecasts and probabilistic/ensemble hindcasts were chosen to accomplish this objective, given that they are a primary source for Yuba-Feather operations.

The ensemble hindcasts were generated using NWS's HEFS in 2015. By design, HEFS translates an ensemble of meteorological inputs through hydrologic models—in this case a coupled snow (SNOW-17)-soil (SAC-SMA) model—to produce an ensemble of streamflow outputs. The ensemble meteorological inputs are produced as meteorological forecast uncertainties using a statistical model called MEFP. MEFP is based on the GEFSv10 precipitation and temperature reforecast datasets that are available from 1985 to 2010. More details on the hindcasts, HEFS, and MEFP can be found in Section 6.2.

Table 6-6 shows the Brier scores for the CNRFC ensemble hindcasts for all time periods versus during AR events only. Lower Brier scores indicate better performance. These results indicate that the hindcast has better performance in predicting 95th percentile flows, particularly during AR events (versus non-AR extreme events), out to seven to nine days and that NBB and ORO have relatively equal skill at this threshold.

Table 6-6. *Brier scores of CNRFC ensemble inflow hindcasts for 1985–2010 at NBB and ORO. The scores are computed with a 95th flow percentile threshold, for lead time aggregates of one to three, four to six, and seven to nine days and for all-time and AR-only scenarios.*

Lead Time Aggregate	Brier Score (All Time)		Brier Score (AR Only)	
	NBB	ORO	NBB	ORO
1–3 days	0.5	0.51	0.39	0.39
4–6 days	0.49	0.48	0.36	0.36
7–9 days	0.49	0.47	0.35	0.35

Figure 6-14 shows the ensemble forecasts' mean biases and RMSEs of the three-day inflow volumes at NBB and ORO for rolling lead time aggregates of one to three days. Three different scenarios are considered: all time, top 5 percent forecast inflow events, and top 5 percent forecast AR-inflow events (i.e., only those coinciding with the AR periods as indicated in the Rutz AR Catalog) between 1985 and 2010. The top 5 percent AR-inflow scenario tends to have a larger and more negative bias and RMSE, especially at longer lead times, except the all-time cases show near zero to slightly positive biases. The variation among the ensemble members is also significant, particularly in the top 5 percent AR-inflow scenario and at longer lead times. Both top 5 percent inflow scenarios, however, exhibit both positive and negative biases across the ensemble members, with mostly negative biases in the ensemble means and interquartile ranges.

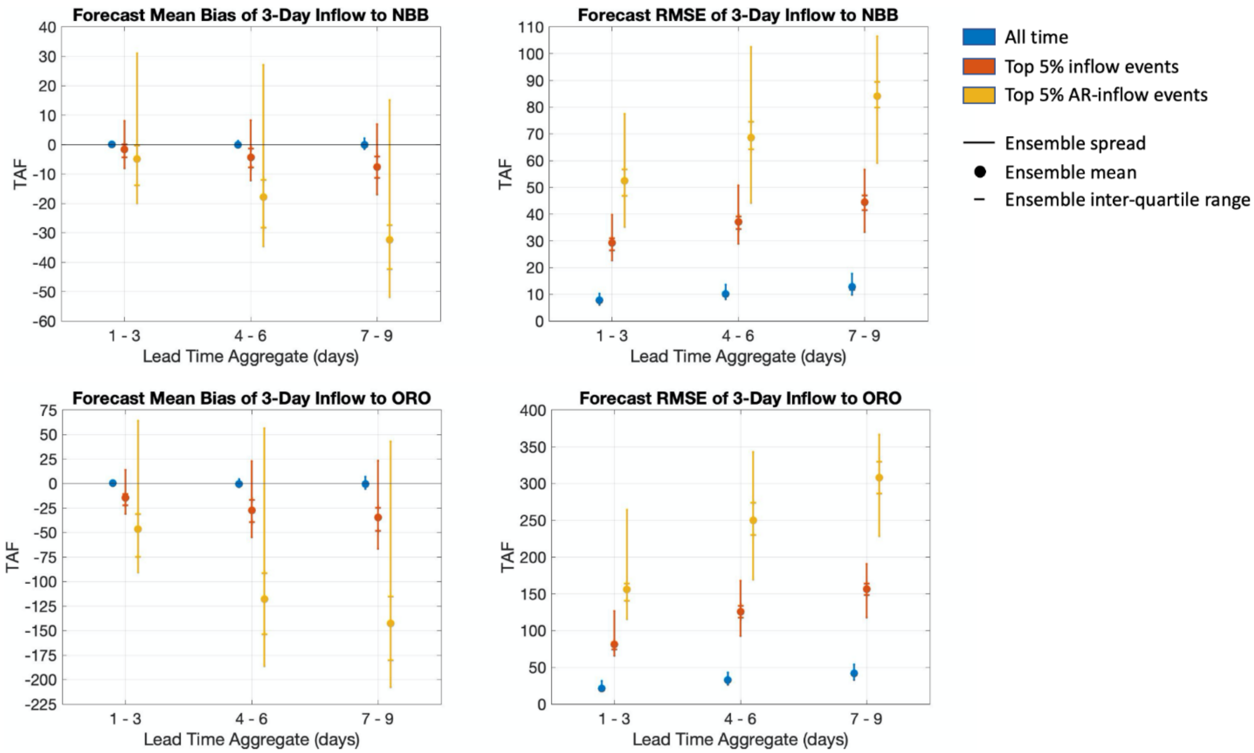


Figure 6-14. *Ensemble forecasts' mean biases (left) and RMSE (right) of three-day inflows to NBB (top) and ORO (bottom) against full natural flows. The colors denote different scenarios: all time (blue), top 5 percent inflow periods (red), and top 5 percent inflow periods corresponding to AR events only (yellow). The lines denote the ensemble spreads, while the circles denote the ensemble means and the stripes denote the interquartile ranges.*

Deterministic forecasts are available for the New Year 1997 AR event at ORO and for 2005 onward at both NBB and ORO. Deterministic forecasts were provided by the CNRFC (the archive is also available for 2015 onward on the CNRFC website, https://www.cnrfc.noaa.gov/csv). The deterministic forecasts are driven by locally developed QPF and temperature forecast products derived from a variety of NWP models and operational sources. Furthermore, the forecasts are generated daily with lead times of five days or less.

They account for upstream regulations, such that they are directly comparable to observed inflow. Reservoir inflow observations are mostly available at a daily resolution from CDEC (https://cdec.water.ca.gov/). When they are not available, the CNRFC also maintains the daily observation archives. For this reason, many of the evaluations focus on a daily time step. The correlations, mean biases, and RMSEs of the 24-hour deterministic reservoir inflow forecasts at NBB and ORO are computed against the daily observations. The computations are repeated for different forecast lead times from one to five days and for different periods: all time, winter (December–February: DJF), spring (March–May: MAM), summer (June–August: JJA), and autumn (September–November: SON) from 2005 onwards, corresponding to the period of availability.

The results in Figure 6-15 indicate that the correlations between the forecasts and observation are above 0.75 in most cases, even when evaluated at different seasons, except in autumn at ORO. (Note that summer cannot be evaluated due to the lack of forecast data availability). Similar results occur in the RMSE, which increases with the lead time (mostly by less than 25 percent from one to five days), except in winter at NBB, where it decreases with the lead time (by about 15 percent from one to five days). On the other hand, the mean biases become more negative with lead time in both NBB and ORO cases. This variation is largest in the winter—when the biases are positive at one- to two-day lead times and negative at longer lead times—and smallest in the autumn. Over the period of record from 2005 onward, the forecast biases become 11 percent overestimation for NBB and 8 percent overestimation for ORO when evaluated during the top 5 percent forecast inflows; they are 17 percent overestimation for NBB and 15 percent overestimation for ORO when evaluated during AR-event inflows only.

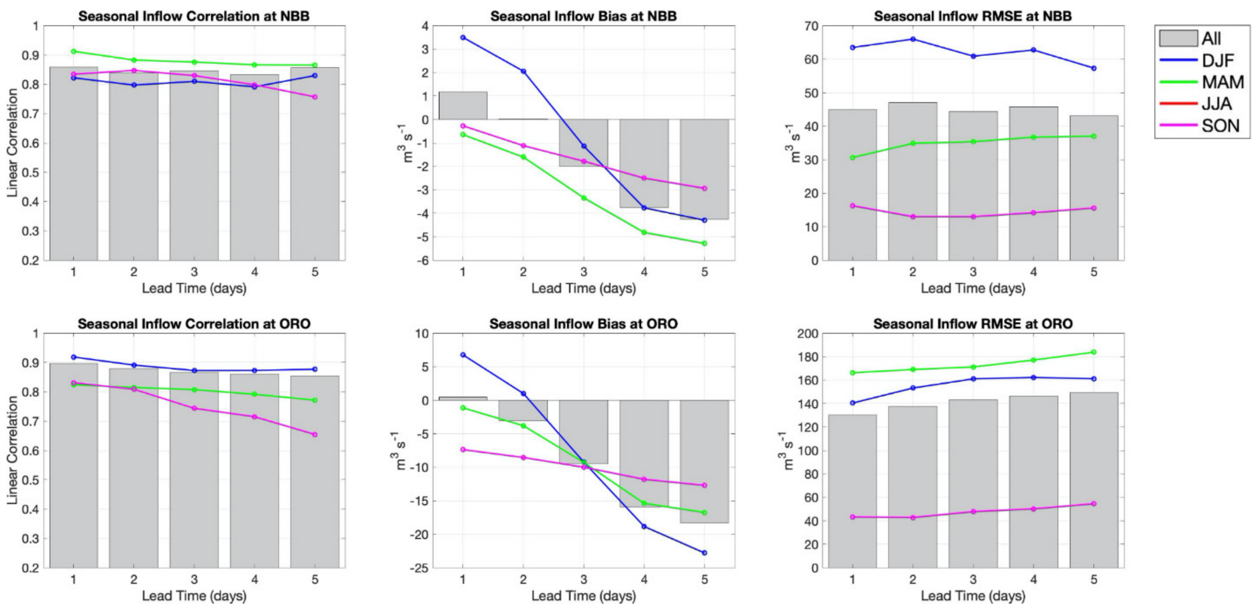


__Figure 6-15.__ The seasonal correlations (left), mean biases (middle), and RMSE (right) of daily deterministic inflow forecasts to NBB (top) and ORO (bottom) against observations. The bars indicate all seasons, while the colored lines indicate the individual seasons: winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

Several case studies of 72-hour inflow were conducted to give context on forecast skill during memorable events (see Appendix P for more details). For each of the evaluated initialization dates, the verification team computed the 72-hour (or three-day) inflows for NBB and ORO by summing up the inflow forecasts/hindcasts (hereby simply forecasts) with rolling lead-time aggregates for one to three, four to six, and seven to nine days from the initialization dates/times. For example, the 72-hour inflow deterministic forecasts initialized on February 3–9, 2017, leading toward the ORO Dam crisis, underestimate the three-day inflow volumes after February 7 in both NBB and ORO cases (by an average of 31 percent at NBB and 17 percent at ORO). The ORO result is similar to the New Year 1997 AR event (see Appendix P).

These findings suggest forecasted flows during AR events are critical for water management decisions in the Yuba-Feather region. Efforts to understand patterns of forecast errors and ways to improve them, specifically with the underestimation of extreme event inflows at seven- to nine-day lead times, will likely yield positive outcomes for FIRO implementation.

6.4.5 Findings

Key findings include:

Key Findings

- For landfalling ARs,
  - Landfall forecasts using West-WRF have skill up to seven days in advance for weaker ARs and up to four days in advance for stronger ARs.
  - Out of the total strong ARs hitting the Yuba/Feather region, 86 percent are correctly detected at a three-day lead time, 80 percent at a five-day lead time, and 53 percent at seven-day lead time.
- For 72-hour total MAP,
  - GEFSv10 and GEFSv12 show forecast skill out to six- to eight-day lead time across the Yuba and Feather basins; West-WRF reforecast is skillful out through its full five-day lead time.
  - The average forecast error for the top 10 events was between 20 and 23 percent across models.
- For freezing level,
  - Freezing level forecast skill from CNRFC forecasts extends to two-day lead times at ORO and three-day lead times at Colfax profiler locations.
  - Major sources of uncertainty exist for the detection and precision of the freezing level observation/forecast.
- For inflow forecasts,
  - CNRFC hindcast ensemble forecasts perform better (a 30 percent improvement in skill) in predicting 95th percentile flows during AR events (as opposed to extremes not driven by AR events) at NBB and ORO.
  - The ensemble forecasts of top 5 percent AR-event inflows tend to be under-forecasted at longer lead times.

6.4.6 Recommendations

The following are recommendations developed and coordinated with the hydrology, observations, WRE, and meteorology teams as a result of the skill assessments of the PVA:

- Examine skill/relationships between operational and reforecast QPF as input for MEFP and correlations to inflow forecasts.
- Continue to investigate skill in the timing and magnitude of high-intensity rainfall events in high-resolution models.
- Develop a catalog of different verification skill scores matched to different scales of meteorological mechanisms within ARs and other extreme events.
- Explore other important AR position- and duration-related metrics to quantify forecast skill.
- Continue to evaluate other aggregation periods (e.g., three-day total vs. seven-day total inflow) of forecasts based on operational needs.
- Expand verification of forecasted inflow to Lake Englebright in order to study the impacts of unregulated flows of the Yuba River.
- Explore seasonal water supply and/or snowpack-related forecast skill and necessary metrics for verification.
- Continue to investigate sources of errors in freezing level radar observations and forecasts including hydrometeor melt levels, isothermal layers, and brightband height uncertainty.
- Evaluate surface air temperature as it relates to impacts of snowmelt and runoff generation during AR events.
- Develop forecast skill assessments for probabilistic precipitation, landfall, and freezing level forecasts.
- Continue to investigate sources of error in probabilistic forecasts of reservoir inflows (including through an updated verification of the GEFSv12 hindcasts when it becomes available) and additional metrics to convey reliability of forecasts.
- Quantify relationships between the ensemble and deterministic inflow forecasts during overlapping periods in order to identify key distributions of forecast spread and uncertainty during extreme precipitation events.
- Continue to develop a case study analysis of the New Year 1997 event, including comparisons between archived forecasts and those using current models and tools.
- Continue to examine different spatial and temporal scales of forecast uncertainty and how they can influence hydrologic outcomes in case studies.

6.4.7 References

Brown, J. D., He, M., Regonda, S., Wu, L., Lee, H., & Seo, D. J. (2014). Verification of temperature, precipitation, and streamflow forecasts from the NOAA/NWS Hydrologic Ensemble Forecast Service (HEFS): 2. Streamflow verification. *Journal of Hydrology*, *519*, 2847-2868.

Caldwell, P., Chin, H.-N. S., Bader, D. C., & Bala, G. (2009). Evaluation of a WRF dynamical downscaling simulation over California. *Climatic Change, 95,* 499–521. https://doi.org/10.1007/s10584-009-9583-5

Davis, C., Brown, A., Bullock, R., & Halley-Gotway, J. (2009). The Method for Object-Based Diagnostic Evaluation (MODE) applied to numerical forecasts from the 2005 NSSL/SPC Spring Program. *Weather and Forecasting, 24*(5), 1252–1267.

Delaney, C. J., Hartman, R. K., Mendoza, J., Dettinger, M., Delle Monache, L., Jasperse, J., Ralph, F. M., Talbot, C., Brown, J., Reynolds, D., & Evett, S. (2020). Forecast Informed Reservoir Operations using ensemble streamflow predictions for a multipurpose reservoir in northern California. *Water Resources Research, 56*(9), e2019WR026604. https://doi.org/10.1029/2019WR026604

Henn, B., Weihs, R., Martin, A. C., Ralph, F. M., & Osborne, T. (2020). Skill of rain–snow level forecasts for landfalling atmospheric rivers: A multi-model model assessment using California's network of vertically profiling radars. *Journal of Hydrometeorology, 21*(4): 751–771. https://doi.org/10.1175/JHM-D-18-0212.1

Hughes, M, Lundquist, J. D., & Henn, B. (2020). Dynamical downscaling improves upon gridded precipitation products in the Sierra Nevada, California. *Climate Dynamics*, *55,* 111–129. https://doi.org/10.1007/s00382-017-3631-z

Johnston, P. E., Jordan, J. R., White, A. B., Carter, D. A., Costa, D. M., & Ayers, T. E. (2017). The NOAA FM-CW snow-level radar. *Journal of Atmospheric and Oceanic Technology*, *34*(2), 249–267. https://doi.org/10.1175/JTECH-D-16-0063.1

Kain, J. S., Goss, S. M., & Baldwin, M. E. (2000). The melting effect as a factor in precipitation-type forecasting. *Weather and forecasting*, *15*(6), 700–714. https://doi.org/10.1175/1520-0434(2000)015<0700:TMEAAF>2.0.CO;2

Minder, J. R., & Kingsmill, D. E. (2013). Mesoscale variations of the atmospheric snow line over the northern Sierra Nevada: Multiyear statistics, case study, and mechanisms. *Journal of the Atmospheric Sciences*, *70*(3), 916–938. https://doi.org/10.1175/JAS-D-12-0194.1

Murphy, A. H. (1995). The coefficients of correlation and determination as measures of performance in forecast verification. *Weather and Forecasting, 10*(4), 681–688. https://doi.org/10.1175/1520-0434(1995)010<0681:TCOCAD>2.0.CO;2

Ricciotti, J. A., & Cordeira, J. M. (2022). Summarizing relationships among landfalling atmospheric rivers, integrated water vapor transport, and California watershed precipitation 1982–2019. *Journal of Hydrometeorology*, 23(9), 1349–1454. https://doi.org/10.1175/JHM-D-21-0119.1

Roebber, P. J. (2009). Visualizing multiple measures of forecast quality. *Weather and Forecasting, 24*(2), 601–608. https://doi.org/10.1175/2008WAF2222159.1

Sumargo, E., Cannon, F., Ralph, F. M., & Henn, B. (2020). Freezing level forecast error can consume reservoir flood control storage: Potentials for Lake Oroville and New Bullards Bar reservoirs in California. *Water Resources Research, 56*(8), e2020WR027072. https://doi.org/10.1029/2020WR027072

[USACE] U.S. Army Corps of Engineers & David Ford Consulting Engineers. (2015). *Central Valley hydrology study.* https://www.hdrinc.com/sites/default/files/inline-files/hdr-central-valley-hydrology-study-report.pdf

White, A. B., Gottas, D. J., Strem, E. T., Ralph, F. M., & Neiman, P. J. (2002). An automated brightband height detection algorithm for use with Doppler radar spectral moments. *Journal of Atmospheric and Oceanic Technology*, 19(5), 687–697. https://doi.org/10.1175/1520-0426(2002)019<0687:AABHDA>2.0.CO;2

Section 7. FIRO Implementation

7.1 Decision Support Systems

Decision support tools (DSTs) are an essential component of reservoir operations. They are widely applied to support release decisions associated with nearly all reservoirs. Water Control Plans (WCPs) used to manage U.S. Army Corps of Engineers (USACE) flood control space have been traditionally engineered to use observations (water on the ground) as the basis for release decisions. Observations, while not perfect, are relatively certain. Forecasts have proven adequately skillful and are considered in the decision-making process, but until recently they have never been formally used. They are uncertain, and that uncertainty increases with lead time—meaning that formal use of forecasts adds a challenging dimension to DSTs.

Data are simply a collection of facts; information puts those facts into context. A decision support system (DSS) is an information system from a related set of tools that supports decision making. A DSS for FIRO is needed to give operators and decision makers current and forecast information about a reservoir system to make informed decisions that meet the established operational objectives. The operation of reservoirs can be very dynamic: current and forecast weather can change very quickly, forcing reservoir operators and decision makers to adjust multiple times per day. A DSS should represent the systemization of a FIRO WCP and the contextual information needed to confidently apply it. To facilitate that, a WCP plan should be defined in a fashion that can be represented by a DSS and should define the necessary attributes of a DSS for implementation.

FIRO information users and decision makers can include reservoir operators, water suppliers, emergency managers, resource managers for fisheries and recreation, forecasters, researchers, and public safety officials. A DSS should be developed to assist all these interests in making decisions related to flood control operations. A consistent source and picture of current and forecast conditions facilitates communication and coordination across the full spectrum of decision-making objectives and associated flood mitigation actions. Figure 7-1 illustrates how a DSS could provide a systemized WCP. It shows the different layers of information provided in a DSS and how different decision makers might interface with these layers. For example, the reservoir operators will mostly work with the reservoir operations models, whereas emergency managers will likely be more interested in weather and water forecasts and associated potential impacts. The figure also shows that all layers of a DSS are informed by a consistent set of data and information to provide a common operating environment for all decision makers.

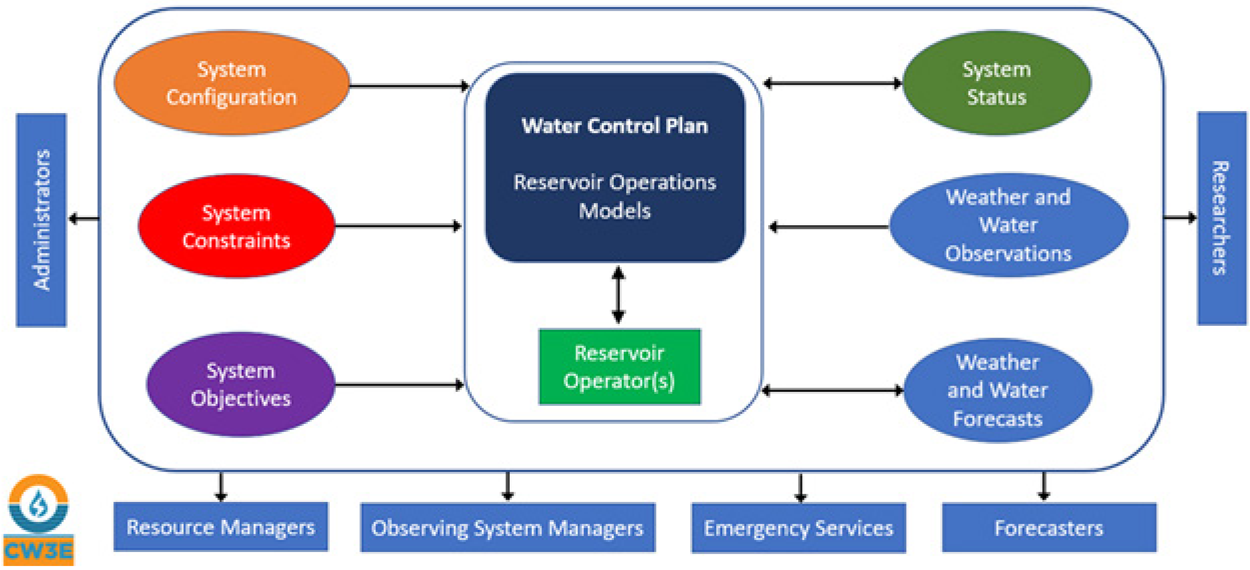


Figure 7-1. *DSS as a systemized WCP.*

7.1.1 Decision Support for the Yuba-Feather System

As described in Section 2, Lake Oroville (ORO) and North Bullards Bar (NBB) flood control operations share responsibility for keeping the Feather River flows at Yuba City and Nicolaus within the safe channel capacity. The need for improved decision support and coordination was recognized following the 1997 flood and resulted in the Forecast-Coordinated Operations (F-CO) project also described in Section 2. The F-CO DSS provides a common operating environment that accounts for system and operational constraints and uses forecast information to help with reservoir operations and the coordination of reservoir releases. The F-CO DSS (including the HEC-ResSim model) reflects the procedures in the existing ORO and NBB WCPs that do not use explicitly use forecast information (FIRO or another method) to formulate release options.

The DST team reviewed and documented existing Yuba-Feather DST tools, identified potential gaps and opportunities for improvement, and developed strategies for supporting FIRO in the Yuba-Feather system.

7.1.2 DST Inventory

Existing and emerging DSTs were reviewed to determine the benefits and limitations of individual tools with a particular focus on managing large winter storm events. The inventory identified over 30 existing DSTs, including tools for real-time reservoir operations, agency-specific reservoir operations, and forecasting and situational awareness. A detailed report on the organization responsible for the DST, DST description, and DST function and status can be found in Appendix Q. The inventory was used to establish the baseline and reference for the gap analysis.

7.1.3 The DST Gap Analysis

Objectives of DST Gap Analysis

- Build an understanding of existing DSTs, including DSS, forecasting tools, and other supporting situational awareness tools used to support real-time reservoir operation decision making for flood and water supply management within the Yuba-Feather watershed system and similar watersheds.
- Explore how existing DSTs meet decision maker/operator needs in the Yuba-Feather watersheds.
- Explore additional needs of decision makers/operators that have not currently been met by existing DSTs in the Yuba-Feather watersheds.

The DST gap analysis was informed by a DST symposium, a survey, and discussion with stakeholders:

- A symposium was held in October 2021 to present and expose the existing DSTs to the stakeholder group (decision makers and managers). Held in two half-day sessions, the symposium was extremely effective at developing understanding and creating discussion around DST interpretation and use.
- The DST gap survey was conducted to gather input on the informational gaps in DSTs and to identify needs and recommendations for enhancing and further evaluating DSTs.
- The symposium and survey were followed by discussions with the agencies responsible for operations, including the California State Water Project (SWP) operations office, the Yuba Water, and the USACE Sacramento District Water Management Section.

The gap analysis covered 18 DSTs, of which seven were DSS tools (for combining and processing information) and 11 were forecast and situational (observational) awareness tools. Surveys were completed by nine people: operators and managers associated with Yuba Water, the SWP, and USACE.

The analysis revealed that reservoir operators and decision makers were most familiar and knowledgeable with the F-CO DSS. The F-CO DSS is meeting the existing operational needs and operators are confident in using it. Most responses suggested that “no changes” were currently needed.

1.1.1.1 Findings

The gap analysis revealed one functionality gap and a series of knowledge gaps associated with forecasts and their application in DSTs. Specifically, there are gaps in:

- Functionality for balancing water storage across competing objectives to maximize benefits and minimize risks.
- Understanding of the Center for Western Weather and Water Extremes (CW3E) and National Oceanic and Atmospheric Administration (NOAA) forecast and observational products.
- Understanding of the uncertainty and accuracy of the forecast products.

The latter two suggest the need for training and/or better documentation of products available through CW3E and NOAA websites.

Through the Water Resources Engineering workgroup's evaluation of the FIRO WCP alternatives, reservoir operations modeling gaps associated with HEC-ResSim were identified. These gaps, described in Section 7.2, will need to be resolved in the Final Viability Assessment (FVA) to facilitate implementation of FIRO in the Yuba-Feather watershed system.

The gap analysis identified several DSS gaps including:

- The several DSTs available from multiple sources have not been effectively organized into a system (i.e., a DSS) that efficiently paints the picture of the current and expected conditions. This potentially underutilizes available DSTs while confusing decision makers.
- More portals and platforms for information exchange between operational models and tools are needed.

Key Finding

The F-CO DSS was identified as the best framework for supporting FIRO in the Yuba-Feather basin.

7.1.4 Supporting FIRO in the Yuba-Feather System

The Yuba-Feather F-CO program and the FIRO project have both commonalities and differences. The F-CO program has a well-established and successful history of investments in observations, forecasting support, training, a common operating environment for coordinated reservoir operations decision making, and improved communication. The major investments in the F-CO have already been made; the program is in a sustainable phase where modest investments will continue into the foreseeable future. The DST gap analysis clearly showed that reservoir operators use, understand, and value the F-CO DSS. The FIRO project complements the F-CO through the addition of meteorological research, the explicit use of forecasts in WCPs, and the linkage to Water Control Manual (WCM) updates. Figure 7-2 shows the components of each project and the common elements.

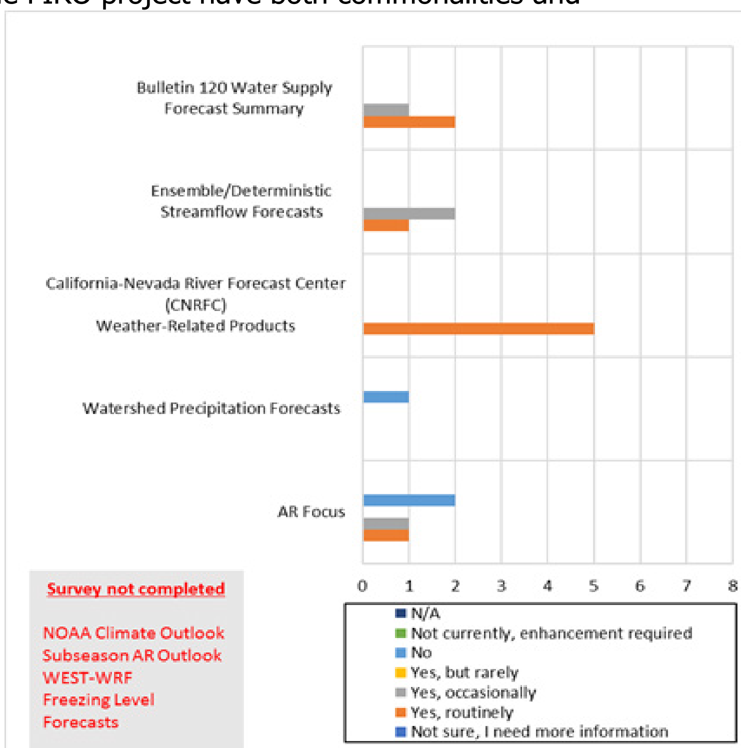


***Figure 7-2**. Components and common features of the Yuba-Feather F-CO and FIRO projects.*

The Yuba-Feather FIRO project will largely come to completion when the WCMs for ORO and NBB have been updated to include explicit use of forecast information. Should the FVA indicate that FIRO strategies can improve management of the YF system, the F-CO DSS is the natural and logical choice for new WCM policies to be operationalized.

And while the major focused effort of FIRO in the watershed will wane, investments in monitoring, technology, and research will continue. As forecast skill and technological improvements are realized, they can be integrated into operations through the FIRO 2.0 concept. The FIRO 2.0 concept provides the framework and flexibility to adapt to forecast skill and technological improvements without the costly process of a traditional WCM update. The F-CO is envisioned as the framework that supports reservoir release decision making today and into the future.

7.1.5 Recommendations

The following recommendations are based on findings of DST assessment efforts:

- Use F-CO DSS as the framework for integrating FIRO strategies codified in the ORO and NBB WCM updates.
- Carry out more DSS work to paint a clearer, more consistent picture of current and expected watershed conditions.
- Provide sustainable training on forecasting and observational DSTs.
- Make enhancements to HEC-ResSim.
- Ensure tools developed through the PVA/FVA process will be fully described and made available for real-time operations through the Research and Operations Partnership.

7.2 Adequacy of CWMS Tools for FIRO in the Yuba-Feather Basin

7.2.1 Application and Context

The Corps Water Management System (CWMS) is the USACE enterprise DSS for real-time water management. CWMS includes a system of hardware and software to collect data; simulate meteorologic, hydrologic, hydraulic, and economic models; and display results. USACE's Sacramento District uses CWMS, and will be actively engaged in the Yuba-Feather F-CO DSS hosted by DWR.

At the center of both CWMS and the F-CO DSS is HEC-ResSim, USACE's standard reservoir simulation program. Given a set of physical properties of a reservoir system, channel routing properties, operational rules, and inflow hydrology, HEC-ResSim simulates the routing of the flow and reports the resulting reservoir releases and downstream flows.

HEC-ResSim is being used currently to simulate reservoir operations in the Yuba-Feather system, and it has been used to simulate the uncertainty of reservoir storage and downstream flows given a selected release pattern and ensembles forecasts of inflows and unregulated flows below the reservoir(s). Depending on the specific FIRO operation alternative ultimately recommended by the team, the program may need further modifications. For operations that rely on a best estimate of future inflow volume, such as the guide curve operations (Alternative 2), the current program does generally meet the need, although some elements of the NBB guide curve and the forecasts themselves must be computed/processed outside HEC-ResSim.

The program currently does not allow for "ensemble-informed" operating rules needed to simulate the Ensemble Forecast Operations (Alternative 3). This release logic framework is not currently in the software. In addition, if such an alternative were selected, further discussions regarding how the DSS is characterized in the approved WCM would also be needed.

Note that the WRE team includes staff from HEC, with whom detailed discussions have taken place related to FIRO-related enhancements.

7.2.2 Recommendations

Recommendations for HEC-ResSim enhancements to support FIRO:

- Include the option to integrate use of forecast (and associated uncertainty) "side flow" time series in the computation of reservoir releases constrained by downstream flow control rules.
- Provide for a FIRO Space so that rules for a FIRO operation can span both traditional conservation and flood control space.
- Coordinate with HEC on current efforts to develop "ensemble readiness" in HEC-ResSim and CWMS.
- Explore default computation windows, number of compute passes, and other HEC-ResSim "options" to help the Water Resources Engineering team ensure the specified priority of FIRO rules is observed.
- Resolve interference issues in inflow rules related to release overrides.

Section 8. Findings and Recommendations

8.1 Overall Summary of PVA Findings

The findings from this PVA are detailed in each section of this document and provide foundational support for the PVA recommendations. Overall, the PVA demonstrated that current forecast skill can support FIRO and that forecasts of atmospheric rivers (ARs) are essential for FIRO operations in the Yuba-Feather watersheds. Several scientific studies, and the continuation of the AR Recon program, are central to improving AR forecast skill and thus achieving greater benefits in meeting FIRO objectives. The preliminary assessment of FIRO alternatives uncovered complexities that will need to be further assessed in the Final Viability Assessment (FVA) to ensure that the alternative strategies can be objectively compared. Alternatives will also be assessed with and without the assumption that the Atmospheric River Control (ARC) Spillway is in place at NBB. Once the preferred FIRO alternative is identified, it will be conditionally operationalized by integrating FIRO parameters into the existing Forecast-Coordinated Operations (F-CO) decision support system for testing and evaluation. Importantly, both this PVA and the forthcoming FVA are sequenced with the Water Control Manual updates for NBB and ORO. These parallel efforts will continue to be closely coordinated to ensure alignment and timely implementation of FIRO.

Water Resources Engineering

These recommendations are drawn from Sections 4 and 5 of the PVA.

- WRE 1: Apply additional rigor to the consistent application of at-site and system constraints, data, hindcasts, and initial starting conditions as defined in the hydraulic engineering management plan to ensure the evaluated alternatives can be objectively compared.
- WRE 2: More directly assess the potential impact (positive or negative) on water supply and an economic benefits assessment. (Full period-of-record simulations should be made for all alternatives.)
- WRE 3: Leverage hindcasts generated using the current GEFSv12 model.
- WRE 4: Consider using synthetically generated ensemble hindcasts to enhance the robustness testing of the alternatives under consideration.
- WRE 5: Investigate objective forecast-informed methods for dynamically coordinating releases to meet the downstream flow objectives at Yuba City and below the Bear River, including developing appropriate metrics for evaluation.
- WRE 6: Evaluate at-site and system performance with and without the ARC Spillway to address Water Control Manual (WCM) update and/or planned deviation needs before construction of the spillway is complete (~2028).
- WRE 7: Further develop concepts for refining system operation. As demonstrated in the PVA results, refinement of the system operation may enhance flood risk management performance.

- WRE 8: Define the FIRO Space for each dam. In the PVA analysis, FIRO Space was delineated differently among the alternatives. The PVA results can inform specification of FIRO Space.
- WRE 9: Enhance consideration of uncertainty in forecasts of unregulated flows for FIRO alternatives. The routing results showed the significance of the uncontrolled flows below the reservoirs and their impact on reservoir releases. Both volume and timing should be considered. Forecast improvement efforts should focus on both inflow to the reservoirs and uncontrolled local flows.
- WRE 10: Continue to coordinate with USACE Sacramento District and integrate information from the WCM update projects. This information may include specification of intermediate release thresholds, fall drawdown and spring refill curves, emergency spillway release diagram alternatives, and updated hydrology.
- WRE 11: Use updated GEFSv12 hindcasts for evaluations, if available.
- WRE 12: Conduct additional water supply impact evaluations.
- WRE 13: Further consider robustness to forecast uncertainty.
- WRE 14: Consider including resiliency to climate change as an evaluation metric.
- WRE 15: Assess additional considerations for alternatives such as practicality for real-time use, including runtime, ability to backcheck model computations, emergency operation, and need for integration into F-CO and Corps Water Management System (CWMS) decision support systems.
- WRE 16: Develop ideas for describing FIRO Space and FIRO 2.0 in the WCMs.

Meteorological Analysis

- MET 1: Develop an extended catalog of landfalling AR and precipitation characteristics affecting the Yuba-Feather watersheds to identify systematic sources of forecast uncertainty as a function of lead time and physical processes.
- MET 2: Analyze the resolution and skill of mesoscale and microphysical processes in numerical weather prediction (such as the Sierra Barrier Jet or precipitation efficiency).
- MET 3: Investigate forecast characteristics of landfalling ARs that lead to systematic sources of precipitation forecast biases (e.g., cold bias in freezing level)
- MET 4: Keep AR Recon in place each year with continued focus on improvements in flight targeting techniques, evaluation of different forecast sensitivity metrics, assimilation methodologies, and innovative data collection. The FVA should assess its impact on forecasts of precipitation in the Yuba-Feather watersheds.
- MET 5: Review lead-time predictability of landfalling ARs specifically for the Yuba-Feather watersheds, including lead-time prediction of specific events.
- MET 6: Continue to evaluate the effectiveness of the West-WRF ensemble in probabilistic and extreme precipitation forecasts over the Yuba-Feather watersheds.

- MET 7: Leverage reforecast or hindcast datasets (e.g., West-WRF) to improve precipitation forecasts over the Yuba-Feather watersheds.
- MET 8: Incorporate forecast information from West-WRF into new forecast tools such as watershed precipitation (Yuba-Feather catchments), freezing level, and barrier jet.
- MET 9: Continue to explore and develop novel AI/machine learning methods to improve AR, ridge, precipitation, and freezing-level forecasts and help improve AR forecast lead times.
- MET 10: Explore methodologies to investigate the influence of climate change on FIRO at ORO and NBB.

Hydrologic Modeling

- HYD 1: Generate streamflow hindcasts using the newer GEFSv12 weather model as the meteorological input with a hindcast period of 1990–2019 plus February 1986.
- HYD 2: Investigate the capacity to generate MEFP snow level ensembles to improve hydrologic modeling and forecasting/hindcasting.
- HYD 3: Generate hindcast data related to seasonal spring runoff forecast volumes (e.g., April–July volume) to assist in the development of spring refill strategies.
- HYD 4: Consider synthetically generated ensemble forecasts to provide more rigorous evaluation of candidate FIRO Water Control Plan alternatives.
- HYD 5: Analyze flood and refill potential for the spring months to help establish dates between which the maximum flood control space could transition to a maximum conservation space without increasing risk to the projects or downstream communities.

Observations

- OBS 1: Develop and implement the CNRFC Mountain Mapper tool to best leverage the precipitation (and ancillary) data collected from existing and newly deployed sensor networks. Use the Mountain Mapper tool to create a high-resolution precipitation dataset. Consider using Mountain Mapper or similar tools to create high-resolution datasets for SWE and temperature.
- OBS 2: Confirm and exhibit the utility of newly available observation types (e.g., snow albedo, Airborne Snow Observatory, Radar Met data including GPS integrated water vapor, snow level, and hydrometeor profiles) to inform/validate forecasts in case studies. Define a clear scope for this work, which may include incorporating other datasets, such as snow reanalyses, or conventional observation types such as temperature and humidity.
- OBS 3: Determine which hydrometeorological monitoring stations exist offline and work with operators to make data available in near real time and more readily integrated into forecast, verification, and decision support tools.
- OBS 4: Investigate the data quality of high-elevation precipitation further and identify the all-weather gages available to improve QPE representation and QPF errors.

- OBS 5: In close collaboration with the meteorology, hydrology, and verification teams, ensure the observations are useful for understanding and verifying the model representation of local-scale processes.
- OBS 6: Conduct and refine the network evaluation plan annually to accommodate partner recommendations and needs.
- OBS 7: Plan network installation/enhancement to fill gaps as they are identified.

Forecast Verification and Skill

- FV 1: Examine skill/relationships between operational and reforecast quantitative precipitation forecast as input for MEFP and correlations to inflow forecasts
- FV 2: Continue to investigate skill in the timing and magnitude of high-intensity rainfall events in high-resolution models.
- FV 3: Develop a catalog of different verification skill scores matched to different scales of meteorological mechanisms within ARs and other extreme events.
- FV 4: Explore other important AR position- and duration-related metrics to quantify forecast skill.
- FV 5: Continue to evaluate other aggregation periods (e.g., three-day total vs. seven-day total inflow) of forecasts based on operational needs.
- FV 6: Expand verification of forecasted inflow to Lake Englebright in order to study the impacts of unregulated flows of the Yuba River.
- FV 7: Explore seasonal water supply and/or snowpack-related forecast skill and necessary metrics for verification.
- FV 8: Continue to investigate sources of errors in freezing level radar observations and forecasts including hydrometeor melt levels, isothermal layers, and brightband height uncertainty.
- FV 9: Evaluate surface air temperature as it relates to impacts of snowmelt and runoff generation during AR events.
- FV 10: Develop forecast skill assessments for probabilistic precipitation, landfall, and freezing level forecasts.
- FV 11: Continue to investigate sources of error in probabilistic forecasts of reservoir inflows (including through an updated verification of the GEFSv12 hindcasts when it becomes available) and additional metrics to convey reliability of forecasts.
- FV 12: Quantify relationships between the ensemble and deterministic inflow forecasts during overlapping periods in order to identify key distributions of forecast spread and uncertainty during extreme precipitation events.
- FV 13: Continue to develop a case study analysis of the New Year 1997 event, including comparisons between archived forecasts and those using current models and tools
- FV 14: Continue to examine different spatial and temporal scales of forecast uncertainty and how they can influence hydrologic outcomes in case studies

Decision Support Tools

- DST 1: Use the F-CO decision support system as the framework for integrating FIRO strategies codified in the ORO and NBB WCM updates.
- DST 2: Carry out more decision support system work to paint a clearer, more consistent picture of current and expected watershed conditions.
- DST 3: Provide sustainable training on forecasting and observational DSTs.
- DST 4: Make enhancements to HEC-ResSim.
- DST 5: Ensure tools developed through the PVA/FVA process will be fully described and made available for real-time operations through the Research and Operations Partnership.

Corps Water Management System Tools

- CWMS 1: Include the option to integrate use of forecast (and associated uncertainty) "side flow" time series in the computation of reservoir releases constrained by downstream flow control rules.
- CWMS 2: Provide for a FIRO Space so that rules for a FIRO operation can span both traditional conservation and flood control space.
- CWMS 3: Coordinate with the HEC on current efforts to develop "ensemble readiness" in HEC-ResSim and CWMS.
- CWMS 4: Explore default computation windows, number of compute passes, and other HEC-ResSim "options" to help the WRE team ensure the specified priority of FIRO rules is observed.
- CWMS 5: Resolve interference issues in inflow rules related to release overrides.

Section 9. FVA Roadmap

9.1 Introduction

This PVA establishes a solid body of work and identifies areas of additional work to finalize the viability assessment and align it with WCM updates for Lake Oroville (ORO) and New Bullards Bar (NBB). Below is an outline for proceeding with the next steps toward completion of the FVA:

- Continue quarterly steering committee meetings.
- Conduct one or more technical workshops to pivot from PVA to FVA—work to include reviewing the PVA recommendations, refining and adjusting them as needed to ensure tasks are within scope; developing a detailed schedule; assigning tasks to allocate workload and ensure accountability; and developing a review system to stay on track.
- Reconstitute work teams as needed and refresh the project charters and associated tasks/assignments.
- Consider forming a new work team on FVA–WCM alignment to ensure maximum coordination on technical and timing aspects.
- Identify expert panel reviewers at least six months before their review for objective feedback on the contents of the FVA.
- Work closely with the FIRO 2.0 cross-FIRO work team to test how draft FIRO 2.0 criteria for Lake Mendocino might apply to ORO and NBB.
- Ensure effective outreach and communication at key points along the transition from final PVA to final FVA, including briefings, fact sheets, webinars, workshops, conferences, press releases, social media, and other conduits to reach target audiences.
- Evaluate progress and adjust as needed.

The sections below further detail key aspects of the FVA that are central to a successful FIRO execution.

9.2 FVA and WCM Alignment Process

The alignment of Yuba-Feather FIRO and WCM updates is a groundbreaking innovation and a model for integrating FIRO into future WCM updates throughout California and beyond. While there are many ancillary benefits (e.g., lessons learned) for alignment processes across FIRO-WCM update projects, this work focuses on aligning WCM updates and FIRO for NBB and ORO specifically.

The Yuba-Feather workplan identified two tasks (Task 7 and Task 9) that were combined and undertaken during development of the PVA by a small leadership team composed of co-chairs John Leahigh and John James and USACE representatives Joe Forbis and Jenny Fromm. They sought input from the Steering Committee throughout their deliberations to carry out their charter, a summary and results for which are shown in the text box below.

Task 7: How can FIRO and the WCM updates be most effectively integrated (including alignment of timing, studies, modeling, data needs, and analysis)?

Results:

A three-day technical workshop was held and resulted in mapping out linkages between WCM and FIRO elements (see PVA Section 3).

Regular meetings were held to develop and refine schedules and identify points of intersection and hand-offs throughout the two parallel processes.

Task 9: Explore FIRO concepts

- Explore, refine, and establish the FIRO Space concept in Corps terminology and policy.
- Explore and develop a Water Control Plan (WCP)/WCM framework that naturally adapts to improvements in forecast skill.
- Create a FIRO 2.0 prototype element for a WCM update and test its potential limitations within an evaluation framework.
- Establish the potential for using thresholds of forecast skill above which additional reservoir operations flexibility can be implemented.
- Document a process for how this forecast evaluation framework will be formulated, including reservoir operator input.

Results:

Because this task was so broad, the Yuba-Feather co-chairs expanded this effort to include co-chairs from all three FIRO pilot projects, as well as FIRO leaders represented on all three steering committees. The group was formed in January 2022 and has scoped out this task as described in Section 9.3 below.

The leadership team is focusing on refining the FIRO-WCM timeline for greater granularity to:

- Maximize inputs from FIRO process into the WCM update.
- Identify any gaps and determine how to address them, including timing and coordination with the NBB Atmospheric River Control (ARC) Spillway and other projects.
- Coordinate and streamline environmental reviews and approvals as appropriate (e.g., National Environmental Policy Act, California Environmental Quality Act) as part of the WCM update process.
- Engage key stakeholders via workshops.
- Provide briefings to agency leadership as needed.
- Adjust schedule as needed.

9.3 Scoping FIRO 2.0

In March 2022, a FIRO 2.0 work team was created consisting of representatives from all three FIRO projects (Russian River, Prado Dam, and Yuba-Feather) and chaired by Joe Forbis and Cary Talbot. The goal of the FIRO 2.0 work team is to develop draft FIRO 2.0 language based on Lake Mendocino (where an FVA has been completed and the WCM is being updated), then refine the language based on the Yuba-Feather FIRO effort. Final language is scheduled for Spring 2023. The language will be as general as possible without being prescriptive and will allow flexibility based on site specific conditions. The goal of the language is to have some thresholds, indicators, or metrics identified in WCMs to guide future adjustments to rule curves or FIRO Space in anticipation of improved technology, forecast skill, improvements/changes to operations or infrastructure, and other considerations, without triggering a lengthy WCM update process. Incorporating language in the WCM will give USACE more flexibility in making considered decisions about further optimizing operations in response to continued improvements and reduced forecast uncertainty. To date, the work team has identified a multi-indicator decision analysis as the preferred method, and is working on refining the following list of parameters:

- Reducing forecast uncertainty
- AR landfall position error
- Precipitation forecast (lead time improvement)
- Reducing streamflow forecast uncertainty
- Significant improvements in sub-seasonal to seasonal forecasts
- Breakthrough technology
- Improved modeling
- Infrastructure changes/improvements
- Operational changes/improvements
- Refined constraints (e.g., ramping rates)

The work described in Sections 9.2 and 9.3 will be closely coordinated throughout development of the FVA to ensure a seamless transition from FVA to WCM update, including FIRO 2.0 language and conceptual diagrams.

9.4 Research and Development

The execution of this PVA involved an array of research and development efforts to address the feasibility of FIRO at ORO and NBB. Specific findings and recommendations are identified and described within the categories of meteorological analysis (Section 6.1), hydrology (Section 6.2), observations (Section 6.3), and forecast verification (Section 6.4). The pathway through which these findings and recommendations translate to FIRO outcomes will be supported through the scope of research within the FVA. PVA recommendations will be reviewed by work teams and scoped into research tasks for the FVA. Work teams will conduct the research and update on progress regularly, with opportunity for the Steering Committee to provide input as needed.

9.5 Interim Operations

"Interim operations" refers to reservoir operations during the period between the completion of the FVA and the approval of the WCM. For the Yuba-Feather FIRO project, they may be handled differently for ORO and NBB because of the planned construction of the ARC Spillway at NBB. To date, the components of interim operations consist of (1) planned deviation(s) from the current WCM and (2) decision support tools (DSTs) that effectively aid reservoir operators who are operating under the planned deviation(s).

9.5.1 Planned Deviations

Planned deviations can be either "minor" or "major" depending upon the magnitude of the requested "deviation" from the existing WCP within the approved WCM. The USACE guidelines for planned deviations are held in EM-1110-2-240, with additional guidance provided by USACE's South Pacific Division. Planned deviations are not to be used as a substitute for updating a WCM but can apply for several years while the WCM is being actively updated. Planned deviations are approved at or below the division level and include some level of environmental assessment. Approval of planned deviations can take a year or more depending upon the complexity and the potential environmental considerations.

For ORO, it is unlikely that a planned deviation will be needed, as the timing of the FVA and the WCM update will be well-aligned. For NBB, the Yuba Water Agency has worked with the USACE Sacramento District for three minor deviation requests over the past three water years (2020, 2021, 2022) while partnering under Yuba-Feather FIRO. Due to the drought, these deviation requests were not needed because water levels did not reach the flood pool. Yuba Water intends to continue to work with the Sacramento District and request these deviations over the coming years until the new WCM update at NBB is issued.

Requests for the planned deviation can come from the owner of the dam (e.g., Yuba Water or the California Department of Water Resources) or potentially from the Yuba-Feather FIRO Steering Committee, as they did for the Lake Mendocino major planned deviation. The Steering Committee will determine the nature and attributes of any planned deviation as the outcomes of the FVA and the timing of the WCM process become clearer.

9.5.2 DSTs

As described in Section 7 of this report, decision support is a key component of implementing any sort of forecast-informed WCP. DSTs that provide situational awareness of current and expected weather and watershed conditions as well as the ability to process forecast inflows and streamflows through reservoir storage and release models that support project objectives are needed. The existing DST team will pivot during the FVA development period toward implementation of key tools needed to effectively make release decisions during interim operations and eventually under updated WCMs.

9.6 Scoping Economic Benefits of FIRO

The FVA will include an economic benefits assessment based on the flood risk reduction and/or water supply impact quantification of the preferred alternative that is identified in the draft FVA. The methodology for conducting this assessment will be based on the method used to monetize FIRO benefits at Lake Mendocino, and to a lesser extent, at Prado Dam in Orange County, California. At those reservoirs, FIRO has been shown to yield economic benefits without increasing downstream flood risk (Jasperse et al. 2020; Woodside et al. 2021). The economic analysis of FIRO benefits at Lake Mendocino estimated that modified operations could generate over $9 million per year in benefits to irrigation water supply; municipal and industrial water supply; hydropower; fisheries; recreation; and reduced operations, maintenance, and replacement costs (Jasperse et al. 2020). An analysis of FIRO benefits at Prado Dam quantified water supply benefits of 3,400 to 7,300 acre-feet per year of additional groundwater recharge (Woodside et al. 2021). In addition, an assessment of forecast-coordinated and forecast-informed operations for the Yuba-Feather watersheds and structural modifications at NBB established a benefit-cost framework for flood risk reduction (Yuba Water Agency 2018), which could be applied to this FIRO FVA. Economic benefits, data needs, and potential data sources are listed in Table 9-1. Once the preferred FIRO operational regime is identified in the draft FVA, the resultant changes in flood storage and releases can be applied, and benefits can be estimated using the data sources indicated below. Further information is provided in Appendix R.

Table 9-1. *Economic benefits, data requirements, and data sources.*

Economic Benefit	Data Requirements	Data Sources
Flood damage risk reduction	Downstream stage-frequency curves and other required inputs to the HEC-FDA model.	HEC-FDA parameters from 2017 and 2022 CVFPP updates (DWR 2017).
Water supply impacts	Period-of-record analysis including spring pool elevations.	Yuba-Feather watershed unit water charge from DWR Bulletin 132 (DWR 2021).
Dam safety	Pool elevation frequency curves combined with a model of dam reliability.	Dam reliability models derived from ORO dam safety studies.
Hydropower generation	Period-of-record analysis of pool elevations throughout the year. Hydropower management guidelines.	Management decision support guidelines for hydropower facilities at ORO and NBB.
Recreation	Period-of-record analysis of pool elevations throughout the year and recreation usage data.	Historical recreation usage. Recreation values from the Recreational Use Value Database (Rosenberger 2016).
Ecological benefits	Period-of-record analysis linked to model of fish population health as a function of streamflow and temperature by time of year.	Yuba Water, NOAA Fisheries, California Department of Fish and Wildlife.
Climate resilience	Analyses of benefits listed above, under a set of possible future climate scenarios.	Hydrologic modeling, water resources engineering, and DST analyses.

9.7 References

[DWR] California Department of Water Resources. (2017). *Central Valley flood protection plan 2017 update.*

[DWR] California Department of Water Resources. (2021). *Management of the California State Water Project*. Bulletin 132-2018.

Jasperse, J., Ralph, F. M., Anderson, M., Brekke, L., Malasavage, N., Dettinger, M. D., Forbis, J., Fuller, J., Talbot, C., Webb, R., & Haynes, A. (2020). *Lake Mendocino Forecast Informed Reservoir Operations Final Viability Assessment*. Technical Report, UC San Diego. Retrieved from https://escholarship.org/uc/item/3b63q04n

Rosenberger, R. S. (2016). *Recreational Use Value Database*. Oregon State University.

Woodside, G. D., Hutchinson, A. S., Ralph, F. M., Talbot, C., Hartman, R., & Delaney, C. (2021). Increasing stormwater capture and recharge using Forecast Informed Reservoir Operations, Prado Dam. *Groundwater*, *60*(5), 634–640. https://doi.org/10.1111/gwat.13162

Yuba County Water Agency. (2018). *Feasibility of Forecast-Informed Operations and structural modifications for Yuba-Feather watersheds.*