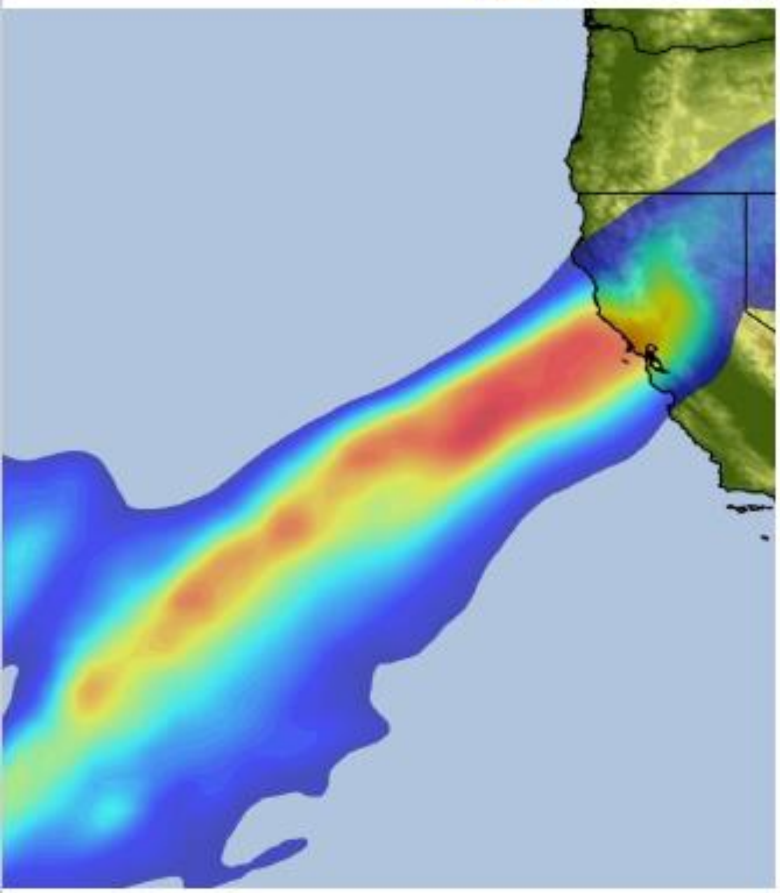
Yuba-Feather
FORECAST INFORMED RESERVOIR OPERATIONS

Final Viability Assessment

February 2025



Yuba-Feather FIRO Steering Committee

- **F. Martin Ralph:** Director, Center for Western Weather and Water Extremes (CW3E), Scripps Institution of Oceanography (SIO), U.C. San Diego (Co-chair)
- **John James:** Director of Resource Planning, Yuba Water Agency (Co-chair)
- **John Leahigh, succeeded by Molly White:** California Department of Water Resources (Co-chair)
- **Michael Anderson:** California Department of Water Resources (DWR)
- **Cary Talbot:** U.S. Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC)
- **Joseph Forbis:** USACE ERDC
- **Jennifer Fromm:** USACE, Sacramento District
- **Alan Haynes:** California Nevada River Forecast Center, (CNRFC) National Weather Service (NWS)

Center for Western Weather and Water Extremes

SCRIPPS INSTITUTION OF OCEANOGRAPHY

YUBA WATER AGENCY

Dedication and Acknowledgements

Curt Aikens

John Leahigh

Collaboration is the essence of FIRO. Many people contributed ideas, time, and expertise to this project. Special thanks go out to two leaders who came together to initiate this effort, with the support of their agencies. Curt Aikens was Yuba Water General Manager and Steering Committee co-chair from the start of this project until he retired in 2021. He embodied the FIRO spirit of discovery and was an optimistic voice throughout his involvement. John Leahigh was former Chief of the State Water Project Water Operations Office and served as Steering Committee co-chair from the start until his retirement at the end of 2023. John's thoughtful and penetrating questions, along with his collegial approach, guided this project with a steady hand toward practical outcomes. This Final Viability Assessment is dedicated to our friends Curt and John.

Steering Committee Co-Chairs:

F. Martin Ralph: Director, CW3E, Scripps Institution of Oceanography, UC San Diego

John James: Director of Resource Planning, Yuba Water

John Leahigh, succeeded by **Molly White:** Water Operations Manager, DWR SWP

Steering Committee Members:

Michael Anderson: State Climatologist, DWR

Joseph Forbis: USACE Water Management Integration Lead, USACE ERDC

Jennifer Fromm: Chief, Water Management Section, USACE

Alan Haynes: Hydrologist-in-Charge, CNRFC, NWS

Cary Talbot: National Lead, Forecast Informed Reservoir Operations Program, USACE ERDC

Key Project Staff: Arleen O'Donnell and Elizabeth Weathers (ERG), Rob Hartman (RKH Consulting), Janel Mayo and Duncan Axisa (CW3E)

Work Team Members and Support Staff:

- **CW3E:** Ava Cooper, Jason Cordeira, Chad Hecht, Julie Kalansky, Tom Corringham, Mike DeFlorio, Anna Wilson, Ming Pan, Luca Delle Monache, Matt Simpson, Mike Dettinger, Rachel Weihs, Laurel Dehaan, Chris Castellano, Peter Yao, Sam Bartlett, Edwin Sumargo, Agniv Sengupta, Brian Kawzenuk, Lauren Wood, Shawn Roj, Lisa Katz, Mahdi Erfani, Lillian Gilmore, Kyla Semmendinger-Raney
- **DWR:** Angelique Fabbiani-Leon, Cale Nasca, Stephanie Chun, Jeremy Hill, Dustin Jones, Tracy Pettit, Mitch Russo, Nathan Burly, Andy Chu, Jason Ince, George Modini, Raquel Borrayo, Chris Orrock, Elizabeth Whitmore
- **ERG:** Elizabeth Weathers, Ben Carlisle, Matt Mitchell, Chris Lamie, Sean van der Heijden
- **GEI:** Naser Bateni, Roger Putty
- **HDR:** Nathan Pingel, Michael Konieczki, Hayley Huerd, Jeffery Weaver, Paul Bratovich, Aimee Kindel, Jim Lynch
- **MBK:** Ben Tustison, Carly Narlesky, Olivia Alexander, Carissa Abrahams
- **NOAA:** Brett Whitin, Eric Danner, Steve Lindley
- **SIO:** Kathleen Ritzman, Christine Castillo, Lauren Wood
- **Sonoma Water:** John Mendoza, Chris Delaney, Jay Jasperse
- **USACE ERDC:** Richard Brown, Eric Shearer, Elissa Yeates
- **USACE Hydrologic Engineering Center:** Beth Faber
- **USACE Sacramento District:** Gary Krongard, Jonathan Moen, Randy Olsen, Zeffy Ruvalcaba, Tyler Stalker, Brian Walker, Kenneth Wright
- **USACE:** Cuong Ly, Sean Smith
- **Yuba Water:** Bonnie Dickson, DeDe Cordell, Kaitlyn Chow

Table of Contents

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 Dam Forecast Informed Reservoir Operations Preliminary Viability Assessment DRAFT. UC San Diego. Retrieved from https://escholarship.org/uc/item/xxxxx

List of Tables

List of Figures

Appendices

Appendices can be found in a separate document, here: https://cw3e.ucsd.edu/firo_yuba_feather/

Appendix A. Water Resources Engineering

Appendix B. Meteorology

Appendix C. Hydrology

Appendix D. Observations

Appendix E. Forecast Verification

Abbreviations

Abbreviation	Definition
ac-ft	acre-feet
AEP	annual exceedance probability
A.I.	artificial intelligence
AR	atmospheric river
ARC	Atmospheric River Control
AR Recon	Atmospheric River Reconnaissance
CDEC	California Data Exchange Center
cfs	cubic feet per second
CHPS	Community Hydrologic Prediction System
CMC	combined mainstem constraint
CNRFC	California Nevada River Forecast Center
CRPSS	continuous ranked probability skill score
CSI	critical success index
CWMS	Corps Water Management System
CW3E	Center for Western Weather and Water Extremes
DAC	disadvantaged community
DLA	Downieville, CA
DSS	decision support system
DST	decision support tool
DWR	California Department of Water Resources
EBNFF	East Branch North Fork
ECMWF	European Centre for Medium-Range Weather Forecasts
EFO	Ensemble Forecast Operations
EIR	Environmental Impact Report
EPS	Ensemble Prediction System
ERA5	ECMWF Reanalysis v5
ERDC	Engineer Research and Development Center
ESRD	Emergency Spillway Release Diagram
F-CO	Forecast-Coordinated Operations
FIRO	Forecast Informed Reservoir Operations

Abbreviation	Definition
FMCW	frequency-modulated continuous wave
FRM	flood risk management
ft	feet
FVA	Final Viability Assessment
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GPS	Global Positioning System
HADS	Hydrometeorological Automated Data System
HEC	USACE Hydrologic Engineering Center
HEC-ResSim	HEC Reservoir System Simulation
HEFS	Hydrologic Ensemble Forecasting System
HEMP	hydrologic engineering management plan
hPa	hectopascal
HRRR	High-Resolution Rapid Refresh
HUC-8	eight-digit hydrologic unit code (USGS)
IVT	integrated vapor transport
IWV	integrated water vapor
KAF	1000 acre-feet (also TAF)
kcfs	thousands of cubic feet per second
kg $m^{-1}s^{-1}$	kilogram-meters per second
LBH	Lower Bath House
MADIS	Meteorological Assimilation Data Ingest System
MAP	mean areal precipitation
MEFP	Meteorological Ensemble Forecast Processor
MEFPPE	MEFP parameter estimator
MFF	Middle Fork Feather River
ML	machine learning
MM	Mountain Mapper
MODE	Method for Object-based Diagnostic Evaluation
MRIS	Moderate Resolution Imaging Spectroradiometer
NAVD 88	North American Vertical Datum of 1988
NAVGEM	Navy Global Environmental Model

Abbreviation	Definition
NBB	New Bullards Bar Reservoir and Dam
NCEP	National Centers for Environmental Prediction
NCFR	narrow cold frontal rainband
NEP	non-exceedance probability
NEPA	National Environmental Policy Act
NFF	North Fork
NGVD 29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction
NWS	National Weather Service
ORO	Lake Oroville and Oroville Dam
PFSE	percentage of FIRO Space evacuation
POFA	probability of false alarms
PVA	Preliminary Viability Assessment
QPE	quantitative precipitation estimate
QPF	quantitative precipitation forecast
RAOP	Research and Operations Partnership
RFC	River Forecast Center
r	correlation coefficient
r^2	coefficient of determination
SAC-SMA	Sacramento Soil Moisture Accounting Model
SBJ	Sierra Barrier Jet
SDAC	severely disadvantaged community
SLP	sea-level pressure
SMOIL	surface metrology with soil moisture
SOM	self-organizing map
SPK	USACE Sacramento District
SWE	snow water equivalent
SWP	State Water Project
TAF	thousand acre-feet (also KAF)
TOC	top of conservation
USACE	United States Army Corps of Engineers

Abbreviation	Definition
WCM	Water Control Manual
WCP	Water Control Plan
West-WRF	Western Weather Research and Forecasting
WPC	Weather Prediction Center
WRE	water resources engineering
WY	water year

Executive Summary

This Yuba-Feather Final Viability Assessment (FVA) evaluates whether improved precipitation and runoff forecasts can reduce flood risk downstream of New Bullards Bar (NBB), owned and operated by Yuba Water Agency (Yuba Water), and Lake Oroville (ORO), owned and operated by the California Department of Water Resources (DWR). These reservoirs are in the Yuba-Feather watersheds in the Sierra Nevada and eastern Sacramento Valley of Northern California (Figure ES-1 and ES-2). Each reservoirs' flood risk reduction operations are regulated by United States Army Corps of Engineers (USACE) through Water Control Manuals (WCMs).

Reducing flood risk by making reservoir releases ahead of storms creates additional temporary flood storage space for anticipated inflows but requires confidence and skill in forecasted conditions.

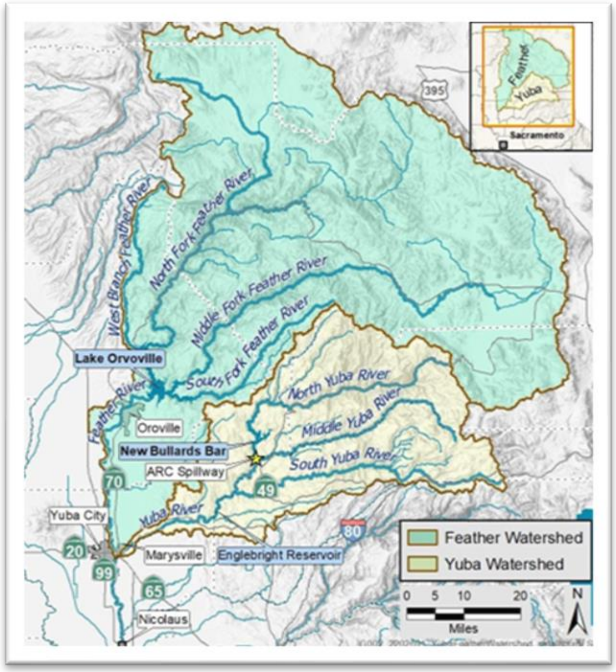


Figure ES-1. *Map of the Yuba-Feather Watersheds. Credit: Yuba Water.*

This pilot study was motivated by historic floods in recognition that improved forecasts of atmospheric rivers (ARs) - the dominant driver of major flood events - can support improved reservoir management.

> Forecast Informed Reservoir Operations (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 the Yuba-Feather FIRO project is to reduce flood risk; a secondary objective is to achieve water supply benefits where possible.

Figure ES-2. *Yuba Water's New Bullards Bar (top) and DWR's Lake Oroville (bottom).*

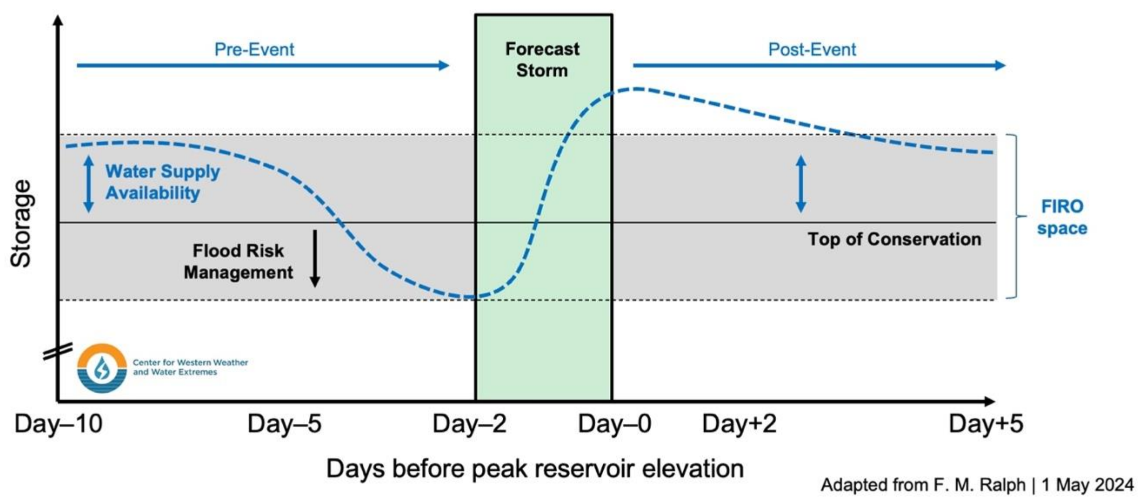


Figure ES-3. *Conceptual diagram illustrating both water supply availability and flood risk management (FRM) benefits of FIRO by pre-releasing water using pre-event forecasts and allowing recovery of the conservation pool post-event when forecasts indicate no storms in sight.*

Benefits of FIRO at New Bullards Bar and Lake Oroville

FIRO strategies provide the flexibility to increase pre-storm flood management storage and reduce downstream peak flood flows.

FIRO strategies achieved drawdowns that approached the flood control space of the proposed (but not constructed) Marysville Reservoir, designed to store 260,000 acre-feet. The drawdowns were made possible by the FIRO space within the conservation pool and the proposed operation of the designed ARC spillway.

FIRO alternatives may lead to potential improved water supply conditions. The post-event storage for the FIRO alternatives showed up to 175,000 acre-feet of additional storage for ORO and 48,500 acre-feet for NBB. The higher post-event storages were possible by the FIRO space within the flood control pool.

Unique Aspects of Yuba-Feather FIRO

- Flood risk reduction as primary objective
- Complex operational constraints
- Multiple reservoirs under different ownership
- Forecast-Coordinated Operations in place
- FVA developed concurrently with WCM updates and NBB spillway design

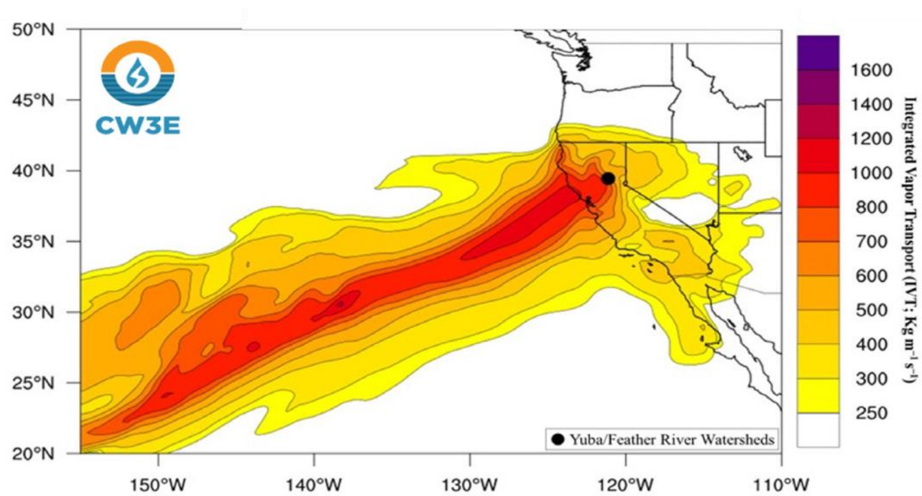


***Figure ES-4**. Image of a strong atmospheric river impacting the Yuba-Feather watershed, February 6–7, 2017, indicated by the concentration of integrated vapor transport. Credit: CW3E.*

The FVA includes improved observations; forecast skill verification; hydrologic and meteorological research; and estimated benefits (see Section 5). This work was aimed at assessing and improving precipitation and inflow forecast skill, which is important because improved forecasts will lead to greater FIRO benefits. Water resources engineering and modeling (Section 3 and Section 4) assessed FIRO alternatives against existing conditions, the results of which are summarized here, along with key findings and recommendations drawn from the complete body of work.

The FVA and WCM Update Are Separate Processes

While this FIRO viability assessment was conducted in parallel with the Water Control Manual updates, the viability assessment is a separate process. The FIRO FVA (a research pilot project) explored a range of FIRO options, is not a decisional document, and is overseen by an inter-agency steering committee. During the WCM update process, the USACE identifies preferred alternatives and analyses a full range of impacts and benefits. The WCM update is under the sole auspices of USACE; it can be informed by the FVA but is not bound to the FVA. It is also important to note that the FVA only analyzed scaled extreme events, the WCM update will include a more robust period-of-record analysis.

Atmospheric River Control (ARC) Spillway

To maximize the benefits of FIRO and better leverage improved forecasts, Yuba Water is designing the secondary ARC spillway to allow for greater forecast-informed pre-releases at lower reservoir elevations at NBB. Using FIRO with the planned spillway will enable up to an additional 117,000 acre-feet of reservoir space to reduce water surface elevations and pressure on levees during high flow events, significantly reducing flood risk for Yuba County and other communities near the lower Yuba and Feather rivers.

To assess FIRO viability at NBB and ORO, a multi-agency Steering Committee guided the development and evaluation of reservoir operation alternatives that explicitly included streamflow forecasts in release decision making. Two forecast-informed alternatives were compared to existing WCM operations for each reservoir and as a system (both reservoirs operated together). The two forecast-informed alternatives were evaluated with the planned ARC spillway at NBB for two storms (1986 and 1997) that produced significant flood impacts. These events were scaled with factors spanning roughly 100-year to 500-year return intervals. Each storm was modeled using current operations (ID1), prescriptive use of forecasts (ID3) and iterative use of forecasts (ID4). The two forecast-informed approaches are defined below:

Prescriptive (ID3). This approach relies on predetermined target storage values and/or releases determined by inflow forecast volume. The ensemble forecast is processed into single value volume to determine the target elevation and/or release magnitude.

Iterative (ID4). The iterative strategy, often referred to as "Ensemble Forecast Operations" or EFO, uses each member of the forecast ensemble to consider the range of potential storage outcomes for a given release. If the range of potential storage outcomes exceeds a prescribed probability tolerance above a given reservoir elevation, a release schedule is formulated that mitigates the tolerance exceedance at lead times up to 14 days. While 14 days is a stretch for forecasts, they are only considered relative to their demonstrated skill through calibration.

Goals and Anticipated Results of the Assessment

- Demonstrate that the explicit integration of streamflow forecasts and the associated uncertainty can improve FRM outcomes (peak event storage and/or peak downstream flows).
- Demonstrate that the ARC Spillway is effective in improving FRM outcomes.
- Demonstrate that "FIRO Space" that augments the flood reserve by including a portion of the water conservation storage is effective in improving FRM outcomes.
- Demonstrate system operations strategies that leverage the uncertainty in the unregulated portion of the watershed can effectively produce additional FRM benefits.
- Demonstrate that water supply availability will not be negatively impacted by FIRO strategies.

The alternatives were evaluated for meeting several flow and elevation constraints stipulated in existing WCMs, including peak flood storage volume, peak reservoir release, and peak downstream flows. Thus, the evaluation focused on achieving management objectives at key points within the Yuba-Feather system.

Key findings and highlights are summarized in the text box below:

Key Findings

- The FVA demonstrated that FIRO strategies combined with a planned second spillway at NBB could provide additional flood control storage capacity in the system and allow for reservoir operations flexibility to reduce downstream peak flows during major prolonged storms like 1986 and 1997 that devastated Yuba County.
- For the scenarios tested, FIRO with the ARC spillway could provide a level of protection equivalent to the proposed (unconstructed) Marysville Reservoir, approximately 260,000 acre-feet (ac-ft).
- Post-event storages were consistently higher than pre-FIRO storages; therefore, there could be a water supply benefit, pending a full analysis in the WCM updates.

Supporting Key Findings and Highlights

- FIRO strategy reductions in downstream flood flows and peak reservoir elevation across all scale factors are attributable to (1) use of forecasts, (2) FIRO space that extends into the water conservation pool, and (3) the planned ARC Spillway.
- Heavy precipitation in the watershed is driven by ARs.
- Enhancements to the existing observational network fill spatial gaps in precipitation observations and improve quantification of the rain–snow transition.
- Landfalling ARs are predicted with lead times of about five to seven days; associated precipitation forecast improvements can be attributed to AR Reconnaissance.
- Forecast errors of inflows associated with precipitation events suggest that 72-hour volume inflows are skillful out to a 7–9-day lead time, and 24-hour total volume flows are skillful out to 6 days lead time.
- Machine learning and artificial intelligence methods applied to the Center for Western Weather and Water Extremes' (CW3E's) Western Weather Research and Forecasting (West-WRF) model improve precipitation forecast skill at 1–3-day lead time.

FIRO strategies, in combination with forecast-coordinated operations (F-CO) were consistently better at delivering FRM benefits than the operations defined in the existing WCMs for ORO and NBB, especially during extreme events. Table ES-1 summarizes the performance of the alternatives, with caveats. Here, the highest event scale factor (for both 1986 and 1997 events) that achieves the listed objective is shown and color coded. Note that this represents only the peak reservoir elevation, release, or downstream flow from a 30-day simulation centered on the 1986 and 1997 events. Furthermore, the significance of differences in performance (e.g., 116 vs. 120) has not been established. Nonetheless, Table ES-1 provides a high-level view of how the FIRO strategies (ID3A, ID4A) compared with baseline operations (ID1E) in meeting FRM objectives. See Section 3, Section 4, and Appendix A for a more complete evaluation.

Table ES-1. *Relative performance of FIRO alternatives (ID3A, ID4A) compared to baseline operations (ID1E). Color coding indicates lower (light green) and higher (medium green) effectiveness in meeting performance metrics, as indicated by the highest scale factor that achieved the objective. The "E" following the baseline alternative designates no ARC Spillway at NBB, while the "A" following FIRO alternatives indicates the evaluation assumed operation of the ARC Spillway.*

	1986			1997		
Objective	**ID1E**	**ID3A**	**ID4A**	**ID1E**	**ID3A**	**ID4A**
ORO Gross Pool (901 feet)	116	118	118	106	108	110
ORO Max. Release (150 kcfs)	116	118	118	106	108	110
Feather at Yuba City (180 kcfs)	116	120	120	108	110	110
NBB Gross Pool (1,956 feet)	114	118	120	102	110	130
NBB Max. Release (50 kcfs)	114	118	120	102	108	108
Yuba at Marysville (180 kcfs)	116	118	120	104	104	106
Feather below Yuba (300 kcfs)	114	118	118	106	106	108
Feather below Bear (320 kcfs)	104	106	106	106	106	108

The FVA focused on demonstrating the effectiveness of FIRO strategies to improve FRM outcomes as opposed to water supply availability. However, post-event reservoir storage for all simulations was consistently higher due to the selection of FIRO Spaces above and below the top of conservation in the existing rule curves of ORO and NBB. This suggests that FIRO strategies could positively impact water supply availability in the basin. Additional analyses associated with the WCM update process will fully address water supply impacts.

Key Recommendations

- HEC Reservoir System Simulation (HEC-ResSim) currently assumes perfect foresight for local flows downstream of the dams but lacks a mechanism to include forecast uncertainty in the timing and magnitude of those flows. Modifying HEC-ResSim can leverage ensemble forecasts to allow for separate time series for (1) observed flow routing and (2) forecast flows used to make computational decisions.
- Implement a "FIRO Space" concept in HEC-ResSim that enables representation of rules that smoothly transition from flood space to conservation space.
- Continue development of system operations concepts that balances risk between ORO and NBB and downstream control points during large flood events. Continue to refine these concepts for inclusion in the Forecast-Coordinated Operations Program.
- Further mature the process for developing scaled historical hindcast events and leverage synthetic ensemble forecasts to improve robustness testing of FIRO alternatives.
- Evaluate seasonal forecast skill to better inform FIRO operations when transitioning from winter to spring.
- Continue to leverage AR Recon and field observations to evaluate model forecasts of dynamic and physical processes within ARs.
- Continue research that further examines operational forecast skill with a focus on forecast errors related to precipitation and resulting inflows/streamflows, including meteorological patterns, partitioning of rain and snow, and lead time analysis of AR characteristics.
- Continue annual observational network evaluations based on feedback from USACE, the California Nevada River Forecast Center, Yuba Water, and DWR to enhance network performance.
- Conduct a period of record analysis and use results to quantify the economic benefits of FIRO.

All recommendations are detailed in Sections 3, 4, and 5 for consideration during the WCM update process currently underway by USACE Sacramento District, and for future FIRO efforts that have the potential to realize FIRO benefits.

Reference

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: Preliminary Viability Assessment*. UC San Diego. https://escholarship.org/uc/item/8x57n58b

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 to increase resilience to droughts and floods. The FIRO pilot study process consists of interagency collaboration and a rigorous assessment that includes dam operations, observations, hydrologic modeling, forecast skill assessment, water resources engineering, research, applied science, and input from reservoir managers. This Research and Operations Partnership (RAOP) is central to FIRO pilot study success.

Research and Operations Partnership

RAOP is a fundamental FIRO concept that describes the symbiotic relationship between research and operations. Unlike research-to-operations, RAOP uses reservoir operational needs to inform research direction; in return, research results are used to inform and improve operations.

FIRO pilot results at Lake Mendocino in Mendocino County, California, show that reservoir operators can use forecast information and tools to store more water when forecasts indicate a low risk of flooding (see Figure 1-1).

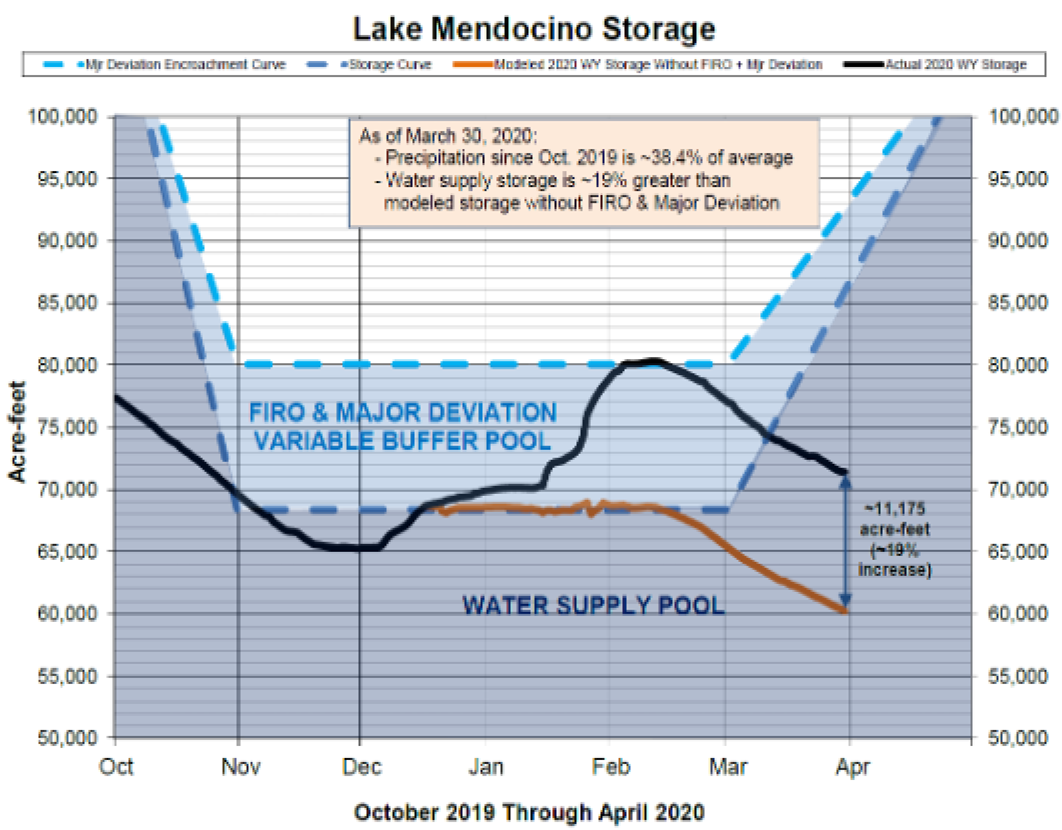


Figure 1-1. *Success with the first FIRO project (at Lake Mendocino) demonstrates that FIRO can be successfully implemented with major benefits. Lake Mendocino storage increased by 19 percent (more than 11,000 acre-feet) during major deviation operations in water year (WY) 2020.*

Building on the success and lessons learned from Lake Mendocino, the Yuba Water Agency and the California Department of Water Resources (DWR) are collaborating with the U.S. Army Corps of Engineers (USACE); the UC San Diego Scripps Institution of Oceanography, Center for Western Weather and Water Extremes (CW3E); and other key partners to advance the Yuba-Feather FIRO pilot project. This project is the largest FIRO assessment to date and the first one conducted in parallel with Water Control Manual (WCM) updates. It is also the first FIRO partnership with the California State Water Project and the first watershed with snowmelt considerations. Lessons learned in the Yuba-Feather watersheds will inform FIRO applications in other locations where reservoirs are operated in parallel and in snowmelt-fed watersheds.

As noted, synchronizing the FIRO pilot study with WCM updates is another unique feature of this project. In 2020, USACE received funding to update the Lake Oroville (ORO) and New Bullards Bar (NBB) dam WCMs concurrently with developing the FIRO Final Viability Assessment (FVA) to more efficiently operationalize FIRO in the WCM updates. A secondary spillway at NBB, called the Atmospheric River Control (ARC) Spillway (design completed in 2023), was another major consideration in timing of the FVA and WCM update. This synchronization provides a valuable learning experience for future efficiencies in transitioning from viability assessment to WCM updates.

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.

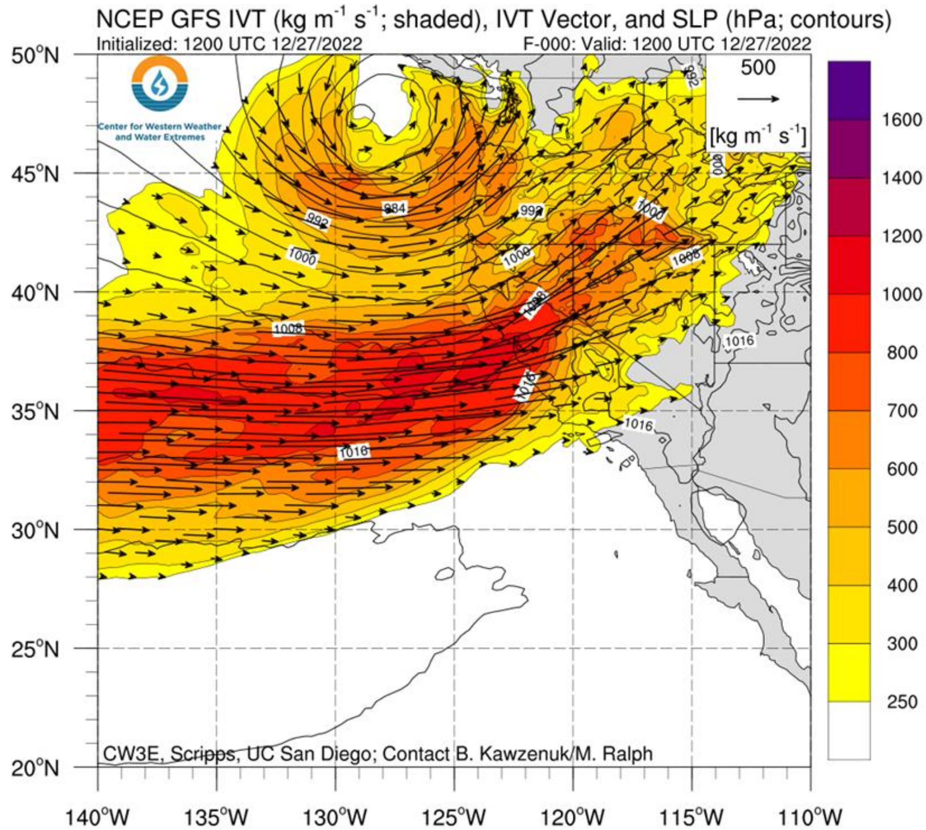


***Figure* 1-2.** *An extreme AR that impacted the Yuba-Feather watersheds on December 27, 2022, measured as kilogram-meters per second (kg m^{-1}s^{-1}), integrated vapor transport (IVT), and sea-level pressure (SLP) in hectopascals (hPa), shown with contours.*

While water managers have always taken forecasts into account, a 2016 change in USACE policy (ER-1110-2-240) explicitly allows forecasts to be incorporated into reservoir operating rules, which represents a paradigm shift for USACE water managers. Water Control Plans 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, for example, water managers in the West take forecasts into account when making release decisions.

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 developed several important tools that reservoir operators can 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, such as droughts and floods. Continued investments in AR forecast skill will allow for greater FIRO benefits.

1.2 FIRO Project Objective

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

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 while maintaining or improving water supply reliability and habitat?

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. The Steering Committee decided to use this previously proposed flood storage volume as an aspirational goal. The combination of operating for FIRO within the conservation space in both NBB and ORO, in addition to using the ARC Spillway during large events, was shown to achieve this aspirational goal. Had FIRO and the ARC spillway been in place during the devastating flood of 1997, reservoir releases could have hypothetically started sooner, and river levels may have been significantly reduced.

While flood risk management was the main reason for this study, FIRO explored a secondary goal of realizing some ancillary water supply availability benefits by achieving higher storage levels. 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 1-3 shows the process used to conduct the Yuba-Feather Viability Assessment, including the Preliminary Viability Assessment (PVA), which was foundational to this FVA. The figure also shows how the viability assessment overlapped with the WCM update timeline, although this figure does not include all aspects of the WCM update process. FIRO alternatives were tested in the PVA to define requirements and scientific improvements needed to support FIRO. The work to evaluate FIRO alternatives and the final FIRO evaluation process is embodied in this document.

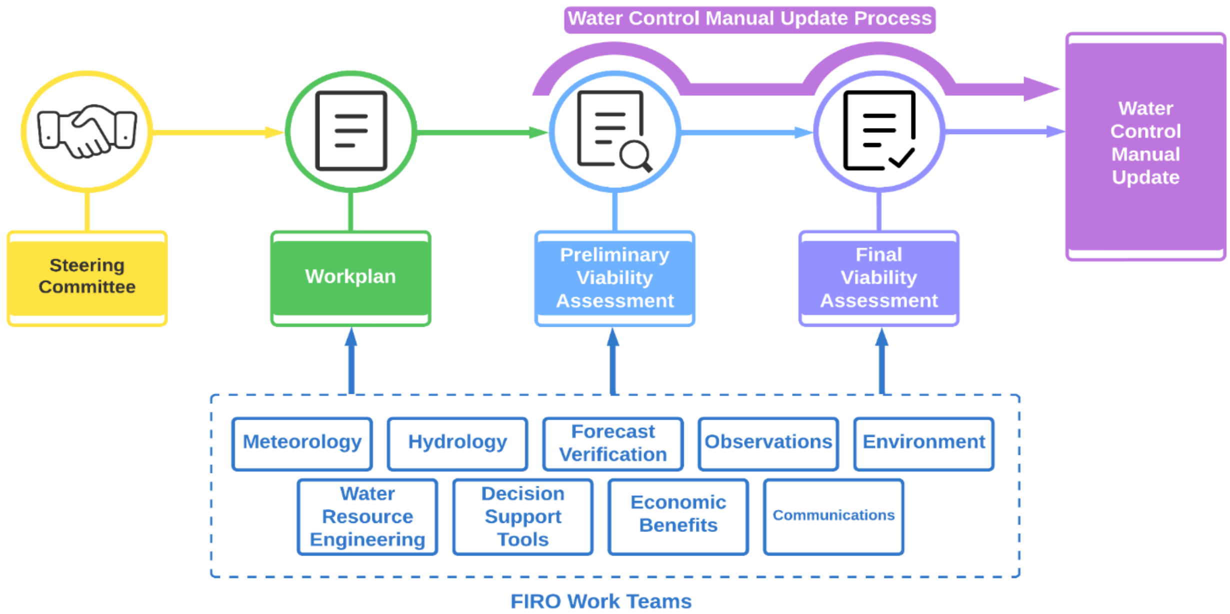


Figure 1-3. *Generalized FIRO process. The timeline for the Yuba-Feather FIRO project includes FIRO integration into the WCM updates. The FVA builds on and follows the work plan, which was completed in the spring of 2021 and the PVA, completed in 2022. The FVA findings will inform the WCM updates, as shown in the aligned schedules. The WCM updates are currently scheduled to be completed in 2026.*

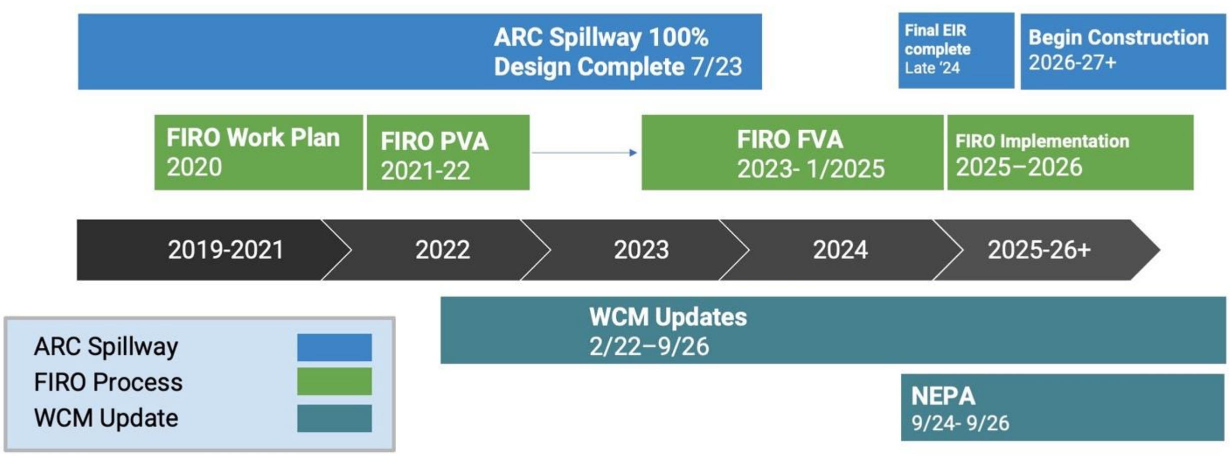


Figure 1-4. *Alignment of Yuba-Feather FIRO, ARC Spillway, and WCM timelines.*

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 1-5). The Steering Committee is governed by 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, and the project objective. See acknowledgements for a list of work team and staff contributors.

Co-Chairs:

- **F. Martin Ralph:** Director, CW3E, Scripps Institution of Oceanography, University of California, San Diego
- **John James:** Director of Resource Planning, Yuba Water
- **John Leahigh,** succeeded by **Molly White:** State Water Project, DWR

Members:

- **Michael Anderson:** State Climatologist, DWR
- **Joseph Forbis:** Water Management Integration Lead, USACE ERDC
- **Jennifer Fromm:** Chief, Water Management Section, USACE Sacramento District
- **Alan Haynes:** CNRFC, National Weather Service
- **Cary Talbot:** National Lead, Forecast Informed Reservoir Operations Program, USACE ERDC

Figure 1-5. *Photo of Yuba-Feather Steering Committee and staff (from left): Duncan Axisa, Dustin Jones, Ben Tustison, Nathan Pingel, Carly Narlesky, Rachel Weihs, Bonnie Dickson, Mike Konieczki, Molly White (co-chair), Joe Forbis, Donna Lee, Marty Ralph (co-chair), Rob Hartman, John Leahigh (past co-chair), Jenny Fromm, John James (co-chair), Arleen O'Donnell, Ava Cooper, Cary Talbot, Roger Putty, and Chris Delaney. Not pictured: Alan Haynes, Mike Anderson, and Steve Lindley.*

Section 2. FIRO at Yuba-Feather

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. Figure 2-1 shows that over 60 percent of each watershed is at or exceeding 5,000 feet in elevation, as well as showing the extent of the upper watershed that has snowpack.

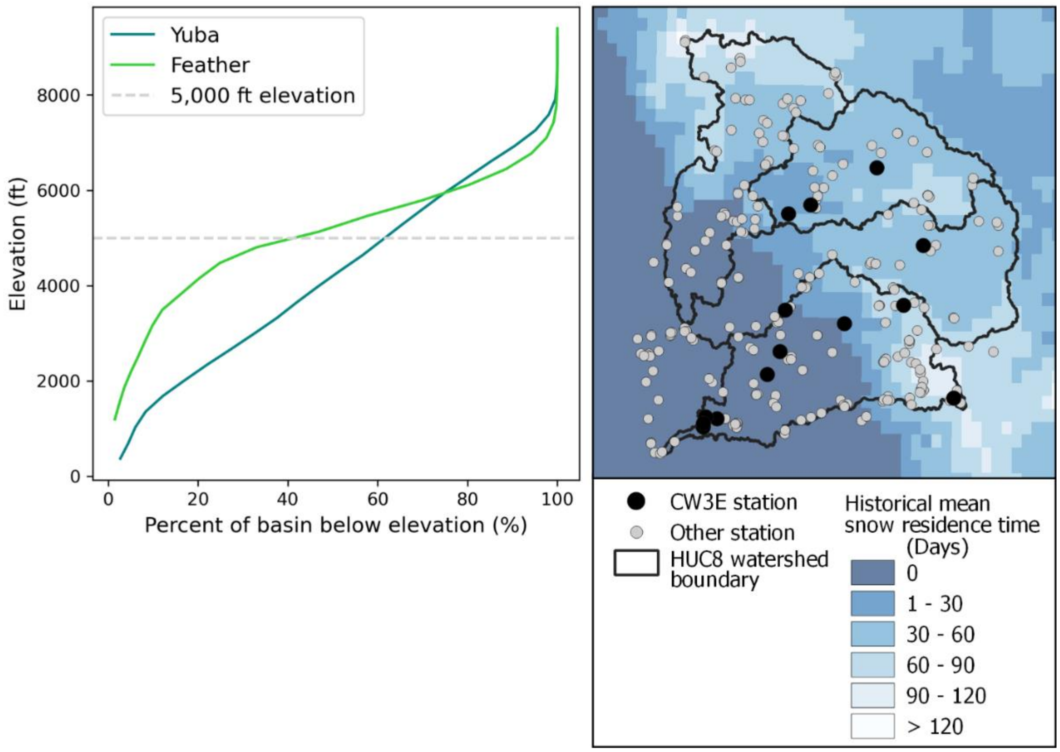


Figure 2-1. *Left: basin hypsometry of the Yuba River watershed (blue) and Feather River watershed (green) with 5,000 feet elevation noted with the gray dashed line. Right: map of the Yuba River and Feather River watersheds showing historical (1975–2005) mean snow residence time in days (Luce et al. 2014) (darker blue = fewer days, lighter blue = more days) and locations of monitoring stations in the Center for Western Weather and Water Extremes (CW3E) network (black markers) and other networks (grey markers).*

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.

The Yuba and Feather 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 (ARs). 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 rise quickly in response 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 major 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 of the Yuba River watershed 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 the Yuba River's downstream communities in the Sacramento Valley.

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 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, 6 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 upstream of 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 3.4 million acre-feet (ac-ft) of water, ORO is the largest water storage facility for the SWP and has the second largest human-made lake in California. It provides water for 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 Meteorology and Climatology

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 originally 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 ARs. A 2017 study on levee breaks in the Central Valley since 1951 found that 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 through levee improvements and other projects; 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.

ARs are projected to increase in intensity and duration in California due to 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.

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 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.

On the heels of one of the driest three-year stretches in California history, water year 2023 saw a return to elevated AR activity and above-normal precipitation, further exemplifying the year-to-year variability in California's hydroclimate. The AR activity was kicked off in late December 2022 through mid-January 2023, when nine ARs brought an onslaught of precipitation extremes over a three-week period. AR activity picked up again in late February through March when an additional series of colder storms increased the snowpack in the Northern Sierra to approximately 200 percent of the April 1 average. By the end of the water year (September 30, 2023), ORO and NBB reservoirs were storing around 2.6 million ac-ft and 701,000 ac-ft of water, respectively.

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. CW3E 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).

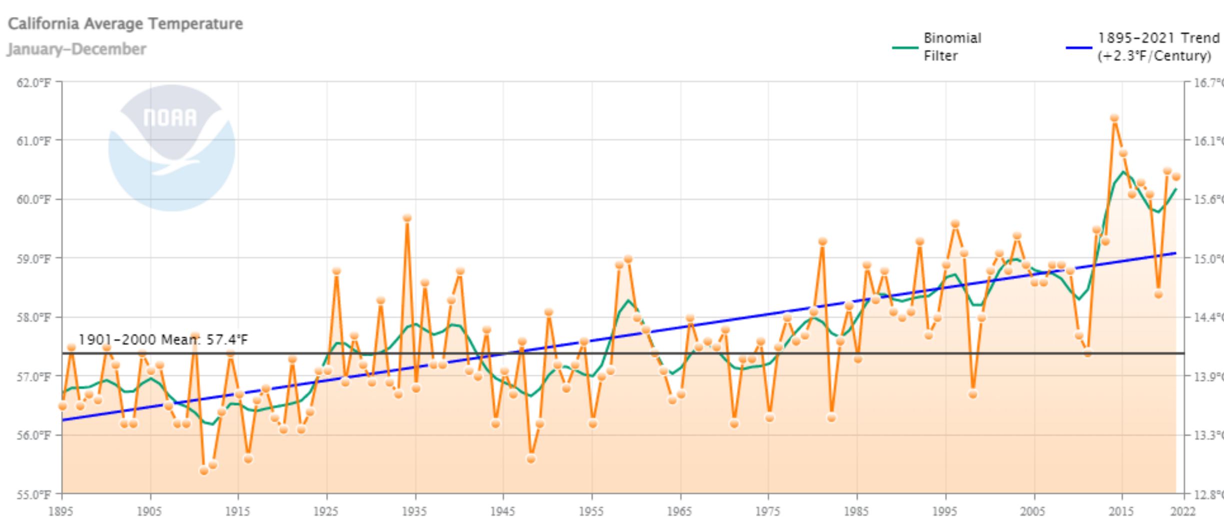


Figure 2-2. *Increase in average annual temperature in California. Credit: National Oceanic and Atmospheric Administration 2022.*

2.2 Current Operations and Infrastructure

2.2.1 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 Water Control Manuals (WCMs) for ORO and NBB acknowledge that interagency coordination is needed daily or hourly to ensure flood control operations are as effective as possible. 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, the U.S. Army Corps of Engineers (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.

The F-CO program 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 Marysville and Yuba City requires reservoir releases to 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.

F-CO is an operational system for real-time coordination of reservoir operations and improved communications among operating entities during flood events. In contrast, Forecast Informed Reservoir Operations (FIRO) is a research-based effort to enhance and inform reservoir decision making through improvements in weather and runoff forecasts. FIRO 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 before a storm to reduce flooding or hold back water for the secondary benefit of water supply when forecasts indicate it is safe. 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.

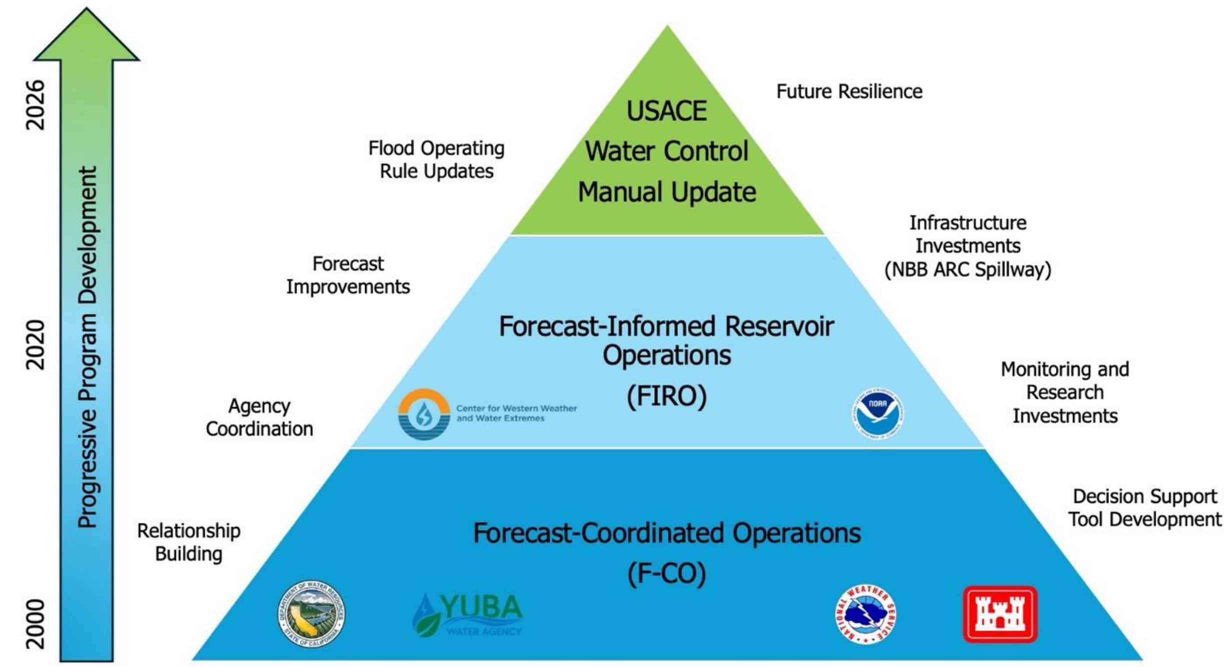


Figure 2-3. *Diagram showing progressive program development from a foundational F-CO, followed by FIRO and ultimately revised WCMs that incorporate F-CO and FIRO into operations, leading to improved resilience to drought and floods.*

2.2.2 Adapting Infrastructure at NBB to Maximize FIRO Benefits

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

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.

Figure 2-4. *The proposed ARC Spillway will have the capacity to handle releases for a 1997-sized storm event without use of the primary spillway. Credit: Yuba Water.*

The proposed ARC Spillway, designed with gates that are 31.5 feet lower than the existing spillway gates, would give Yuba Water the ability to release water lower in the flood pool in advance of large storms. The spillway would have a discharge capacity of 35,000 cubic feet per second (cfs) at the bottom of the flood pool (at 1,920.8 feet in elevation) and 64,000 cfs at the top of the flood pool (at 1,958.5 feet in elevation). These releases will evacuate space in the reservoir to capture peak flows for the biggest part of the storm (Figure 2-5).

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

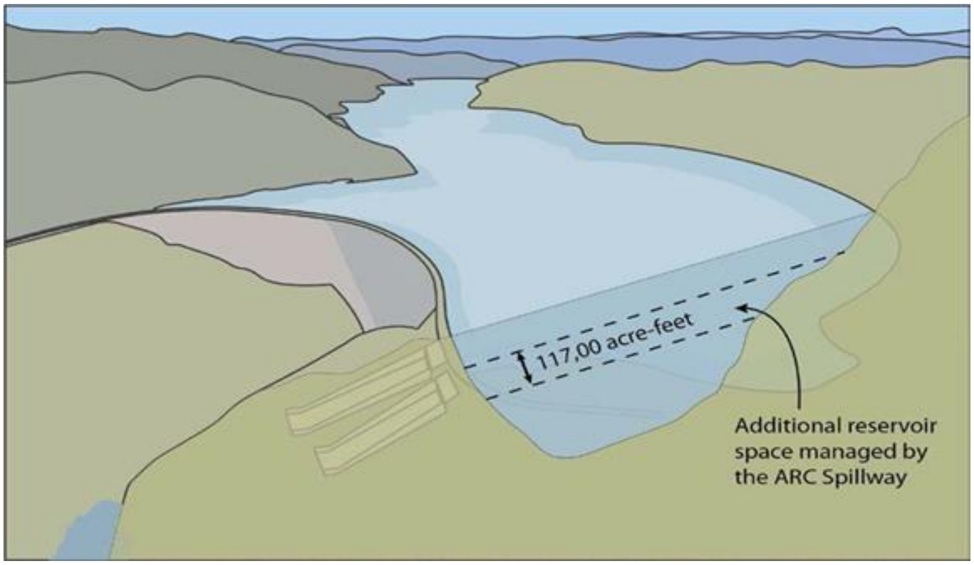


Figure 2-5. *Additional reservoir storage space managed by the ARC Spillway.*

Design of the ARC Spillway was substantially completed in 2023. Yuba Water is pursuing state and federal funding partnerships to construct the project.

2.3 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/s41558-021-01166-801166-8

Berg, N., & Hall, A. (2017). Anthropogenic warming impacts on California snowpack during drought. *Geophysical Research Letters, 44,* 2511–2518. https://doi.org/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). 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 P. Hudson & H. Middelkoop (Eds.), *Geomorphic approaches to integrated floodplain management of lowland fluvial systems in North America and Europe* (pp. 119–141). Springer. 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., ... and Ralph, F. M. (2019). Precipitation regime change in Western North America: The role of atmospheric rivers. *Scientific Reports, 9*(1), 1–11.

Luce, C. H., Lopez-Burgos, V., & Holden, Z. (2014). Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. *Water Resources Research, 50*(12), 9447–9462. DOI: 10.1002/2013WR014844.

Alison C. Michaelis, Alexander Gershunov, Alexander Weyant, Meredith Fish, Tamara Shulgina, and F. Martin Ralph. Atmospheric River Precipitation Enhanced by Climate Change: A Case Study of the Storm that Contributed to California's Oroville Dam Crisis. *Earth's Future*, Vol. 10, Issue 3. February 2022. https://doi.org/10.1029/2021EFO02537

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

Section 3. How FIRO Viability Was Assessed

This section describes the framework used to objectively assess Water Control Plans (WCPs) that leverage streamflow forecasts in their decision logic through developing and evaluating Forecast Informed Reservoir Operations (FIRO) alternatives. The process used to generate the streamflow forecasts and a description of the forecasts used to evaluate the WCP alternatives are provided in Section 3.6 (Simulation Plan) and in Section 5.3 (Hydrology).

The Preliminary Viability Assessment (PVA) (Ralph et al. 2022) summarized work to evaluate the potential for FIRO to provide enhanced flood risk management (FRM) benefits without impacting water supply availability or environmental objectives. That work demonstrated potential benefits but also provided keen insight into how the evaluation process could be improved. To the extent possible, the PVA recommendations (see Table 3-1 below) were integrated into the Final Viability Assessment (FVA) evaluation described in this section.

Table 3-1. *Engineering recommendations from the PVA.*

ID	PVA Recommendations
1	Further develop concepts for system operation. As demonstrated in the PVA results, refining the system operation may enhance flood risk management performance.
2	Define the FIRO Space for each dam. In the PVA analysis, FIRO Space was delineated differently among the alternatives. The PVA results can inform the specifications of the FIRO Space.
3	Enhance accounting for unregulated flows in alternatives and forecast improvements. The routing results showed the significance of the uncontrolled flows below Lake Oroville (ORO) and New Bullards Bar (NBB) reservoirs and their impact on reservoir releases. Both volume and timing should be considered. Forecast improvements should focus on both inflow to the reservoirs and uncontrolled local flows.
4	Continue to coordinate with the U.S. Army Corps of Engineers (USACE) Sacramento District (SPK) and integrate information from the Water Control Manual (WCM) update projects. Coordination may include specifying intermediate release thresholds, fall drawdown and spring refill curves, Emergency Spillway Release Diagram (ESRD) alternatives, and updated hydrology.
5	Use updated Global Ensemble Forecast System (GEFS) version 12 hindcasts for evaluations, if available.
6	Conduct additional water supply reliability evaluations.
7	Further consider robustness to forecast uncertainty.
8	Consider resilience to climate change.
9	Assess additional considerations for alternatives, such as practicality for real-time use (including runtime), ability to backcheck model computations, emergency operation capability, and the need to integrate forecast into Forecast-Coordinated Operations (F-CO) and USACE Corps Water Management System decision support systems.
10	Develop ideas for describing FIRO Space and FIRO 2.0 in the WCMs.

A key element of the work performed under this FIRO project is to apply information (e.g., data, models, parameters, metrics) to the WCM update effort concurrently underway by USACE SPK. The FIRO water resources engineering (WRE) team worked closely with and included individuals from SPK staff to ensure the insight and information it generated supported SPK's efforts both in terms of content and timeline. To this end, the models used by the FIRO WRE team adopt key modeling assumptions from SPK's WCM update project.

Note that the development and evaluation of FIRO alternatives in this study is fundamentally independent yet supportive of SPK's efforts to update the ORO and NBB WCMs. In addition, the FIRO alternatives for NBB include the anticipated Atmospheric River Control (ARC) Spillway as well as the associated revised ESRD.

3.1 Approach

Goals and Anticipated Results of the Assessment

- Demonstrate that the explicit integration of streamflow forecasts and the associated uncertainty can improve flood risk management (FRM) outcomes (i.e., peak event storage and/or peak downstream flows).
- Demonstrate that the ARC Spillway at NBB is effective in improving FRM outcomes.
- Demonstrate that FIRO Spaces that augment the flood reserve by including a portion of the water conservation storage are effective in improving FRM outcomes.
- Demonstrate system operations strategies that leverage the uncertainty in the unregulated portion of the watershed can effectively produce additional FRM benefits.
- Demonstrate that water availability will not be negatively impacted by FIRO strategies.

To assess FIRO viability in the Yuba and Feather watersheds, the WRE team developed and evaluated operations alternatives that explicitly include inflow forecasts in release decision making. The alternatives were modeled based on FIRO alternatives developed in previous studies, namely the Folsom Dam and Lake WCM (USACE 2019) and the Lake Mendocino FVA, described further in Section 3.4.

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

USACE EM 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 assessment into key components: Baseline Operations and Key Locations for WCM Evaluations.

3.1.1 Baseline Operations

Baseline (i.e., existing) operations for ORO and NBB are defined and described by the 1970 ORO and 1972 NBB WCMs. The WCPs within the WCMs were developed in an era when forecast skill was substantially lower than today, and thus they do not take full advantage of the forecasts available today. FIRO WCP strategies developed as a part of the FIRO viability assessment are designed to leverage forecast skill, and their performance is judged by comparing them with baseline operations.

Once flows in the system become high enough, coordination between the dams is needed to avoid impacts below the confluence of the Yuba and Feather Rivers. A cooperative program utilizing common decision support tools between reservoir operators and regulatory agencies was established following the 1997 flood. This Yuba-Feather F-CO program includes a common reservoir system operations model configured within the USACE Hydrologic Engineering Center (HEC) Reservoir System Simulation (HEC-ResSim). This model represents the flow constraints (Table 3-6) for the Yuba River near Marysville (Rule ID3) and the Feather River at Yuba City (Rule ID4) at 180 thousand cubic feet per second (kcfs). The HEC-ResSim model uses a reservoir-balancing algorithm to suggest releases from the ORO and NBB reservoirs to maintain the same percentage of flood space encroachment when other operating rules are otherwise in conflict. HEC-ResSim is presented to program participants within an F-CO Program Decision Support System (David Ford Consulting Engineers 2008), which both provides real-time forecasts and modeling results and makes it easier to comprehend them. The F-CO program is described in Section 2.2.1.

3.1.2 Key Locations for WCP Evaluations

Figure 3-1 provides geographical context for the locations of ORO and NBB dams, as well as the control points on the Feather and Yuba Rivers identified in the standing WCMs and evaluated as a part of FVA.

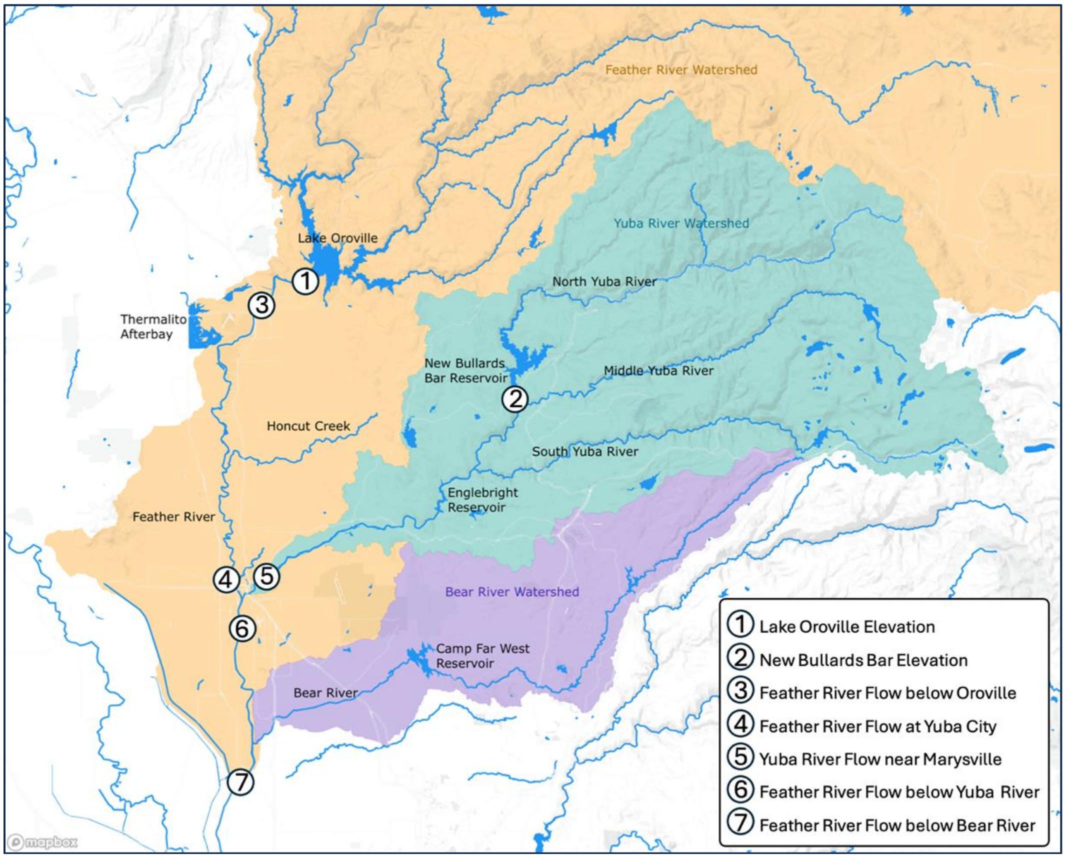


Figure 3-1. *Map of the Yuba-Feather watersheds with key locations for the evaluation of WCP alternatives.*

3.2 Studies Informing the Evaluation Framework

To develop FIRO alternatives, the WRE team built on previous Yuba-Feather and FIRO studies. Key studies informing the PVA are listed in Table 3-2.

Table 3-2. *Foundational Yuba-Feather and FIRO studies that informed the FVA.*

ID	Study	Relevance	Key Reference
1	Oroville Dam Safety Comprehensive Needs Assessment	Preliminary development and assessment of forecast-based alternatives for ORO Dam.	DWR. (2020). *Oroville Dam safety comprehensive needs assessment—Task 2: Operations*.
2	New Bullards Bar ARC Spillway evaluations	Preliminary development and assessment of forecast-based alternative for NBB Dam considering additional release capacity from the ARC Spillway.	Yuba Water Agency. (2020). *New Bullards Bar secondary spillway: Evaluation of flood management performance for candidate secondary spillway outlets.*

3	Lake Mendocino FIRO Program	Development and assessment of Ensemble Forecast Operation (EFO) alternatives for Lake Mendocino. Operation strategy serves as an example for ORO and NBB dams.	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.* UC San Diego. 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.
4	Folsom Dam and Lake WCM	Development and assessment of forecast-based alternatives for Folsom Dam. Operation strategy serves as an example for ORO and NBB dams.	USACE SPK. (2019). *Folsom Dam and Lake: Water Control Manual* (Rev. ed.). (Original published 1987).
5	Yuba-Feather F-CO Program	Description of decision support system to facilitate coordinated releases for ORO and NBB dams.	David Ford Consulting Engineers. (2008). *Oroville–New Bullards Bar Forecast-Coordinated Operations: Decision support system technical documentation.*
6	Yuba-Feather PVA		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 Preliminary Viability Assessment*. UC San Diego.

3.3 Evaluation Framework: The Hydrologic Engineering Management Plan

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

The HEMP includes the following:

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

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

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

3.3.1 Boundary Conditions

Both hard constraints and performance objectives were defined for the analysis. Table 3-3 provides the operational constraints that must be explicitly followed by each of the FIRO alternatives.

Table 3-3. *Operational constraints that all FIRO strategies must satisfy.*

ID	Operational Constraint	Description
1	Satisfy ORO WCM ESRD.	Meet all specific requirements stated in the ESRD.
2	Satisfy NBB WCM ESRD.	Meet all specific requirements stated on the draft candidate ESRD being developed for NBB Dam with the ARC Spillway (for FIRO alternatives that include the new NBB ARC Spillway).
3	Do not assume Marysville Dam is in place.	The WCM operations for ORO and NBB assume storage is available in Marysville Dam. Marysville Reservoir was authorized but never built.
4	Satisfy release rate of change constraints associated with increases and decreases of ORO and NBB reservoir levels.	As documented in the ORO and NBB WCMs.
5	Include the function of the new NBB secondary spillway.	The FIRO alternatives must incorporate the function of the new NBB ARC Spillway.
6	Do not require forecasts other than currently available streamflow forecasts.	California Nevada River Forecast Center (CNRFC) deterministic and ensemble streamflow forecasts are available up to four times per day during major runoff events. For evaluation purposes, forecast updates will be once per day.

Performance objectives are provided in Table 3-4. These objectives establish the basis for the metrics described in Section 3.3.2.

Table 3-4. *Performance objectives evaluated in the hydrologic engineering study.*

ID	Performance Objective	Description
1	Reduce the frequency of critical release exceedance from ORO and NBB.	Alternative should decrease the frequency of critical releases from both dams.
2	Reduce the frequency of ORO releases that result in more than 180,000 cfs in the Feather River at Yuba City.	Maximum F-CO flow target for ORO.

ID	Performance Objective	Description
3	Reduce the frequency of NBB releases that result in more than 180,000 cfs in the Yuba River at Marysville.	Maximum F-CO flow target for NBB.
4	Reduce the frequency of ORO and NBB releases that result in more than 300,000 cfs in the Feather River below Yuba River and 320,000 cfs in the Feather River below Bear River.	Combined F-CO flow targets for ORO and NBB.
5	Avoid negative impacts to spring refill.	Alternatives should not reduce the ability of ORO and NBB to meet water supply delivery objectives.

Table 3-5. *Systemwide performance objectives that should be evaluated in the hydrologic engineering study.*

ID	Performance Objective	Description
1	Implement F-CO at ORO and NBB reservoirs.	Consider and support the existing Yuba-Feather F-CO program.
2	Operational resiliency.	The FIRO alternative should be resilient to a wide range of hydrologic events within the watershed. For example, the operation should be resilient to a range of storm-centering events and events of key frequencies occurring within the Yuba-Feather watersheds.

As described in the PVA, Yuba Water is pursuing the construction of an additional spillway outlet structure for NBB (with a lower elevation invert) that will allow for the earlier and/or greater pre-releases needed to better leverage the FIRO approach associated with extreme flood events. The design for this ARC Spillway passed the 100 percent design milestone in 2023; pending final approval, funding, permitting, and construction is expected to be completed in either 2028 or 2029. The analysis performed for the FVA assumes the ARC Spillway is in place and fully functional.

3.3.2 Metrics

The flow constraints defined in the NBB and ORO WCMs form the basis of the FRM metrics. Table 3-6 shows the flow constraints for the Yuba and Feather Rivers as described in the current WCMs. For the initial at-site WCP development, only the objectives associated with locations above the confluence (ID3, ID4, and ID5) are considered. Feather River mainstem constraints (ID1 and ID2) are considered in the system operation.

Table 3-6. *Flow constraints as defined in the NBB and ORO WCMs.*

Rule ID	Location	Flow Constraint (kcfs)	NBB	ORO
1	Feather River below Yuba River	300	x	x
2	Feather River below Bear River	320	x	x
3	Yuba River near Marysville	120 when Feather is high[a]	x	
		180 when Feather is low[a]	x	
4	Feather River at Yuba City	180		x
5	Feather River downstream of ORO	150		x
6	North Yuba below NBB	50	x	

a. High and low are not defined in the WCMs.

The metrics to be evaluated for each WCP alternative are shown in Table 3-7. These metrics cover FRM and water availability. Environmental requirements are codified in the HEC-ResSim configuration and will be thoroughly evaluated in the National Environmental Policy Act process associated with the WCM updates.

Table 3-7. *Metrics for the evaluation of FIRO alternatives.*

ID	Metric Description	Category	Method of Computation
M1	Maximum discharge from ORO Dam	FRM	Simulated peak flow for selected historical and scaled historical events.
M2	Maximum pool elevation at ORO Dam	FRM	Simulated peak reservoir elevation for selected historical and scaled historical events.
M3	Maximum discharge from NBB Dam	FRM	Simulated peak flow for selected historical and scaled historical events.
M4	Maximum pool elevation at NBB Dam	FRM	Simulated peak reservoir elevation for selected historical and scaled historical events.
M5	Maximum flow at key downstream locations	FRM	Simulated peak flow for selected historical and scaled historical events. Key downstream locations are Yuba River at Marysville, Feather River at Yuba City, below Yuba River, and at Nicolaus.
M6	Post-event ORO Reservoir storage	Water availability	Summarize post-event storage levels.
M7	Post-event NBB Reservoir storage	Water availability	Summarize post-event storage levels.

3.4 At-Site Water Control Plans

As described in Section 3.1, the first step of the FVA is to develop alternative operations at each dam that achieve performance objectives at the dams, absent downstream confluence considerations. This preliminary analysis step builds to the development of a complete alternative that considers system operation. Based on the PVA, the evaluations performed for the FVA were narrowed to one prescriptive and one iterative alternative for ORO and NBB dams. These alternatives will be compared to the existing operation, which does not include the ARC Spillway at NBB. All FIRO alternatives include the ARC Spillway at NBB.

Prescriptive. The prescriptive strategies were based on elements from the 2019 WCM operation of Folsom Dam. The prescriptive strategy relies on predetermined target storage values and/or releases, both determined based on inflow forecast volume. The ensemble forecast is processed to a single-value volume, such as a 75 percent non-exceedance probability (NEP) value, to determine the target elevation and/or release magnitude. The prescriptive alternatives for NBB and ORO are designated as ID3 henceforth.

Iterative. The iterative strategies were based on elements from the Lake Mendocino FIRO program alternatives. The iterative strategy uses each member of the forecast ensemble to consider the full range of potential storage outcomes for a given release. If the range of ensemble forecasts exceeds a prescribed tolerance of uncertainty above a given reservoir elevation, a release schedule is formulated that mitigates the tolerance exceedance at lead times up to 14 days given forecasted release constraints. While 14 days of lead time is a stretch for forecast skill, the hindcasts provided by the CNRFC have 14-day lead times, and the iterative strategies leverage forecasts in proportion to the demonstrated skill in forecasts at all lead times (i.e., short lead time forecasts have greater skill and therefore greater weight than longer lead time forecasts). The iterative alternatives for NBB and ORO are designated as ID4 henceforth.

For clarity, Table 3-8 qualifies the ID1, ID3, and ID4 alternatives so they explicitly show the existence or non-existence of the proposed NBB ARC Spillway. "E" indicates the existing condition (no ARC Spillway) and "A" indicates the functionality of the proposed NBB ARC Spillway.

Table 3-8. *Designation of at-site alternatives with explicit notation related to the NBB ARC Spillway.*

Approach	NBB At-Site	ORO At-Site	Special Notes
Baseline	ID1E	ID1E	No ARC Spillway at NBB.
Prescriptive	ID3A	ID3A	ARC Spillway at NBB.
Iterative	ID4A	ID4A	ARC Spillway at NBB.

3.4.1 FIRO Space

Consistent with the recommendations from the PVA (Table 3-1), the FIRO Space for each reservoir was established and adhered to for the at-site alternatives. Figure 3-2 and Figure 3-3 show the FIRO Space for NBB and ORO reservoirs respectively. Note that the FIRO Space is the elevation range within the reservoir where forecast informed decisions can be made. The FIRO Space can be located within both the flood reserve and the conservation space. Below the FIRO Space, release rules associated with conservation storage are followed. Above the FIRO Space, release rules associated with FRM are strictly followed (i.e., draft excess water as soon as safely possible).

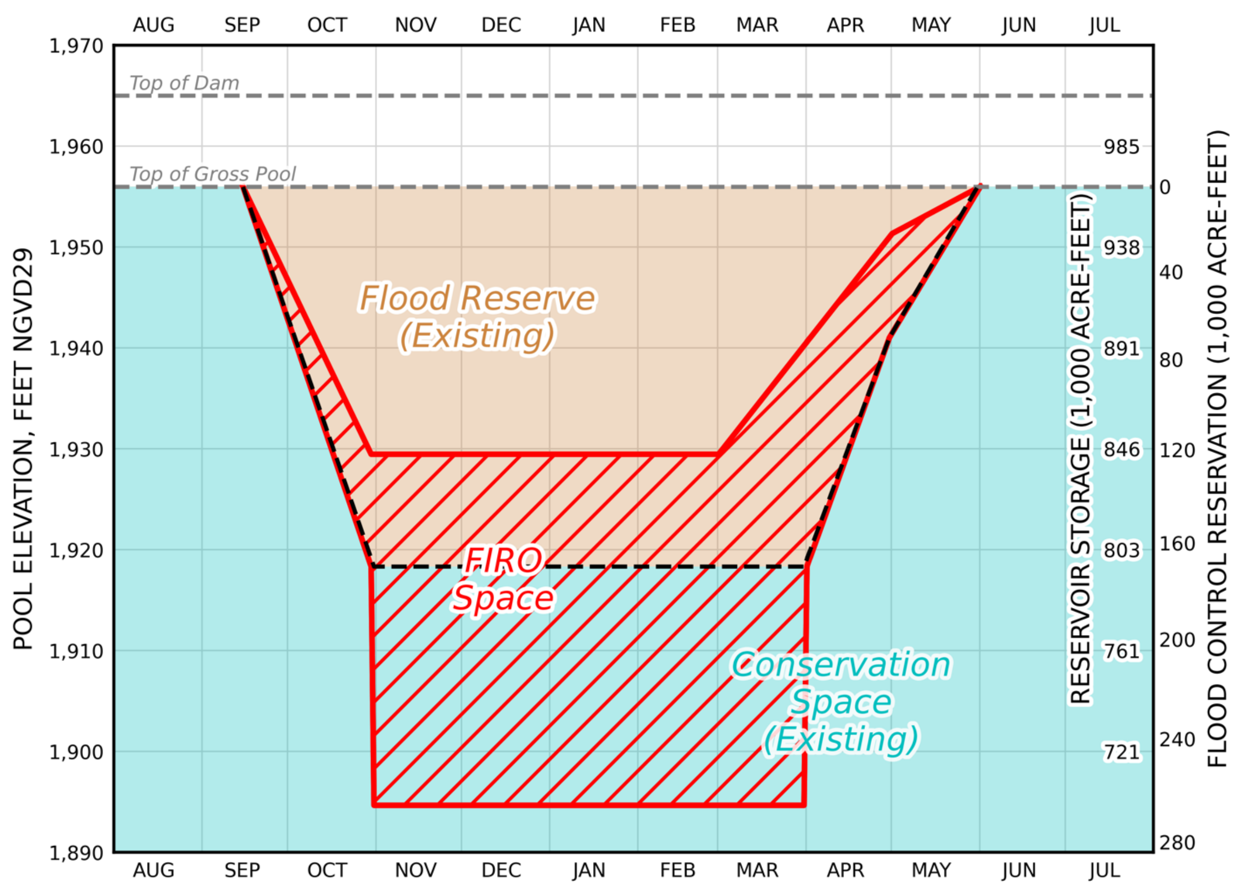


Figure 3-2. *FIRO Space for NBB Reservoir.*

The FIRO Space at NBB varies seasonally and notably overlaps with both the existing flood reserve and conservation pool. In the winter months of November through March, the FIRO Space is used to augment the existing flood reserve. Evacuation of this space is triggered by using forecasts in advance of a flood, allowing the reservoir to absorb and manage greater volumes. When conditions are forecast to be dry, however, the reservoir is permitted to maintain storage within the flood reserve. This process provides operational flexibility during the spring refill season, allowing operators greater opportunity to capture spring inflows for beneficial use later in the season.

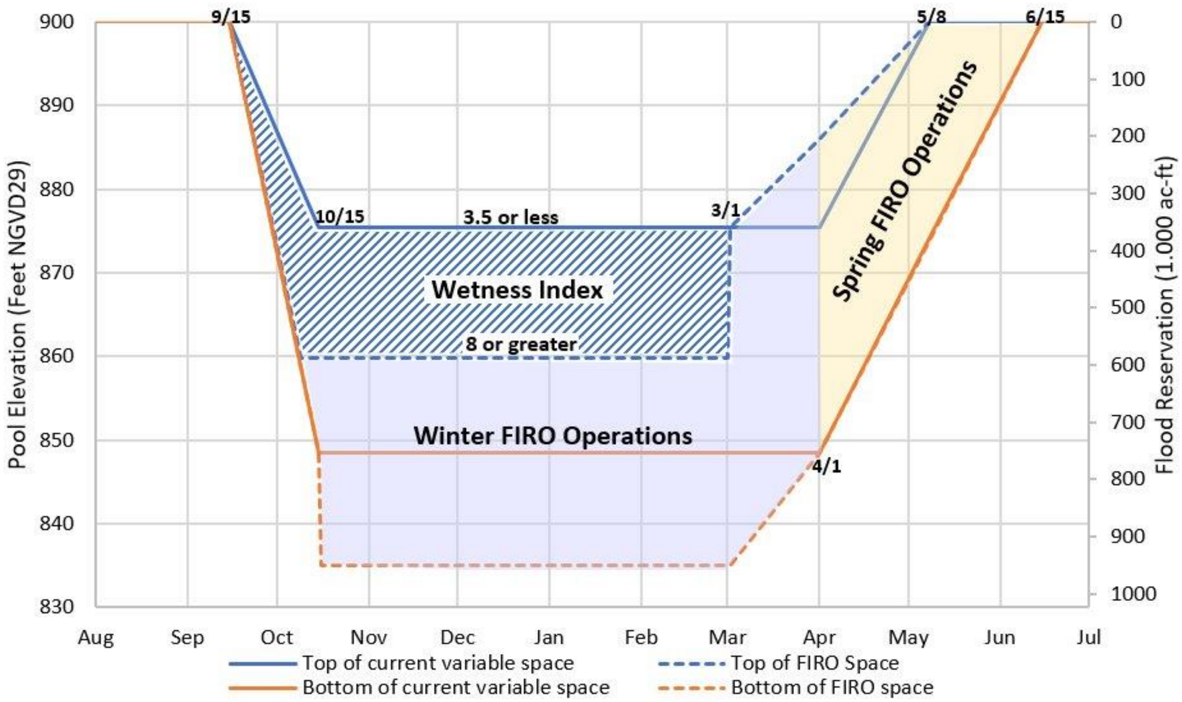


Figure 3-3. *FIRO Space for ORO Reservoir.*

The FIRO Space at ORO also varies seasonally and overlaps with both the existing flood reservation and conservation pool. From September 15 to March 1, the FIRO Target storage varies based on wetness index parameters and forecasted inflow volumes. The ORO wetness index is based on accumulated precipitation at a defined set of gauges with a decay factor (1970 ORO WCM). If the forecasted inflow volumes are not triggered, then the FIRO Target will follow the wetness index. From March 1 to June 15, the FIRO Target storage varies based on only forecasted inflow volumes. This process provides operational flexibility during the spring refill season, allowing operators greater opportunity to capture spring inflows for beneficial use later in the season.

3.4.2 ID3 At-Site Operations for NBB

The NBB ID3 alternative builds on the forecast-informed operations developed in the PVA and incorporates feedback provided through ongoing coordination with USACE on the WCM update project. This alternative provides flexibility to maintain higher reservoir storage when no flood events are signaled in the forecast, but it is responsive enough to evacuate this storage when necessary. When an incoming extreme flood is predicted, the existing flood reserve can be augmented by drafting into the conservation pool.

Fundamentally, ID3 relies on a forecast-informed target (i.e., FIRO Target) to specify evacuation of the FIRO Space in advance of a flood event. The FIRO Target is computed in terms of FIRO Space utilization, or the target percent evacuation of the FIRO Space. Using a percentage allows the same relationship to be applied throughout the entire year, though the magnitude of the FIRO Space varies seasonally, as shown in Figure 3-3. FIRO releases are informed by a calculation based on the difference between current reservoir storage and the FIRO Target. Table 3-9 lists other operational considerations for the reservoir operations model.

Table 3-9. *Operational considerations represented for NBB in the hourly timestep HEC-ResSim model.*

Consideration	Category
ESRD (including adjustments associated with the ARC Spillway)	Emergency operations
Maximum objective flows for: Yuba River near Marysville (180,000 cfs) Feather River below Yuba River (300,000 cfs) Feather River below Bear River (320,000 cfs)	Downstream flow constraints
FIRO release	FIRO
Rate of increase limit (5,000 cfs per hour) Rate of decrease limit (5,000 cfs per hour)	Rate of change limitations
Primary spillway ARC Spillway Colgate Penstock (operationally restricted based on tailwater thresholds) Lower River Outlet, operationally restricted to 1250 cfs	Capacity of existing and planned outlet works and spillways
Minimum in-stream flow requirements	Simplified representation for flood season only

The FIRO release decisions are guided by FIRO Target storage. Computing the FIRO Target depends on forecast volumes derived from the CNRFC's ensemble forecast. Figure 3-4 illustrates how the NBBC1 ensemble inflow forecast to NBB (top pane) is converted to an ensemble of cumulative forecast volumes (bottom pane). At each duration (24, 72, 120, and 168 hours), the ensemble member volumes are ranked, and the 75 percent NEP volume is selected as a representation of the forecast. Note that the same ensemble member may be selected for multiple durations, as is the case here for 24 and 72 hours. Each of these ranked 75 percent NEP volumes is represented by a square marker in the bottom pane of Figure 3-4. For this example, the resulting volumes are 44 TAF, 291 TAF, 344 TAF, and 370 TAF for ranking horizons 24, 72, 120, and 168 hours, respectively. The simulated inflow time series is included for reference on both panes in black. Parameterization of the FIRO Target calculation has evolved from an initial candidate with durations of 24, 48, 72 ,96, 120, and 168 hours (MBK Engineers 2021b) to a leaner set that is as effective and easier to apply.

The 75 percent NEP was selected because the ensemble hindcasts exhibit a dry bias for large storms (Yuba Water Agency 2018). The 75 percent NEP was found to be a closer approximation of the historical inflow volumes, when evaluated for the unscaled ensemble period of record.

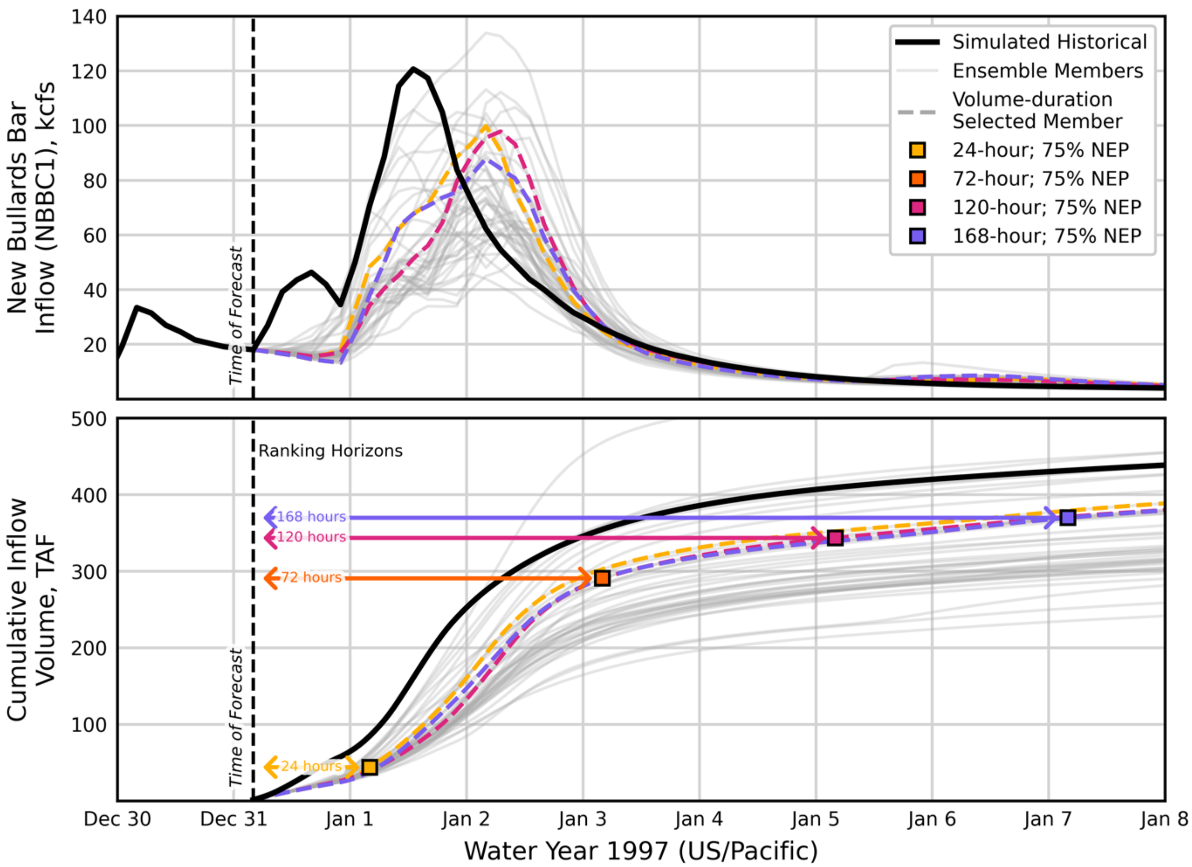


Figure 3-4. *NBB inflow volumes derived from unscaled hindcast ensemble for December 31, 1996.*

The four values synthesized from the volume ensemble are multiplied by a seasonal factor (1.0 for winter season and 1.67 for spring refill season) and placed on the FIRO Target lookup, depicted in Figure 3-5, before being used to evaluate the percentage of FIRO Space evacuation (PFSE) for each forecast duration. The most conservative (lowest) PFSE value is adopted as the FIRO Target. The corresponding FIRO Target value as a reservoir storage volume is given by the following equation:

$$FIRO\ Target_{storage} = Top\ of\ FIRO\ space - PFSE\ (Top\ of\ FIRO\ space - Bottom\ of\ FIRO\ space)$$

where the top and bottom of FIRO Space are determined from the FIRO Space boundaries for the specified date in Figure 3-4.

For the December 31, 1996, hindcast, this equation results in a FIRO Target specifying 100 percent evacuation of the FIRO Space, or a storage value of just over 700 TAF.

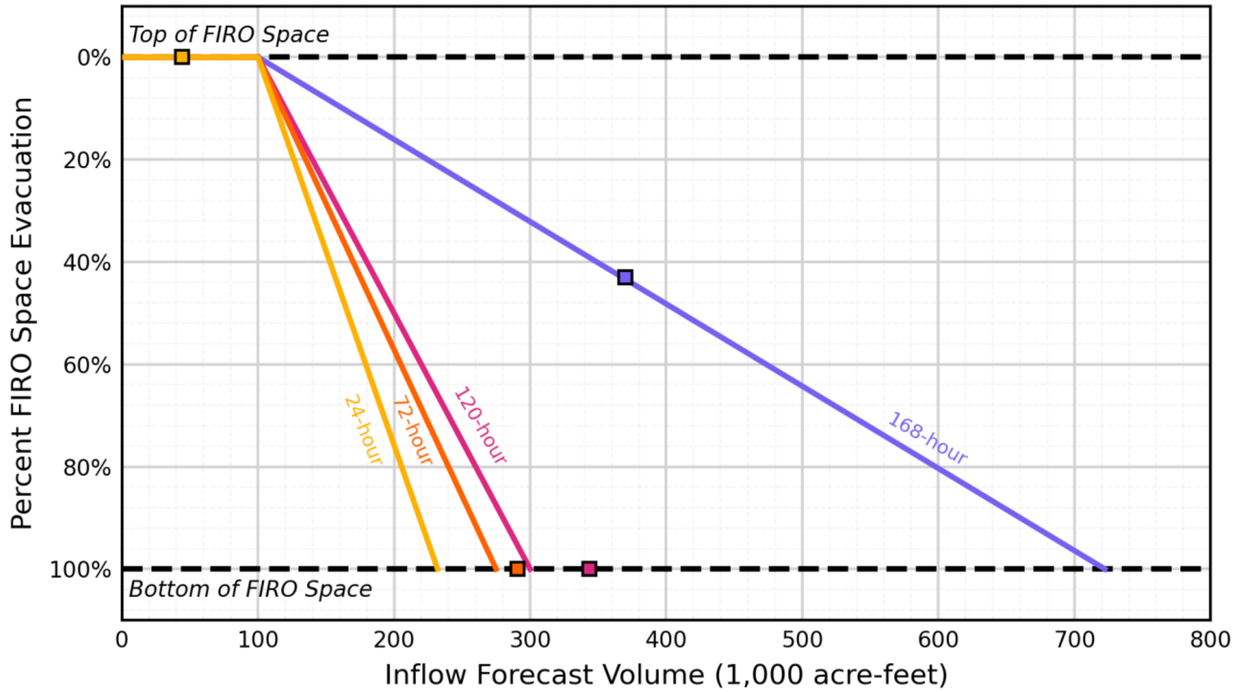


Figure 3-5. *NBB FIRO Target lookup, a function of four inflow forecast volumes.*

The seasonal inflation factor is introduced as a mechanism to allow the single diagram in Figure 3-5 to represent FIRO Target relationships for the full year. The minimum forecast volume to initiate FIRO drawdown is 100 TAF, which is rarely observed in March through June, so the spring forecast volumes have been inflated for the purpose of this evaluation, such that the FIRO Space will be utilized for managing spring events. Proof of concept has been explored using the spring 1995 hindcasts provided by the CNRFC for the FVA. This seasonal inflation factor is expected to be further refined in the WCM update program.

The FIRO release is computed from the current storage and the FIRO Target storage. After initiating FIRO releases, an increasing release pattern is maintained to the extent possible until the event recedes. This rule will also have a certain amount of operational flexibility. When implemented, it may also consider the maximum rate of inflow experienced over the course of the FIRO release (typically, the last 120 hours). For the purposes of the FVA, the FIRO release is represented as the maximum of the difference in (1) current NBB storage and FIRO Target released over 12 hours and (2) the most recent FIRO release. In real-time operations, this will be subject to reduction if storage is significantly below the FIRO Target. During event recovery as the flood begins to recede, the release should be consistent with falling pool ESRD operations.

The typical progression of ID3A operations consists of an initial period of FIRO release, causing a reduction of reservoir storage to make room for an incoming flood. At a certain point, the release from the reservoir becomes physically restricted due to reduced head in the reservoir. In larger flood events, there is then a transition to a period where flows are reduced to meet downstream maximum flow objectives. This reduction may require joint operation of NBB with ORO to meet flow objectives in the Feather River below Yuba and Bear Rivers. At this point, the ESRD may call for higher releases, which take priority according to dam safety protocols. As the flood event recedes, releases are made to recover to the FIRO Target, typically at the top of the FIRO Space.

3.4.3 Prescriptive At-Site Operations for ORO (ID3)

The ORO ID3 alternative builds on the forecast-informed operations developed in the PVA (derived from the Folsom WCM operations). The ORO alternative now includes a truncated wetness index, based on the existing water control diagram, in the peak flood season and an additional 170,000 acre-feet (ac-ft) of FIRO Space into the conservation pool. This alternative provides the flexibility to maintain higher reservoir storage when appropriate based on hydrologic conditions of the watershed when flood forecasts are lacking, but it is responsive to changes in conditions and forecasts to evacuate this storage when necessary. When an incoming extreme flood is predicted, the existing flood reserve can be augmented by drafting into the conservation pool.

From September 15 to March 1, the minimum FIRO Space flood management requirements of 600,000 ac-ft (at 859.5 feet in elevation) and maximum FIRO Space flood management requirements of 925,000 ac-ft (at 835 feet elevation) are defined by the p = 0.2 (1/5-year) and p = 0.01 (1/100-year) annual exceedance probability (AEP) quantiles, respectively. If the forecasted inflow volumes are not triggered, then the FIRO Target will follow the wetness index. The variable FIRO Space elevation is calculated based on the wetness index and the AEP of the forecast inflows averaged for 24-, 48-, 72-, 120-, and 168-hour durations, as follows:

- The wetness index controls from 375,000 ac-ft to 600,000 ac-ft of the flood management storage if the FIRO Target forecasted inflow volumes are not exceeded. Wetness index parameters are computed daily from the weighted accumulation of seasonal basin mean precipitation by multiplying the preceding day's parameter by 0.97 and adding the current day's precipitation in inches.
- The FIRO Target would be at 600,000 ac-ft of flood management storage (859.5 feet) for forecast average inflows of any duration less than or equal to the p = 0.2 (1/5-year) AEP quantile (1-day average inflow ≤ 90,631 cfs, 2-day average inflow ≤ 80,404 cfs, 3-day average inflow ≤ 70,177 cfs, 5-day average inflow ≤ 60,007 cfs, and 168-hour average inflow ≤ 49,836 cfs).
- The FIRO Target would be at 750,000 ac-ft of flood management storage (848.5 feet) for forecast average inflows of any duration less than or equal to the p = 0.04 (1/25-year) AEP quantile (24-hour average inflow ≤ 185,503 cfs, 48-hour average inflow ≤ 166,252 cfs, 72-hour average inflow ≤ 147,000 cfs, 120-hour average inflow ≤ 121,128 cfs, and 168-hour average inflow ≤ 95,256 cfs).
- The FIRO Target would be at 925,000 ac-ft of flood management storage (835 feet) for forecast average inflows of any duration greater than or equal to the p = 0.01 (1/100-year) AEP quantile (24-hour average inflow ≥ 284,175 cfs, 48-hour average inflow ≥ 256,973 cfs, 72-hour average inflow ≥ 229,770 cfs, 120-hour average inflow ≥ 183,484 cfs, or 168-hour average inflow ≥ 137,197 cfs).
- For forecast average inflows between the p = 0.2 and p = 0.01 AEP quantiles, the FIRO Target would be interpolated from elevations (859.5 feet, 848.5 feet, and 835 feet) and the corresponding (p = 0.2, p = 0.04, and p = 0.01) average inflow thresholds. The lowest top of conservation (TOC) of the five durations would be used.

The 96- and 144-hour duration forecasts were thinned from the procedure to improve the ease of application without sacrificing effectiveness. Figure 3-6 details the ID3 forecast-based inflow FIRO Target requirements.

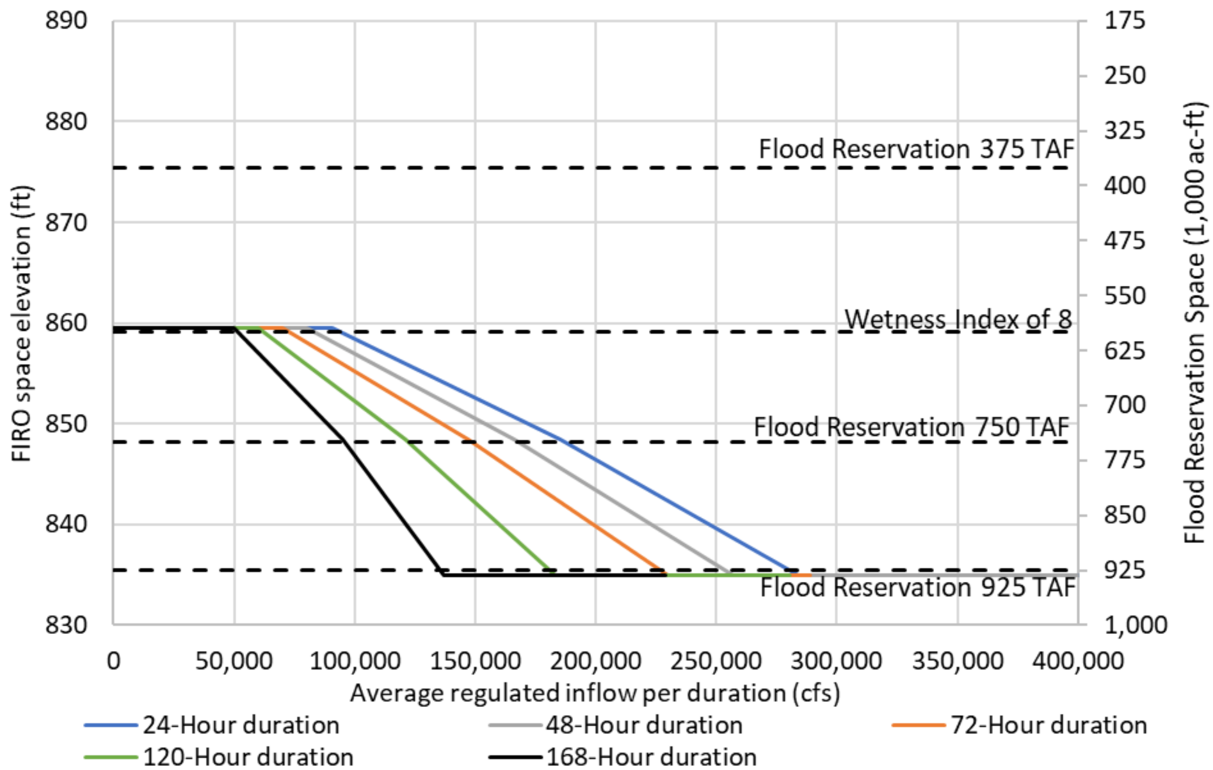


Figure 3-6. *Drawdown curves for ID3 FIRO Target computation.*

Starting March 1, the wetness index is dropped and the candidate forecast-based variable FIRO Target elevation is defined by a minimum FIRO Space flood management requirement of 375,000 ac-ft (875.4 feet) and maximum FIRO Space flood management requirement of up to 925,000 ac-ft (835 feet), defined by the p = 0.2 (1/5-year) and p = 0.01 (1/100-year) AEP quantiles respectively. March FIRO operations for ID3 compute the variable FIRO Space elevation based on the AEP of the forecast inflows averaged for 24-, 48-, 72-, 120-, and 168-hour duration, as follows:

- The March FIRO Target would be at 0 percent FIRO Space utilization for forecast average inflows of any duration less than or equal to the p = 0.2 (1/5-year) AEP quantile (24-hour average inflow ≤ 90,631 cfs, 48-hour average inflow ≤ 80,404 cfs, 72-hour average inflow ≤ 70,177 cfs, 120-hour average inflow ≤ 60,007 cfs, and 168-hour average inflow ≤ 49,836 cfs).
- The March FIRO Target would be at 66 percent FIRO Space utilization for forecast average inflows of any duration less than or equal to the p = 0.04 (1/25-year) AEP quantile (24-hour average inflow ≤ 185,503 cfs, 48-hour average inflow ≤ 166,252 cfs, 72-hour average inflow ≤ 147,000 cfs, 120-hour average inflow ≤ 121,128 cfs, and 168-hour average inflow ≤ 95,256 cfs).

- The March FIRO Target would be at 100 percent FIRO Space utilization for forecast average inflows of any duration greater than or equal to the p = 0.01 (1/100-year) AEP quantile (24-hour average inflow ≥ 284,175 cfs, 48-hour average inflow ≥ 256,973 cfs, 72-hour average inflow ≥ 229,770 cfs, 120-hour average inflow ≥ 183,484 cfs, or 168-hour average inflow ≥ 137,197 cfs).
- For forecast average inflows between the 0 and 100 percent FIRO Space utilization, the FIRO Target would be interpolated based on the elevations depicted in Figure 3-6 and the average inflow thresholds. The lowest TOC of the five durations would be used.

Forecast-based releases would occur when the FIRO Target drops below the current storage. Maximum releases would be a function of 24-, 48-, 72-, 120-, and 168-hour forecast average inflows and stepped as follows:

- If any duration forecast average inflow is greater than or equal to the p = 0.2 (1/5-year) AEP quantile, release up to 30,000 cfs.
- If any duration forecast average inflow is greater than or equal to the p = 0.1 (1/10-year) AEP quantile or current inflow is greater than 30,005 cfs, release up to 60,000 cfs.
- If the 120-, 72-, 48-, or 24-hour forecast average inflow is greater than or equal to the p = 0.04 (1/25-year) AEP quantile or current inflow is greater than 120,005 cfs, release up to 100,000 cfs.
- If the 48- or 24-hour forecast average inflow is greater than or equal to the p = 0.01 (1/100-year) AEP quantile or current inflow is greater than 175,005 cfs, release up to 150,000 cfs.

Forecast average inflows would be evaluated based on 24-, 48-, 72-, 120-, and 168-hour averaging durations. Release decisions would be informed by interpreting Figure 3-7.

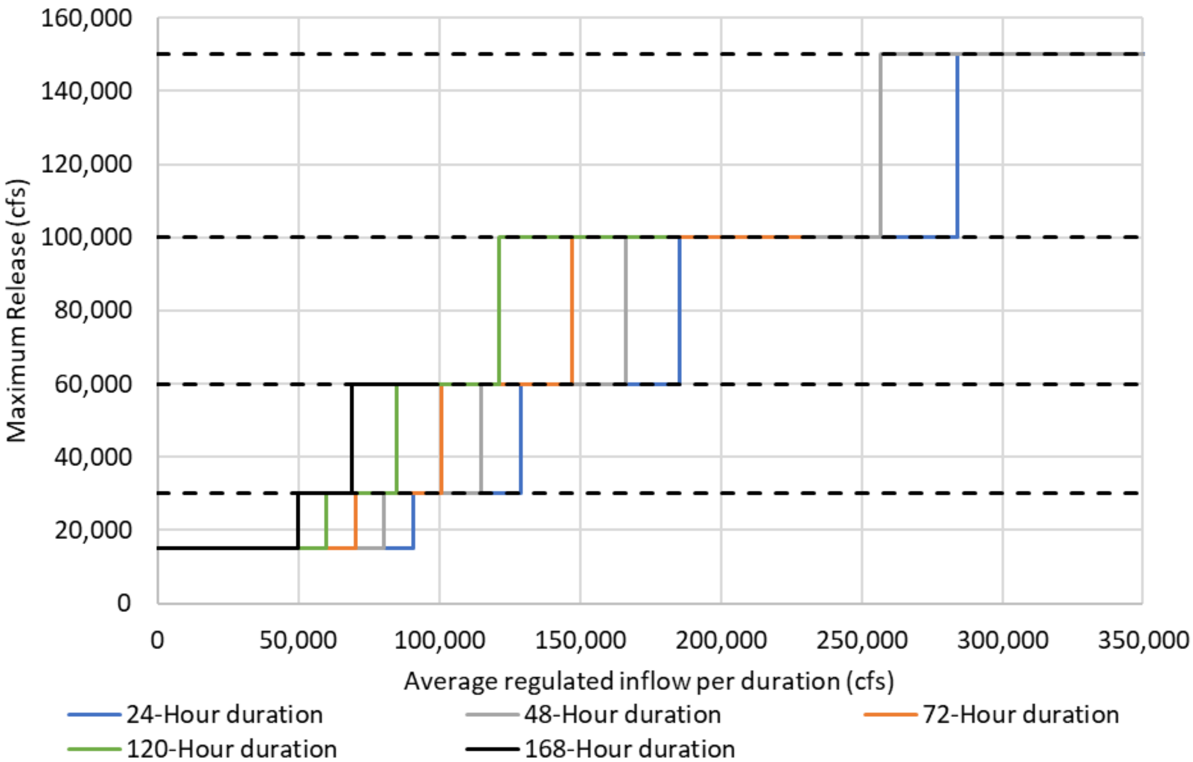


Figure 3-7. *Forecast based releases for Oroville ID3.*

3.4.4 Iterative At-Site Operations for NBB and ORO (ID4)

The iterative alternative, or ID4, is EFO, a FIRO method that utilizes ensemble streamflow predictions to evaluate forecast uncertainty to help inform release decisions. This methodology was originally developed for Lake Mendocino (Delaney et al. 2020) on the Russian River in Mendocino County, California, and was critical in demonstrating the viability of FIRO for Lake Mendocino through evaluations completed in both the PVA and FVA (Jasperse et al. 2020). EFO was also evaluated in the Yuba-Feather PVA (Ralph et al. 2022) and showed significant promise for leveraging ensemble flow forecasts to reduce flood risk and enhance water availability.

With the EFO methodology, each hydrologic ensemble member is independently modeled to forecast reservoir storage assuming no water is released. Forecasted risk of exceeding a defined maximum storage threshold is evaluated for each time step in the forecast horizon (14 days) as the percentage of ensemble members that exceed that threshold. For ORO and NBB, the maximum storage threshold is defined as the top of the flood pool of 3,538 ac-ft and 965 TAF, respectively. The use of longer forecast lead times (14 days) in ID4 is possible because the methodology inherently discounts the reduced skill as lead time increases through the risk tolerance curve described below.

A central component of the EFO methodology is the risk tolerance curve that establishes the maximum allowable forecasted risk of exceeding the defined storage threshold. If the risk tolerance curve is exceeded, then a release is formulated that seeks to mitigate the forecasted risk at or below the risk tolerance curve. Figure 3-8 provides the risk tolerance curves developed for ORO and NBB. These risk tolerance curves were developed using an optimization methodology where thousands of candidate risk tolerance curves were simulated and evaluated for each reservoir, and an optimal curve was identified that maximizes water released in advance of a forecasted storm event yet minimizes storage not recovered at the end of a storm event due to over-release. A similar optimization methodology was used to develop the risk tolerance curve for Lake Mendocino (Delaney et al. 2020).

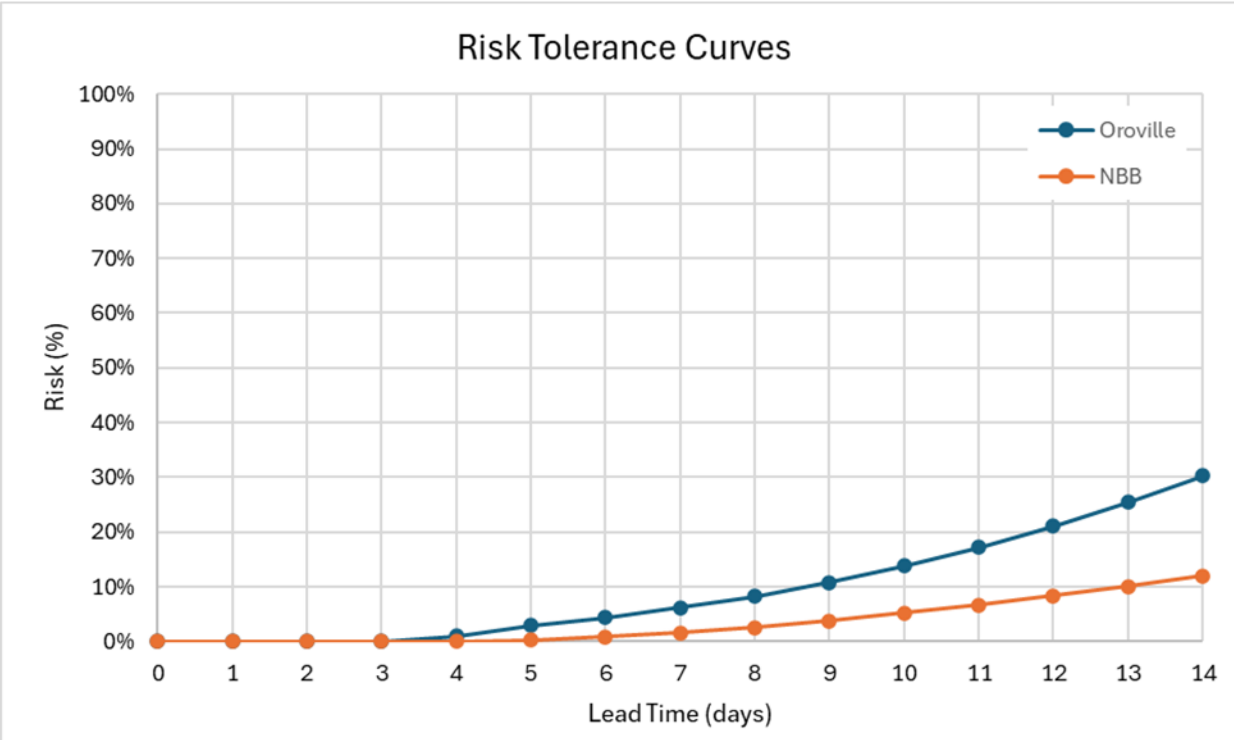


Figure 3-8. *ORO and NBB risk tolerance curves.*

Figure 3-9 shows an example of how the EFO methodology works for NBB by using scaled hindcasts developed by the CNRFC for December 24, 1996 (i.e., in advance of the 1997 flood event). The top panel provides an example of a storage forecast for NBB with a 14-day forecast lead time, with the maximum storage threshold shown as the black dashed line. The bottom panel provides an example of the risk forecast shown as the red line and the risk tolerance curve shown as the blue dashed line.

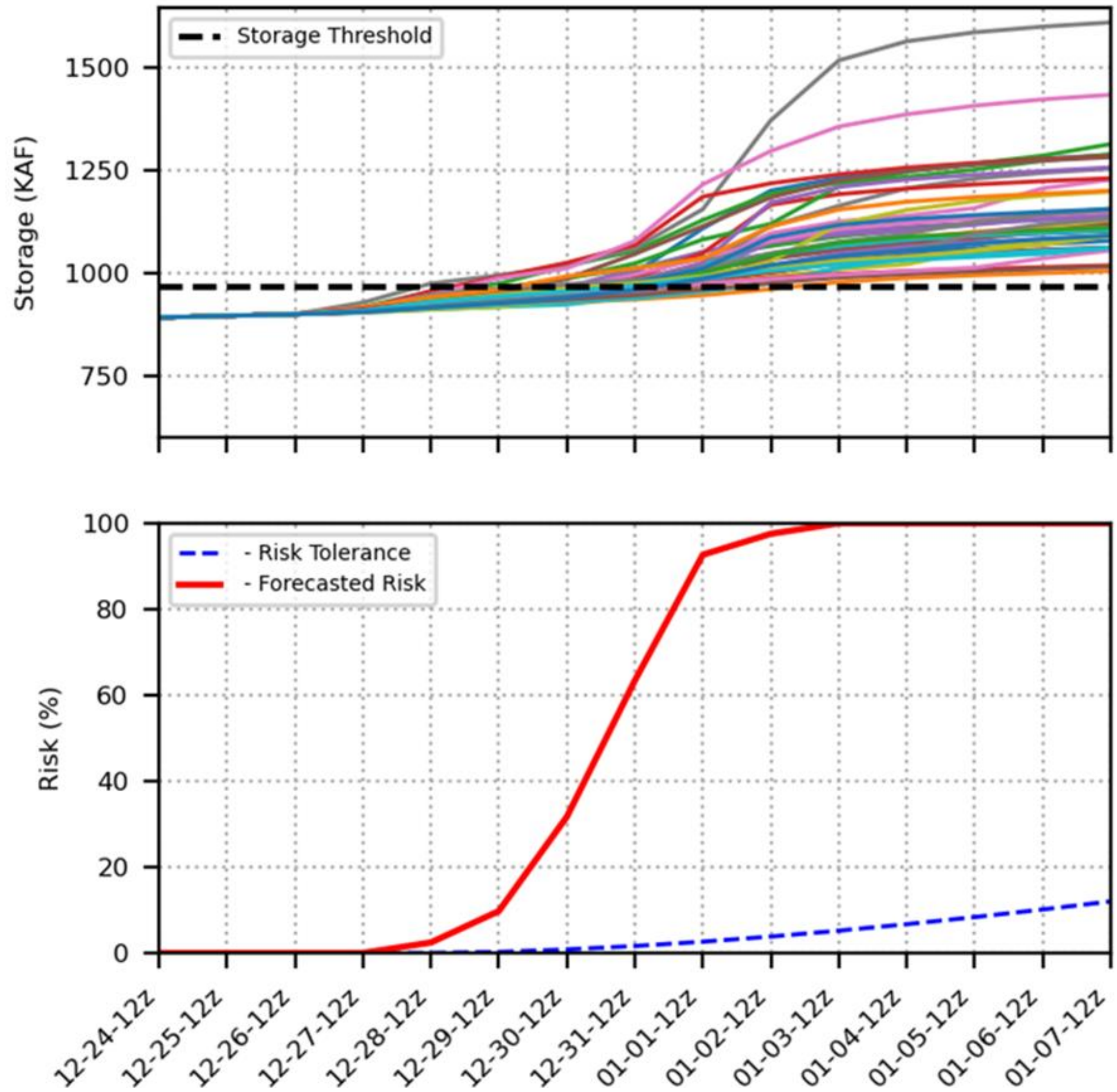


Figure 3-9. *Example pre-release forecast for NBB using CNRFC scaled hindcasts from December 24, 1996.*

If forecasted risk exceeds the risk tolerance curve, as in the example above, then a release schedule is developed that mitigates the forecasted risk at or below the tolerance curve. For this example, the model simulated a release of 18.6 kcfs to reduce the forecasted risk to the risk tolerance level. This is illustrated in Figure 3-10, which shows forecasted risk and storage levels after the release schedule has been applied. The top panel shows that forecast storage has been reduced for all the ensemble members, and the bottom panel shows that forecast risk has been mitigated at or below the risk tolerance curve. The model completes this process, updating release schedules whenever a new forecast is issued. For the simulation studies of the FVA, hindcasts are available once per day. In operations, the CNRFC will issue forecasts four times per day during major flood events.

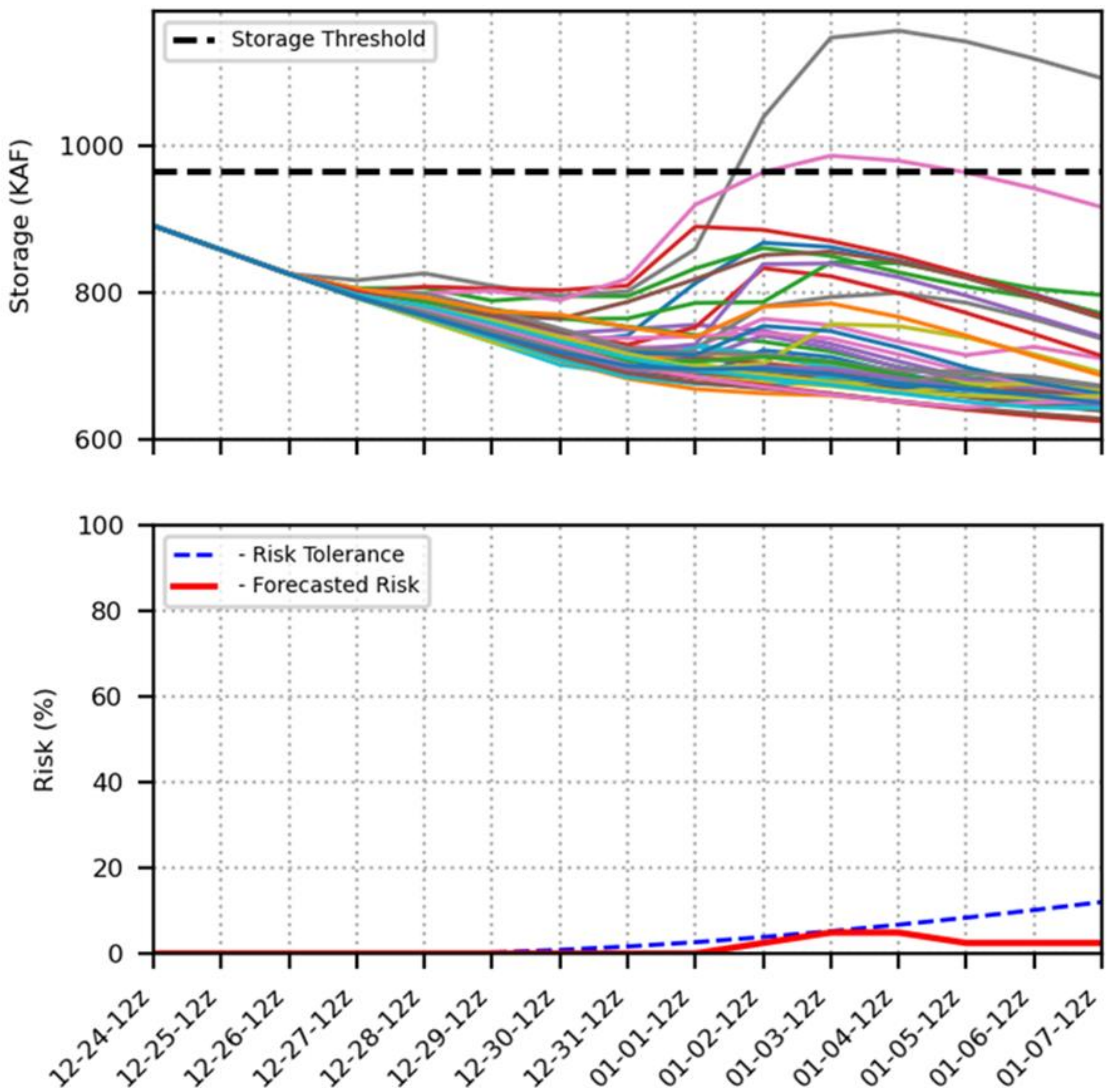


Figure 3-10. *Example post-release forecast for NBB using CNRFC scaled hindcasts from December 24, 1996.*

The EFO alternative, labeled ID4, was simulated for the FVA by limiting forecast-based releases to only occur within the defined FIRO Space at each reservoir, as previously discussed in Section 3.4.1. The ID4 alternative is simulated using the EFO model, which uses Python code developed by Sonoma Water and the Center for Western Weather and Water Extremes to generate release schedules at an hourly time step for ORO and NBB for each day of the simulation. Additionally, to apply the F-CO system operations rules defined in HEC-ResSim and ensure flow routing was consistent for all alternatives evaluated in the FVA, the release schedules developed for ID4 with the EFO model were then processed as a “suggested release” in the HEC-ResSim rule stack. HEC-ResSim then evaluates these proposed EFO release schedules against all the other rules defined in the rule stack and may implement these release schedules depending on priority. The EFO alternative (or ID4) was simulated for the 1986 and 1997 scaled events.

3.4.5 Illustration of Event Simulation

Figure 3-11, Figure 3-12, and Figure 3-13 illustrate the three WCPs operated for the unscaled 1997 hindcast event. The ID1E (baseline) condition is included for context, starting at the winter TOC and characterized by releases for the existing release schedule, cutbacks for downstream flow constraints, a return to the objective flow (Table 3-7), and subsequent reservoir drawdown back to the TOC. The FIRO alternatives at both reservoirs are characterized by an extended period of advanced releases (i.e., FIRO releases) triggered by the inflow volume forecast. Evacuating the FIRO Space frequently reduces the reservoir head enough to cause a physical limitation to the amount of flow through the spillways and outlet structures. As inflows increase during the main flood wave, the head and release capacity rise again. For large events, a period of cutbacks for downstream control flows results in increased reservoir storage. In some cases, these cutbacks may lead to activation of the ESRD. As the event begins to recede, releases are specified to target recovering to the top of the FIRO Space.

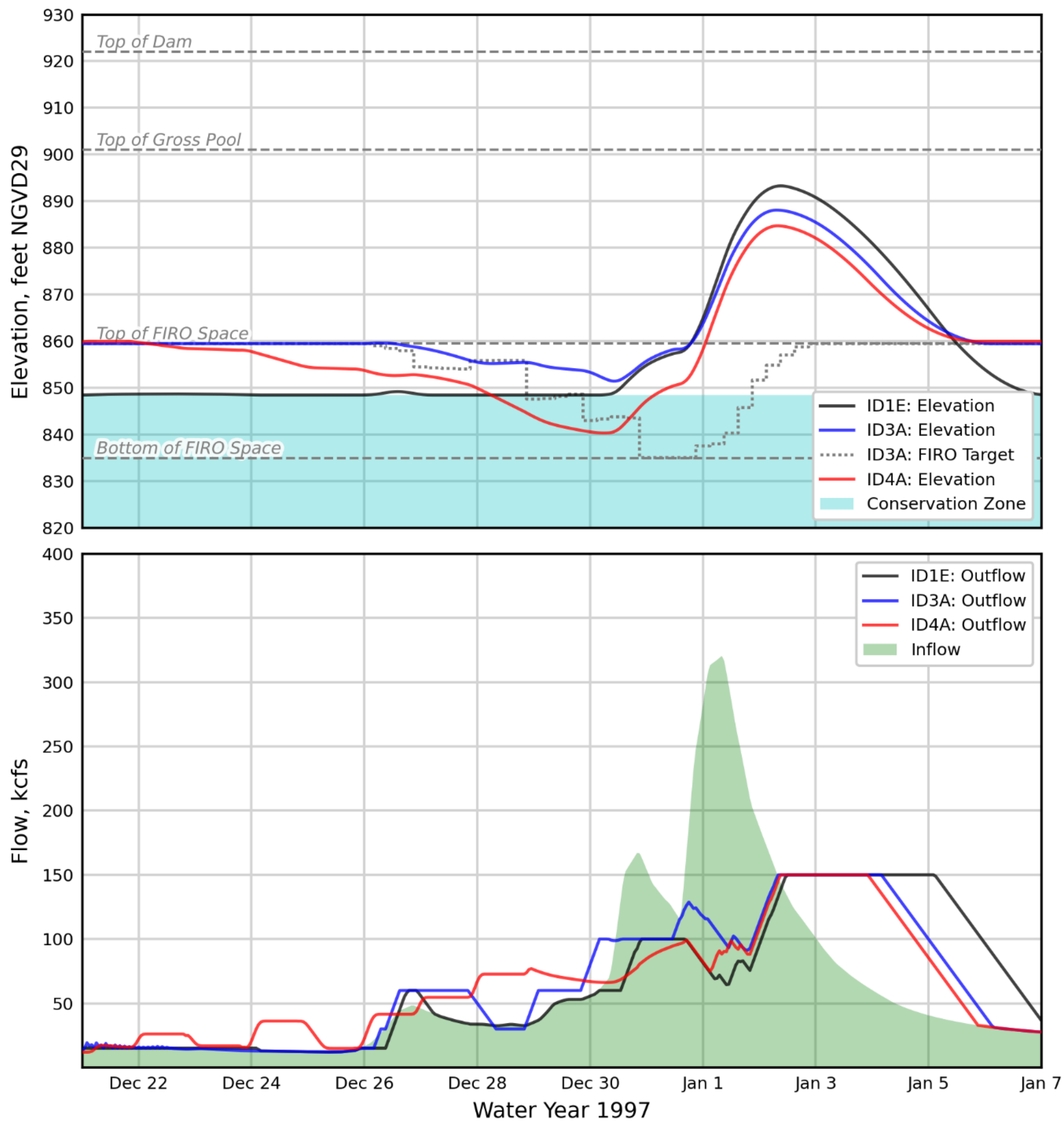


Figure 3-11. *ORO operations for the 100 percent scaling of the 1997 flood event.*

The 1997 scaled hindcast event is characterized by under-forecasts through the beginning of the flood wave, which are reflected in the ORO FIRO Target time series activating only six days before the event peak. Ultimately, ID3A cannot meet the specified FIRO evacuation. ID4A, in contrast, initializes FIRO releases an additional four days earlier, enabling much greater evacuation of the flood reserve and a portion of the conservation space. Both FIRO alternatives demonstrate improved FRM performance compared to ID1E, with both reductions in peak storage and a reduced duration of releases at the objective flow rate of 150,000 cfs.

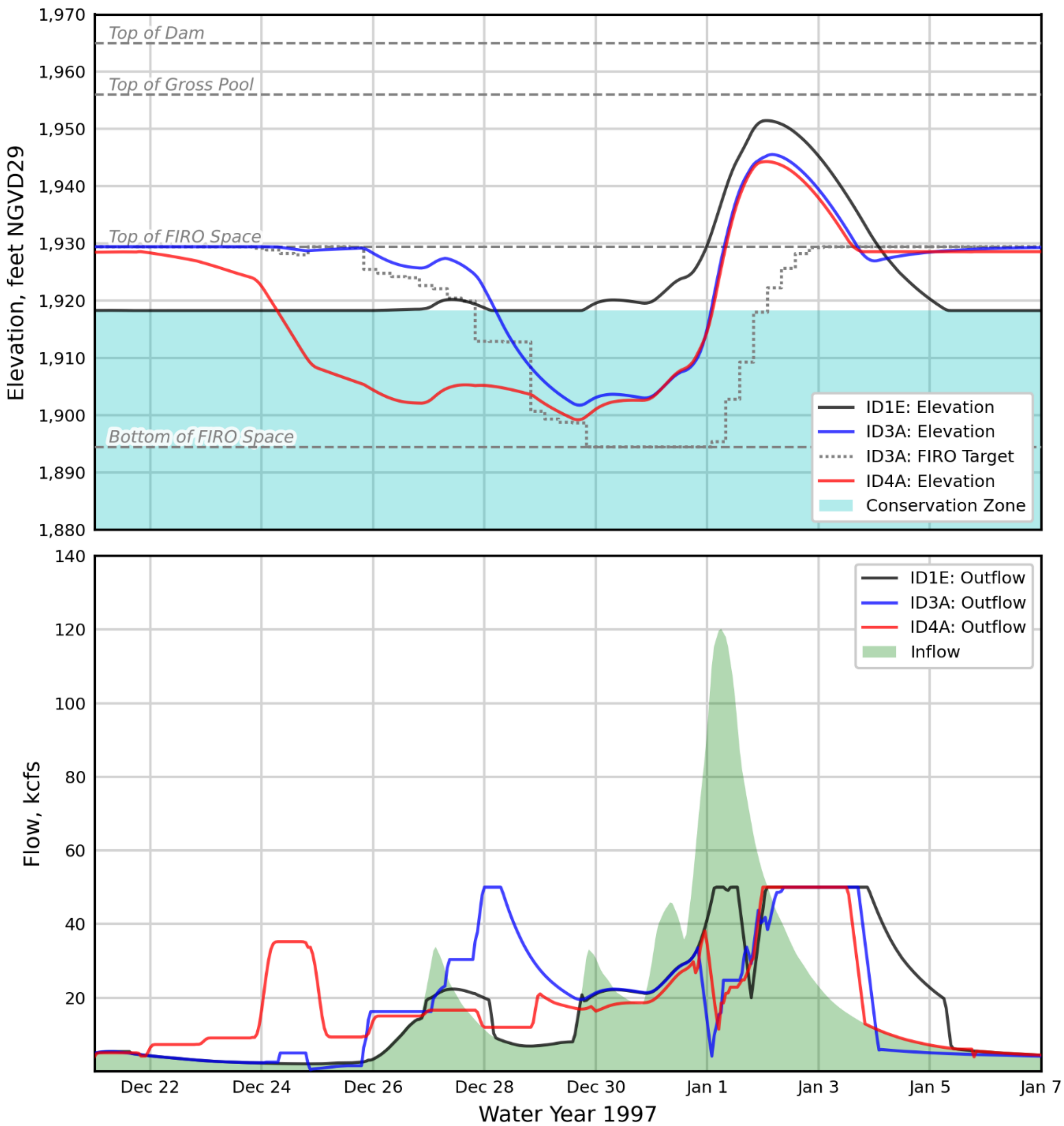


Figure 3-12. *NBB operations for the 100 percent scaling of the 1997 flood event.*

The pattern of under-forecasting is also present in NBB inflows for the 1997 scaled hindcast events. Under the 100 percent scaling of the 1997 flood event, ID3A initiates FIRO release eight days before the event peak. ID4A activates two to three days earlier. The marked difference between the alternatives is the timing of the major advanced releases (December 24 for ID4A and December 28 for ID3A). Both alternatives evacuate significant portions of the FIRO Space overlapping with the conservation space, leading to an eventual release capacity restriction (starting December 28 for ID4A and 29 for ID3A). The two FIRO alternatives perform very similarly in terms of peak reservoir storage, ability to recover post-event, and duration of flows at 50,000 cfs.

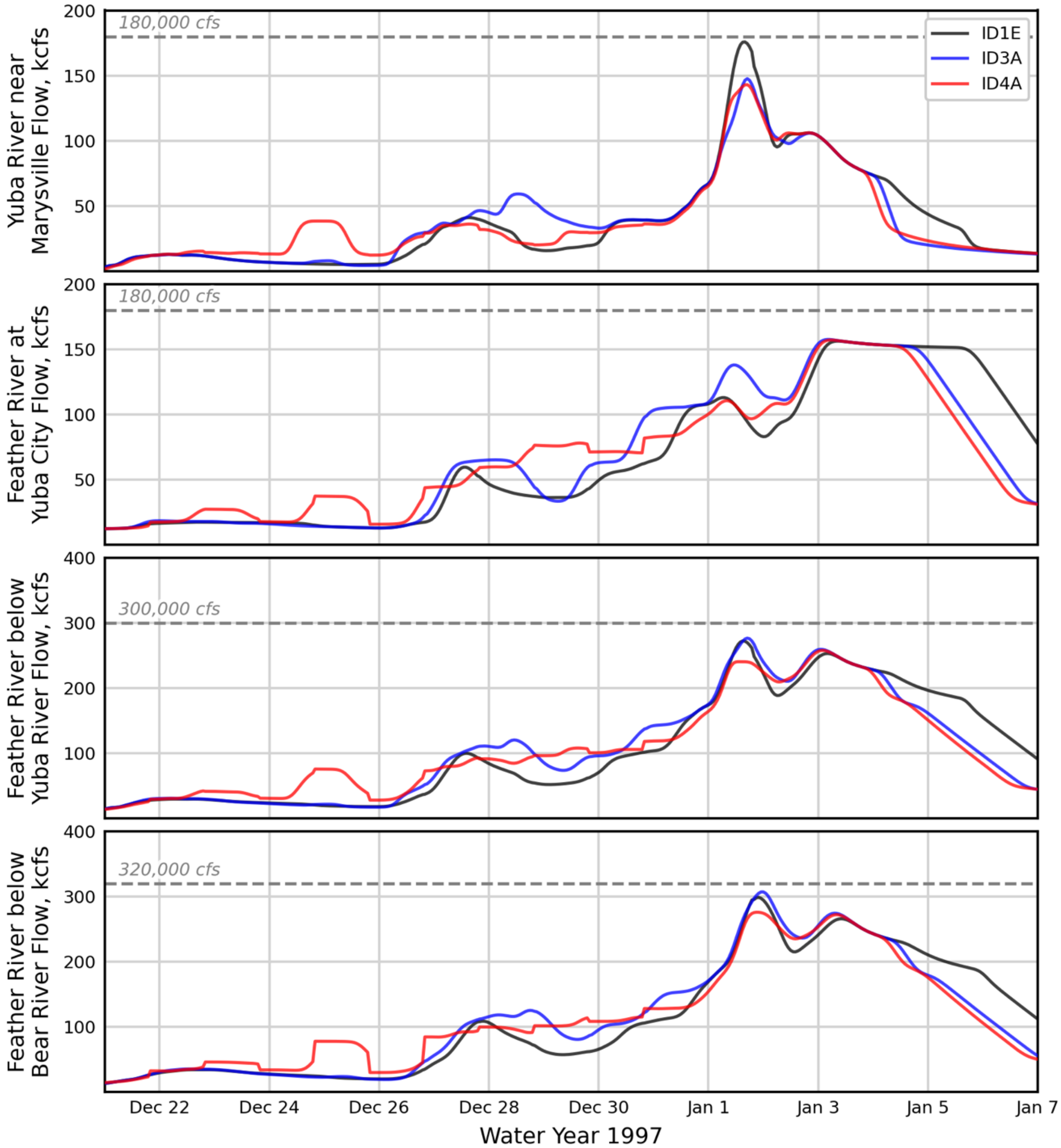


Figure 3-13. *System flows for ID1E, ID3A, and ID4A for the 100 percent scaling of the 1997 flood event.*

3.5 System Operations

3.5.1 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. This requires 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 TAF of flood reserve (USACE SPK 1970, 1971, 1972). Without Marysville Dam, NBB (relative to the Yuba River) and ORO (relative to the combined Yuba and Feather Rivers system) have shouldered an unanticipated flood management operations burden for the last 50 years.

This burden has been recognized in the interim as ORO has been designated to surcharge to manage for the Standard Project Flood without Marysville Dam. Similarly, the NBB operating rule limiting releases to a challenging downstream flow threshold has been conditionally relaxed.

The Yuba-Feather watersheds are managed with a joint downstream flow constraint of 300 kcfs in the Feather River below Yuba City. Both ORO and NBB are expected to constrain releases so flows in the Feather River below Bear River do not exceed 320 kcfs. The existing WCMs also define downstream flow constraints specific to the Feather and Yuba Rivers at locations upstream of the Yuba-Feather confluence; these flow constraints are listed in Table 3-6.

3.5.2 Forecast-Coordinated Operations (F-CO)

The F-CO system operations (Section 3.1.1) is the baseline for the FVA assessment and is henceforth referred to as S1.

3.5.3 System Operations Considerations and Development

Careful and thorough consideration was given to exploring the potential for alternative approaches to the F-CO system operation that more effectively addresses the uncertainty in the local flows below the reservoirs and more appropriately balances the responsibility for meeting downstream confluence flow constraints. This effort is considered a "work in progress." Nonetheless, simulation results are provided in Section 4 as a demonstration of what is possible.

3.5.3.1 Explicit System Target Approach (S3)

The alternative system operations framework detailed herein differs from the F-CO framework in two significant ways:

1. It extracts the tributary constraint selection/application from the reservoir simulation model and puts it into the portion of the framework that wraps the simulation model. This method allows for variation in the Yuba and Feather River tributary constraints in their limited range between 120 and 180 kcfs, but it still removes the ambiguity in why the simulation model suggests a particular release. These explicitly defined tributary constraint combinations are clearer to understand and interpret.
2. It provides explicit system operations objectives that:
    - Determine a desired downstream mainstem target flow, based upon forecast hydrology and current reservoir storage, and the desired balance between forecast reservoir storage and mainstem flows in the system.

- Determine the reservoir priority and tributary constraint flow values predicted to facilitate those downstream flows and perform optimally with respect to key system metrics identified by operators.

The routing algorithm itself is comprised of two major components:

1. Combined mainstem constraint (CMC):
   - The CMC consolidates the Feather River below Yuba City and the Feather River below Bear River constraints into one unified constraint. This consolidation is achieved by pre-routing Bear River contributions to its confluence with the Feather River at Nicolaus. Because Bear River flows are virtually unregulated, the CMC can incorporate the forecasted Bear contributions directly into the downstream constraint. This simplification allows the reservoirs to operate to a single joint downstream constraint rather than two separate ones.
2. Reservoir independence:
   - One reservoir assumes responsibility for maintaining the mainstem flow constraint, while the other reservoir is considered "independent." The independent reservoir operates solely based on its tributary constraint, while the dependent reservoir adheres to both its tributary constraint and the CMC. This new framework simplifies and enables optimization of the joint downstream burden.
   - The proposed routing algorithm implements the CMC and allows one of the two reservoirs to operate independently of its tributary constraint.
   - These concepts are integral parts of the full system operations process, as outlined by the flowchart in Figure 3-14. More details of this process can be found in the system operations workshop presentations located in Appendix A.

The flowchart shows the process that is initiated whenever the CNRFC releases an inflow forecast for the system. In a real-time event, the CNRFC may release forecasts every six to 24 hours (defined as "*F* hours" in flow chart). When a forecast is issued, each ensemble member from the forecast is run through a model assuming the standard FIRO release schedule and at-site conditions (or not cutting back for joint downstream constraints). From there, operators determine whether they need to run more simulations to make the best release decision for how to operate. If each decision point in the flow chart is a yes, the operator would simulate the ensemble with many more combinations of joint downstream constraints (i.e., the CMC), reservoir independence, and tributary constraint distributions. The best combination per forecast is determined from performance metrics computed from the results of the ensemble simulations.

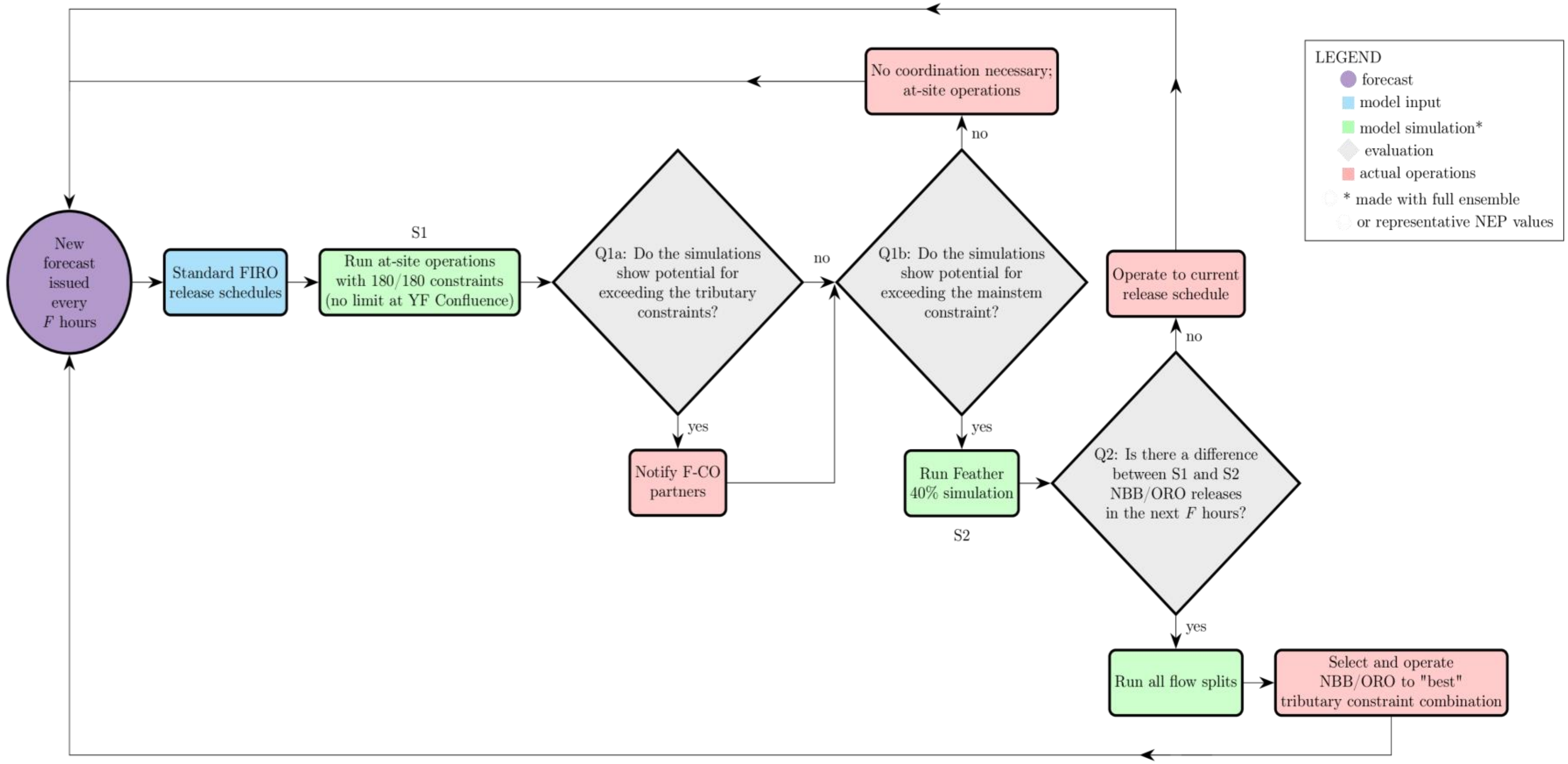


Figure 3-14. *Alternative system operations flowchart.*

3.5.3.2 EFO System Operations (S4)

A system operations methodology (alternative S4) was also developed that uses the EFO principles to balance releases from ORO and NBB to minimize forecasted flood risk at the Yuba-Feather River confluence and Feather River at Nicolaus. As with the EFO methodology, risk is calculated as the percentage of ensemble members that exceeds the objective flow. A flood risk tolerance curve is defined for downstream locations, and the model seeks to minimize flood risk above the defined risk tolerance curve. The risk tolerance curve developed for the Yuba-Feather confluence and Nicolaus is provided in Figure 3-15. The development of the flood risk tolerance curve did not undergo the same rigorous optimization process that was used for the reservoir storage risk tolerance described in Section 3.4.4. Due to the longer times required for simulating the system operations, it was not feasible to complete a full optimization process. However, several curve shapes were evaluated to develop a curve that would function adequately for this demonstration.

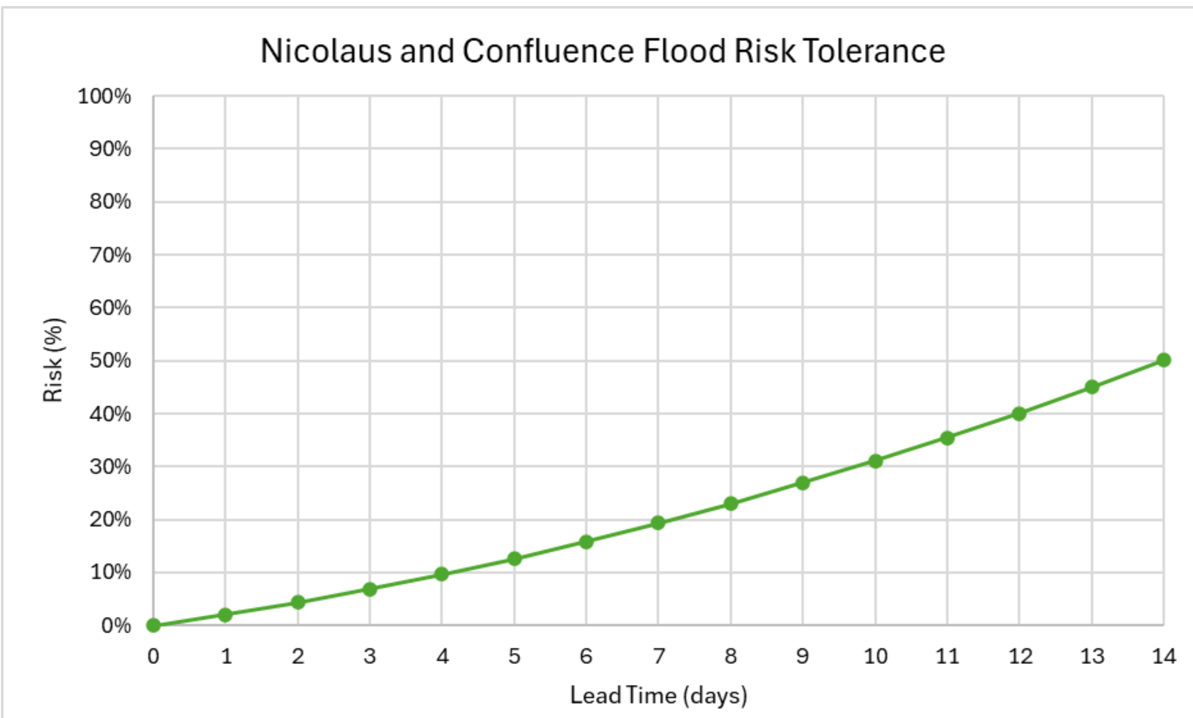


Figure 3-15. *EFO risk tolerance curve for system operations.*

Figure 3-16 provides an overview of the EFO system operations methodology. In summary, release schedules are initially estimated for each reservoir using the at-site EFO methodology described in Section 3.4.4 and shown in row 1 of Figure 3-16. These release schedules are routed downstream for each member of the ensemble flow forecast (as shown in row 2). Flood risk is evaluated for the confluence and Nicolaus (right panel of row 2). For demonstration purposes, Figure 3-16 just shows flows and flood risk at Nicolaus; however, the EFO model accounts for flood risk at the confluence as well.

If forecasted flood risk exceeds the flood risk tolerance, then the initial releases must be reduced for certain time steps (row 3) to minimize flood risk above the risk tolerance. Reducing releases from either ORO or NBB reservoir will increase forecasted storage and potentially increase storage risk. The EFO model seeks to balance release reductions for each reservoir by also balancing intolerable storage risk, which is the forecasted storage risk above the risk tolerance (row 4). Figure 3-16 shows intolerable storage risk to be perfectly balanced between ORO and NBB; however, this balance cannot always be achieved. The EFO model will therefore attempt to minimize the difference in intolerable storage risk between ORO and NBB. After releases are reduced and intolerable storage risk is balanced, downstream flows are reduced, and flood risk is mitigated (row 5).

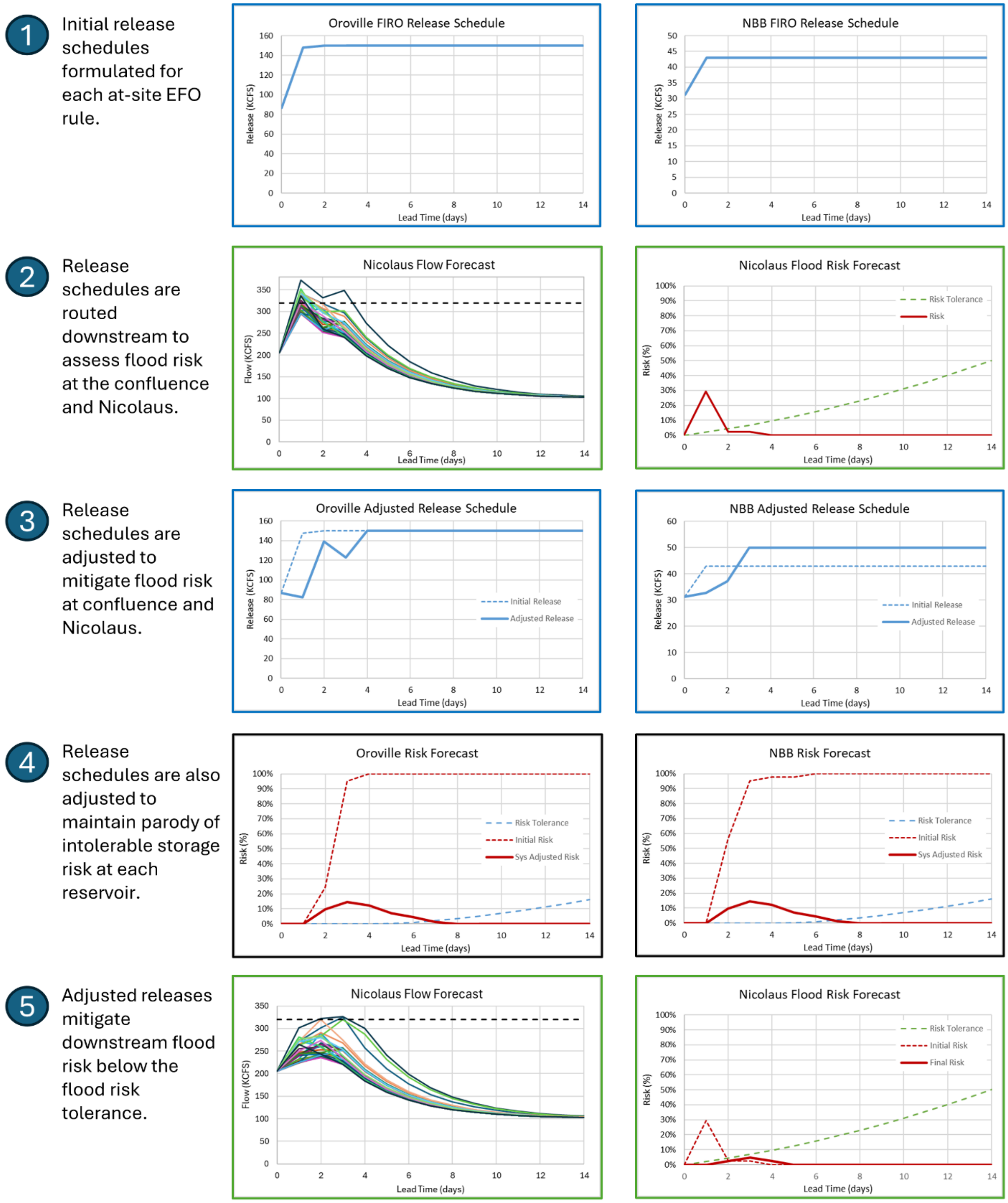


Figure 3-16. *Summary of EFO system operations process.*

3.5.4 Combining At-Site WCPs into a System Operation

At-site alternatives and system operations were combined as shown in Table 3-10. Note that the at-site alternatives are only evaluated as configured for the ARC Spillway at NBB, which is denoted with an "A" following the at-site identifier (ID3A, ID4A). The WCM baseline was evaluated without the ARC Spillway and is denoted with an "E" following the at-site identifier (ID1E). All at-site alternatives were simulated and evaluated with S1 system operations. System operations S3 was simulated and evaluated with ID3 only. System operations S4 was simulated and evaluated with ID4 only.

Table 3-10. *Combined at-site and systems operations.*

NBB At-Site	ORO At-Site	S1	S3	S4
ID1E	ID1E	Full evaluation		
ID3A	ID3A	Full evaluation	Demonstration	
ID4A	ID4A	Full evaluation		Demonstration

3.5.4.1 Incorporating Forecast Uncertainty into Release Decisions for Downstream Control Flows

Demonstrations of S3 and S4 incorporate novel techniques that leverage ensemble forecasts. S1 is meant to represent the existing Yuba-Feather F-CO framework. Currently, the F-CO program uses HEC-ResSim in conjunction with the deterministic flow forecasts to produce a candidate set of release schedules, which can then be evaluated and refined by operators using ensemble forecast simulations.

Simulations of the F-CO system operation under the PVA included a simplifying assumption of perfect forecasts of downstream cumulative local flows. This assumption was identified as a key area for improvement, motivated by a desire to simulate a more realistic decision-making environment for coordinated reservoir operations. As such, strategies for enhancing the incorporation of forecast uncertainty into release decisions generated in the HEC-ResSim modeling framework were a key focus of the FVA.

Alternative performance was evaluated for events spanning multiple forecasts, so the available forecast information for making release decisions changes at a regular interval. The simulation framework was further developed for the FVA to ensure decisions were made with imperfect forecast information. The following key factors were identified for this effort:

- Deterministic forecasts were not available in the scaled hindcast dataset.
- HEC-ResSim currently assumes perfect foresight for local flows downstream of the dams but lacks a mechanism to include forecast uncertainty in the timing and magnitude of those flows.
- A time series was generated to approximate the difference in the total local flow runoff and the forecasted local runoff to each control point, plus the maximum objective flow at that location. This time series provided the operational input required for HEC-ResSim to approach proper functionality using the F-CO configuration.

As in the PVA, forecasts of reservoir inflow at NBB and ORO are represented using the ensemble forecast with either a single-value approximation (75 percent NEP volumes for ID3A) or the full ensemble (ID4A). These values are used in computing the FIRO release. However, flow forecasts are also critical in determining the limits on releases to account for downstream maximum objective flows, as summarized in Table 3-7. While ORO regulates nearly 90 percent of the Feather River watershed above the Yuba River, NBB regulates around one-third of the Yuba River watershed area, leaving significant, largely unregulated flow contributions to the joint operational targets in the Feather River below Yuba River. The forecasts used to estimate the downstream flow at key decision locations play a critical role in operational performance.

For each reservoir operations rule representing a downstream maximum objective flow, HEC-ResSim computes a time series of "flow space" in the river at the control location. Essentially, this flow space is the difference between the maximum objective flow (as a scalar value or a time series) and the projected cumulative local flows (i.e., total tributary or local flow contributions that do not pass through the reservoirs). HEC-ResSim performs this calculation using the provided boundary condition flows at each location, meaning a perfect forecast of these flows is used to determine the reservoir releases. The ideal solution, which HEC-ResSim is currently unable to directly accommodate, would be to replace the flow information used to compute the flow space with imperfect forecast data. This solution would isolate the time series used to make the release decisions from the series used to determine the impacts of the reservoir operations.

To force HEC-ResSim to facilitate our analytical needs, the WRE team developed a technique using the difference in forecast and simulated historical cumulative local flow contributions to each control point. Because no deterministic hindcasts are available, the 90 percent NEP hourly histogram (constructed by ranking ensemble hindcast flows at every hour) was used as a surrogate. Comparing the evolution of the shape and magnitude of the forecast local flows informed the preliminary selection of the 90 percent NEP. Further discussion on the methodology and justification for this selection is provided in MBK 2023. Figure 3-17 illustrates these totals for the December 29, 1996, hindcast, with the total simulated historical and forecast values for each watershed contributing to the control point at Nicolaus, in the Feather River below Bear River.

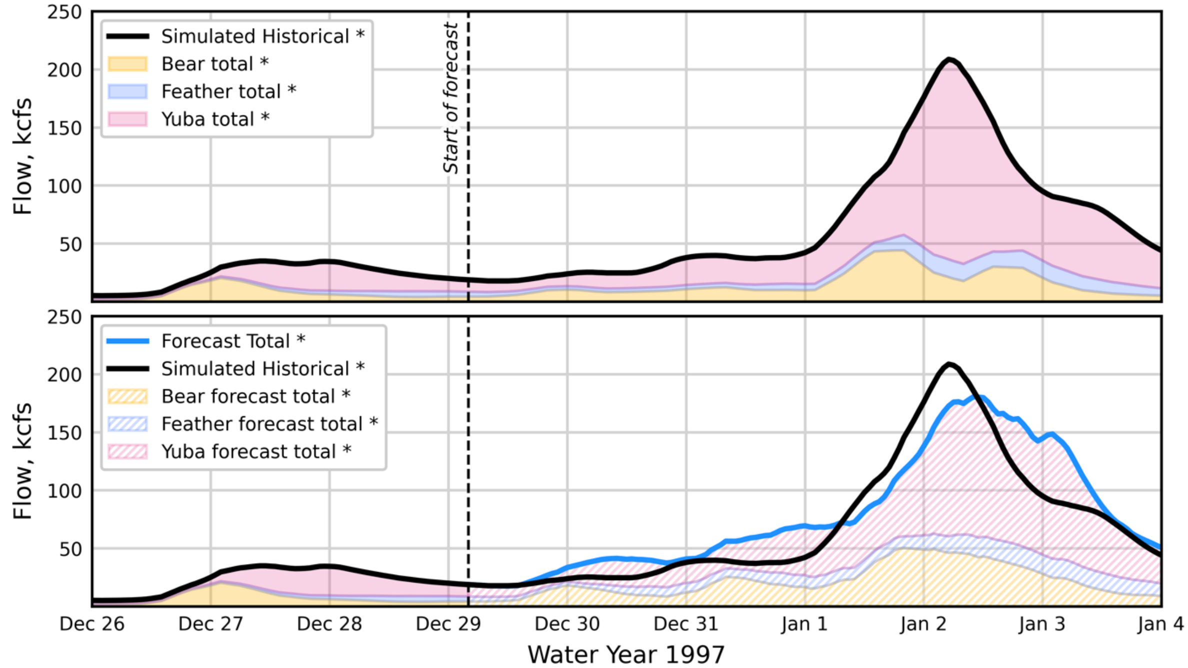


Figure 3-17. *Total local flow contributions to the Feather River below Bear River (Nicolaus).*

The flow space can be computed by subtracting the total local flow hydrograph from the maximum objective flow (320,000 cfs). Flow space is indicated in the top pane of Figure 3-18, in dashed lines corresponding to the perfect (simulated historical) and imperfect (forecast) totals. The goal was to configure the model so HEC-ResSim would represent a flow space at Nicolaus corresponding to the blue dashed line.

Each HEC-ResSim downstream control flow rule was defined as a function of an external time series, represented in red in Figure 3-18. These time series were designed so HEC-ResSim's underlying computation of flow space would approximate a calculation based on the 90 percent NEP forecast. The red line is equivalent to the sum of the maximum objective flow and total cumulative local flows (gray striped area), minus the total cumulative local 90 percent NEP forecast flows. The calculation was performed for each ensemble hindcast issuance at each of the four downstream maximum objective flow locations.

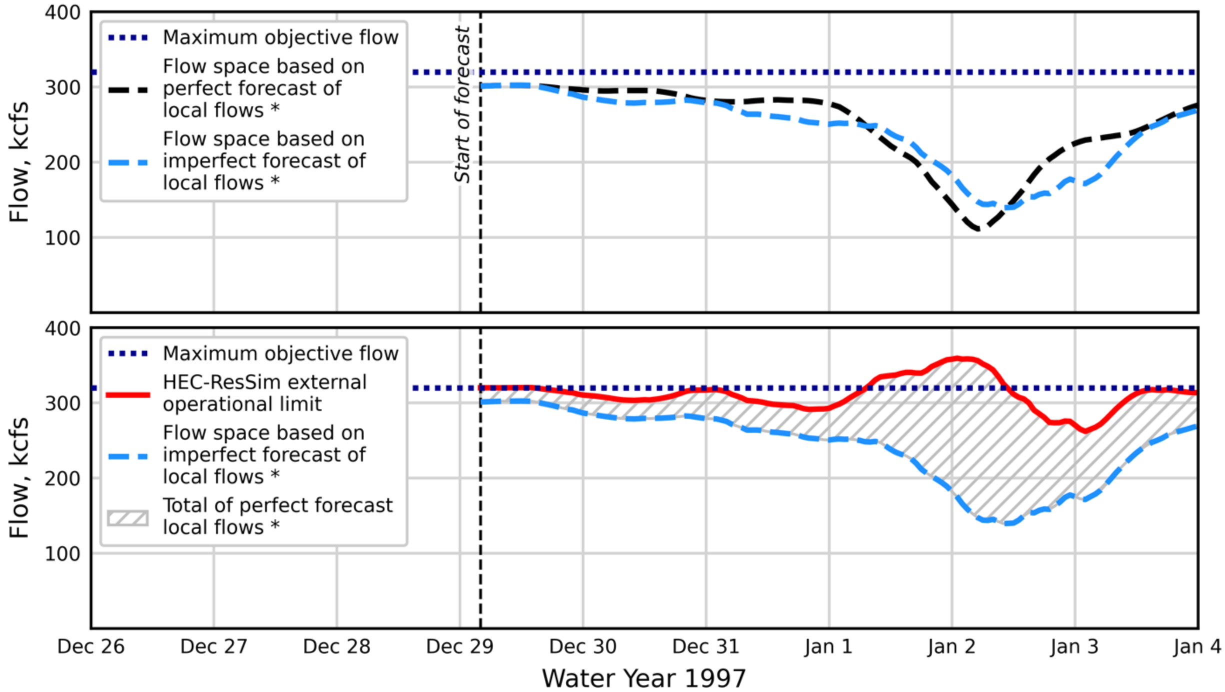


Figure 3-18. *Derivation of the forecast uncertainty override for HEC-ResSim downstream control flow release decisions at the Feather River below Bear River (Nicolaus).*

In addition to this time series representation of forecast uncertainty, a constant contingency factor of 2 percent is also applied to the cumulative local flows, as shown in Figure 3-19. Conflicts between the HEC-ResSim guide curve operation and downstream control flow rules initially resulted in unexpected oscillations in FIRO releases. To address this problem, the WRE team adopted the "No Correction" for flow attenuation option in the Advanced Options for each downstream control flow rule, shown in Figure 3-19. While this option addresses concerns about HEC-ResSim-induced reductions to computed FIRO releases, it also decreases the efficacy of the algorithm to accurately predict downstream flows. To overcome this deficit, a 2 percent contingency factor was introduced to inflate the cumulative local flows for estimates of the space in the channel available for reservoir releases.

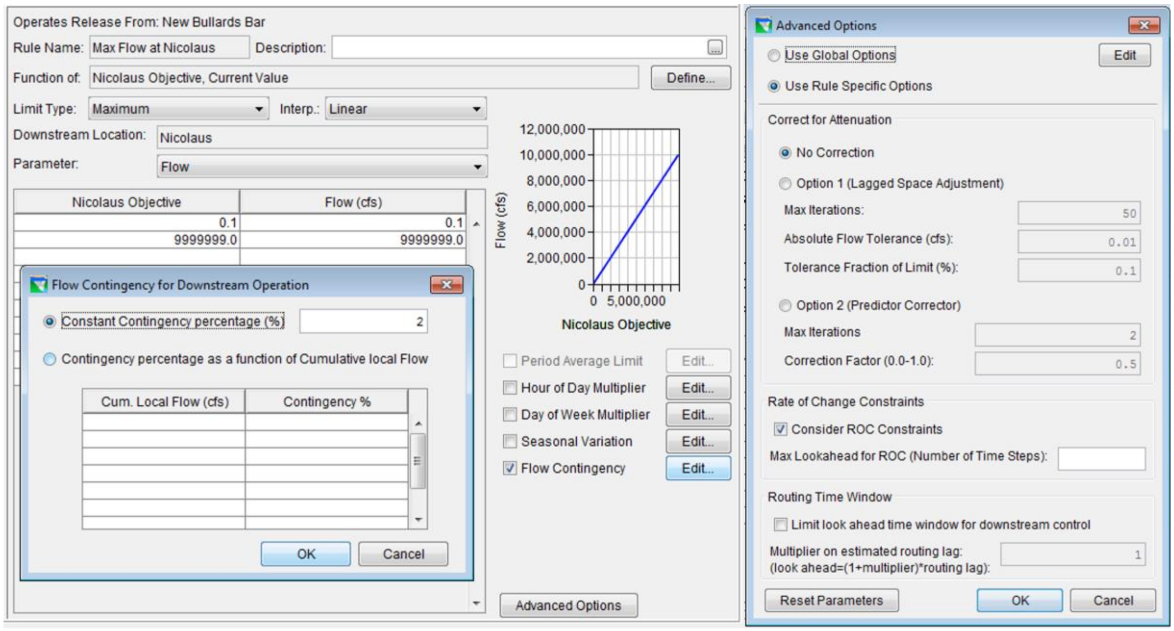


Figure 3-19. *HEC-ResSim downstream control flow rule: max flow at Nicolaus with advanced flow contingency options.*

3.5.5 Transferring Reservoir Storage Benefits to Downstream Locations

Applying FIRO in the Yuba-Feather system has the potential to improve FRM outcomes by reducing peak reservoir storage during flood events and peak flows downstream of ORO and NBB. The system balance configured in HEC-ResSim controls the release decisions for each reservoir to avoid exceeding the configured downstream maximum objective flows at Marysville, Yuba City, the Feather River below Yuba River, and the Feather River below Bear River (at Nicolaus), as detailed in Table 3-7. Within a single HEC-ResSim simulation, there is no mechanism to induce higher reservoir storages to minimize downstream flows, short of reducing the configured downstream maximum objective flow value. To transform the FRM benefits into downstream flow and stage reductions, a series of simulations was executed with incremental reductions in the joint downstream constraints on the Feather River. The simulation with storage levels most closely matching but not exceeding ID1E peak reservoir storages was selected to illustrate the benefits transfer for this F-CO system operation configuration (S1). See Section 3.5.1. for additional details on targeting reduced peak downstream flows in system operations frameworks. The transfer of FIRO storage benefits to downstream benefits is demonstrated for selected scaled events in Section 4.

Note that lowering the downstream objectives would naturally introduce risk tradeoffs, which could include increased peak reservoir storage and potentially longer duration elevated flows on the downstream levees. Regardless, the goal of this analysis is to demonstrate that the priority of the objectives can be shifted from the reservoirs to the downstream locations.

3.6 Simulation Plan

The simulation plan describes the necessary components to simulate reservoir operations and develop the data for the evaluation process. The full simulation plan is provided in Appendix A.

A summary of the observations, forecasts, selected events, and scaling process are provided here.

3.6.1 Yuba-Feather System and Key Locations

Figure 3-1 shows the Yuba-Feather watersheds with key locations associated with evaluating WCP alternatives.

3.6.2 Streamflow Observations

Streamflow observations from reservoir inflows and local contributing areas to key points downstream were provided by the CNRFC as a component of the provided hindcast dataset. These consist of a simulation of flows at each of the forecast locations. The modeling system and modeling parameters are exactly as used in the operational forecast process (see Section 5.3). This was required because the local flows are not directly observable, and reservoir inflows are inherently noisy at the required 1-hour timestep. While the CNRFC simulations (generated using observed precipitation, temperature, and freezing level) are adequate, they are not perfect and introduce some level of uncertainty. The use of simulated flows for the scaled events is required because the observations for these events do not exist in the historical record.

3.6.3 Streamflow Forecasts

Streamflow forecasts for reservoir inflows and the local contributing areas to key control points downstream were provided by the CNRFC. Streamflow forecasts are described in detail in Section 5.3. Current and archived river forecasts can be found on the CNRFC website (www.cnrfc.noaa.gov).

3.6.4 Streamflow Hindcasts

Hindcasts are forecasts generated for dates in the past using a specific set of models and data. The process of generating the hindcasts used in this evaluation is described in Section 5.3.

The period of record hindcasts provide a limited timeframe to test reservoir management alternatives and do not contain floods large enough to appropriately challenge the proposed FIRO alternatives. The process of developing scaled Hydrologic Ensemble Forecasting System (HEFS) hindcasts is provided in Section 5.3.

The specific scaled events used in this evaluation are listed in Table 3-11.

Table 3-11. *Simulation periods and scale factors for FVA evaluation.*

Event	Dataset	Scale Groups (%)	Time Zone	Simulation Lookback	Simulation Start	Simulation End
1986	GEFSv12 hindcasts	100, 102, 104, 106, 108, 110, 112, 114, 116, 118, 120, 130, 140	UTC	Feb 04, 1986, 1200	Feb 06, 1986, 1200	Mar 14, 1986, 1200
1997	GEFSv12 hindcasts	84, 86, 88, 90, 92, 94, 96, 98, 100, 102, 104, 106, 108, 110, 120, 130	UTC	Dec 18, 1996, 1200	Dec 21, 1996, 1200	Jan 12, 1997, 1200

Note that the scaling for HEFS events was performed independent of specific return period targets or thresholds. The scale factors were selected to cover a wide range of return periods without committing to a specific frequency level or assessment.

3.6.5 Simulation Plan Summary

The simulation plan consists of combining the modeling configurations shown in Table 3-10 with the scaled events shown in Table 3-11. At-site alternatives and system operation simulations were processed through the same HEC-ResSim model to ensure consistent adherence to established operating rules, physical constraints, and routing methodologies.

3.7 References

David Ford Consulting Engineers. (2008). *Oroville–New Bullards Bar Forecast-Coordinated Operations: Decision support system technical documentation.*

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*.

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

HDR. (2020). *Yuba-Feather system storage balance* [Memorandum].

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.* UC San Diego. https://cw3e.ucsd.edu/FIRO_docs/LakeMendocino_FIRO_FVA.pdf

MBK Engineers. (2021a). *Yuba-Feather system operations: Framework to depict system risk balance* [Memorandum].

MBK Engineers. (2021b). *Preliminary Viability Assessment of at-site operations: Developing a FIRO guide curve for New Bullards Bar* [Memorandum].

MBK Engineers. (2021c). *Yuba-Feather system operations: Sensitivity to downstream flow constraint split* [Memorandum].

MBK Engineers. (2021d). *Forecast-Coordinated Operations activation frequency* [Memorandum].

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 Preliminary Viability Assessment*. UC San Diego. https://escholarship.org/uc/item/8x57n58b

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

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

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

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

USACE SPK. (2019). *Folsom Dam and Lake: Water Control Manual* (Rev. ed.). (Original published 1987.)

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

Yuba Water Agency. (2020). *New Bullards Bar secondary spillway: Evaluation of flood management performance for candidate secondary spillway outlets*.

Section 4. Evaluation of FIRO Water Control Plan Alternatives

This section describes the results of the Water Control Plan (WCP) alternatives simulation and evaluation described in Section 3. The WCP alternatives considered in this section are described in Section 3.4. The baseline alternative for comparison is ID1E, which follows the existing WCM guidelines with the Forecast-Coordinated Operations (F-CO) system operations and does not include the Atmospheric River Control (ARC) Spillway at New Bullards Bar (NBB) Dam.

The goals of this assessment were to:

- Demonstrate that WCP alternatives that define a Forecast Informed Reservoir Operations (FIRO) Space and leverage forecasts can improve flood risk management (FRM) outcomes associated with extreme flood events while not affecting—or perhaps improving—water supply availability outcomes.
- Demonstrate that refined/enhanced system operations approaches have the potential to provide additional value in guiding reservoir operations through explicit, quantitative procedures that leverage the entire ensemble forecast.
- Support U.S. Army Corps of Engineers (USACE) Sacramento District's efforts to update the Water Control Manuals (WCMs) for the Lake Oroville (ORO) and NBB dams.
- Support the evolution of the F-CO program.
- Evaluate WCP performance in an environment with forecast uncertainty.

WCM updates are a USACE process. As stated in Section 3, the development and evaluation of FIRO alternatives in this study is fundamentally independent but support the USACE Sacramento District's efforts to update the ORO and NBB WCMs.

Key Findings

- FIRO strategies succeeded in reducing downstream flood flows across a range of scale factors applied to the 1986 and 1997 flood events.
- FIRO strategies succeeded in reducing peak reservoir storage across a range of scale factors applied to the 1986 and 1997 flood events.
- FIRO strategies achieved drawdowns into the FIRO Space that approached the flood control space of the unconstructed Marysville Reservoir (260,000 acre-feet) when tested with scaled flood events.
- FIRO strategy reductions in downstream flood flows and peak reservoir elevation across all scale factors are attributable to (1) use of forecasts, (2) FIRO Space that extends into the water conservation pool, and (3) the existence of the planned ARC Spillway.
- The FIRO Space, which extends into the flood pool, consistently leads to higher post-event reservoir storage and potential water supply availability benefits.

The simulation plan described in Section 3.6 focuses on WCP performance associated with extreme events. Specifically, detailed scalings of the 1986 and 1997 Hydrologic Ensemble Forecasting System (HEFS) hindcasts formed the fundamental testing datasets for WCP performance. Earlier FIRO evaluations have scaled HEFS hindcasts to reflect specific annual return period frequencies (e.g. 100-year, 200-year). To avoid the complexity and inherent instability with updated regulated and unregulated flow frequencies, the FIRO water resources engineering (WRE) team chose to scale the HEFS hindcasts across a range of factors that were expected to cover the needed return frequencies without assigning specific frequencies to those scaled events. This approach also allowed for greater granularity in sensitive zones of scale factors, as shown in Table 3-11.

FIRO strategies were consistently better at delivering FRM benefits than the existing WCMs for ORO and NBB paired with the F-CO systems operation. Summarizing the performance of the alternatives is extremely difficult and requires synthesizing reservoir operations and downstream flows for each event and each scaling. Table 4-1 attempts to provide a summary, with significant caveats. The table shows the highest scale factor for baseline operations and two FIRO alternatives that does not exceed the listed objective. It is color coded based on lower and higher effectiveness, with release values in thousands of cubic feet per second (kcfs). Please note that this table represents only the peak reservoir elevation, release, or downstream flow from a 30-day simulation centered on the scaled 1986 and 1997 events. The details on how these alternatives draw down storage in the reservoir before the event and handle changing forecasts are very important, but they are not captured in Table 4-1. Furthermore, the significance of smaller differences in the highest scale factor has not been established.

Table 4-1. *Relative performance of FIRO alternatives (ID3A and ID4A) compared to baseline operations (ID1E). Color coding indicates lower (light green) and higher (medium green) effectiveness in meeting performance metrics, as indicated by the highest scale factor that achieved the objective. The "E" following the baseline alternative designates no ARC Spillway at NBB, while the "A" following FIRO alternatives indicates the evaluation assumed operation of the ARC Spillway.*

	1986			1997		
Objective	**ID1E**	**ID3A**	**ID4A**	**ID1E**	**ID3A**	**ID4A**
ORO Gross Pool (901 feet)	116	118	118	106	108	110
ORO Max. Release (150 kcfs)	116	118	118	106	108	110
Feather at Yuba City (180 kcfs)	116	120	120	108	110	110
NBB Gross Pool (1,956 feet)	114	118	120	102	110	130
NBB Max. Release (50 kcfs)	114	118	120	102	108	108
Yuba at Marysville (180 kcfs)	116	118	120	104	104	106
Feather below Yuba (300 kcfs)	114	118	118	106	106	108
Feather below Bear (320 kcfs)	104	106	106	106	106	108

Table values indicate the maximum scale factor through which the objective is achieved.

4.1 FRM Metrics

The FRM metrics (IDs M1 through M5 from Table 3-7) are focused on maximum pool elevation and discharge for both ORO and NBB and the maximum flows at the downstream control points.

For review, the FIRO reservoir strategies described in Section 3 are ID3A (prescriptive) and ID4A (iterative) and include the operation of the ARC Spillway at NBB. ID3A uses derivatives of the ensemble forecasts (non-exceedance probability volumes) up to seven days. ID4A uses individual ensemble members for up to 14 days. The baseline operation (i.e., the WCM plus F-CO system operations) is ID1E and does not include operation of the ARC Spillway.

4.1.1 Downstream Control Point Metrics

The downstream control points of interest identified in Table 3-7 are shown in Table 4-2 along with their maximum objective flows in cubic feet per second (cfs).

Table 4-2. *Downstream control points and maximum objective flows.*

Control Point	Maximum Objective Flow (cfs)
Feather River at Yuba City	180,000
Yuba River at Marysville	180,000
Feather River below Yuba River	300,000
Feather River below Bear River	320,000

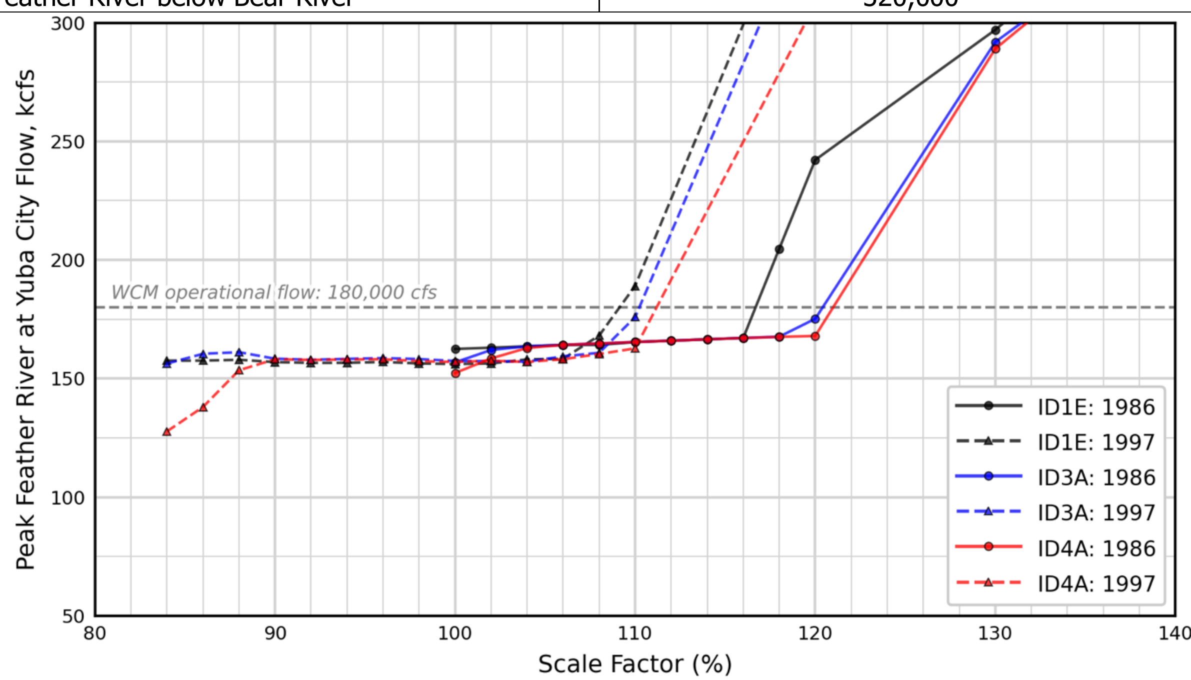


Figure 4-1 Figure 4-1 through Figure 4-4 show the maximum flows associated with the HEFS scalings of the 1986 and 1997 flood events for the control points listed in Table 4-2. Note that these routings include the F-CO system operations for balancing releases between ORO and NBB when the objective flows on the Feather River below Yuba River and/or the Feather River below Bear River are projected to exceed the objectives shown in Table 4-2.

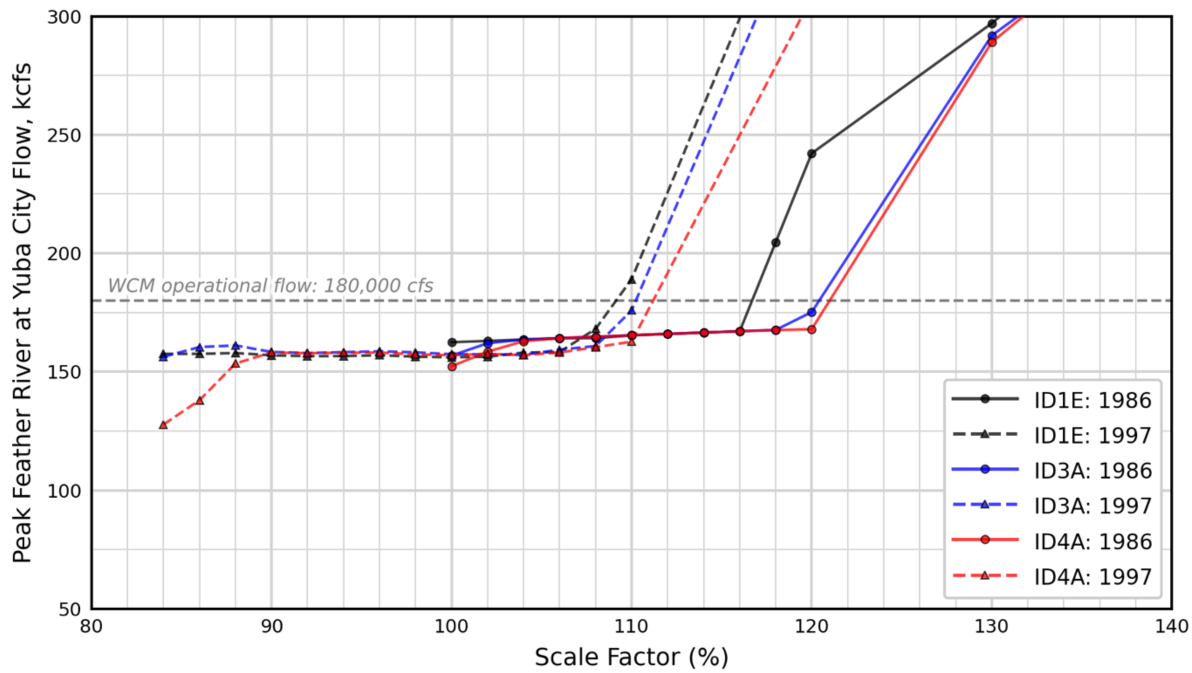


Figure 4-1. *Peak flows for Feather River at Yuba City for the HEFS scalings of the 1986 and 1997 flood events.*

For the Feather River at Yuba City case (180,000 cfs objective flow), the findings show:

- For the 1986 event, the objective flow can be achieved for scale factors through 120 percent for both ID3A and ID4A, compared to 116 percent for ID1E.
- For the 1997 event, the objective flow can be achieved for scale factors through 110 percent for both ID3A and ID4A, compared to 108 percent for ID1E.
- ID3A and ID4A can manage larger scale factors than ID1E while achieving the objective flow at Yuba City. ID1E shows significantly higher peak flows for 1986 for scale factors between 118 and 130 percent.

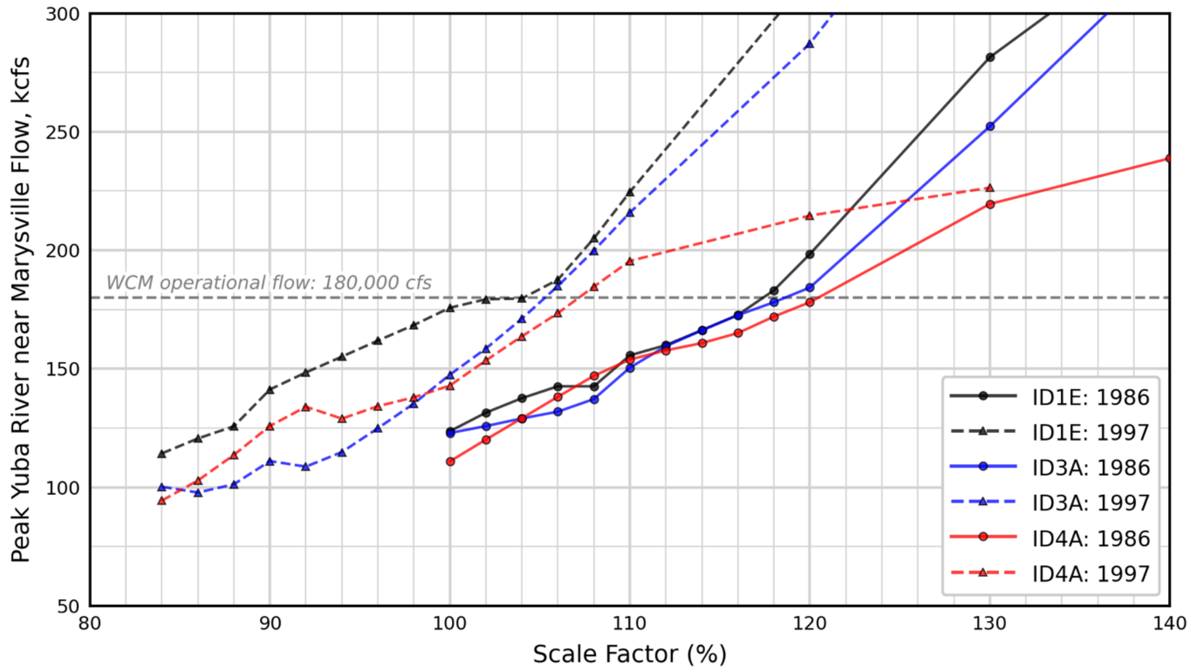


Figure 4-2. *Peak flows for Yuba River near Marysville for the HEFS scalings of the 1986 and 1997 flood events.*

For the Yuba River at Marysville case (180,000 cfs objective flow), the findings show:

- For the 1986 event, the objective flow can be achieved for scale factors through 118 and 120 percent for ID3A and ID4A, respectively, compared to 116 percent for ID1E.
- For the 1997 event, the objective flow can be achieved for scale factors through 104 and 106 percent for ID3A and ID4A, respectively, compared to 104 percent for ID1E.
- ID3A and ID4A can manage similar-scale factors to ID1E while achieving the objective flow at Marysville but are able to deliver lower peaks at the highest scale factors simulated.

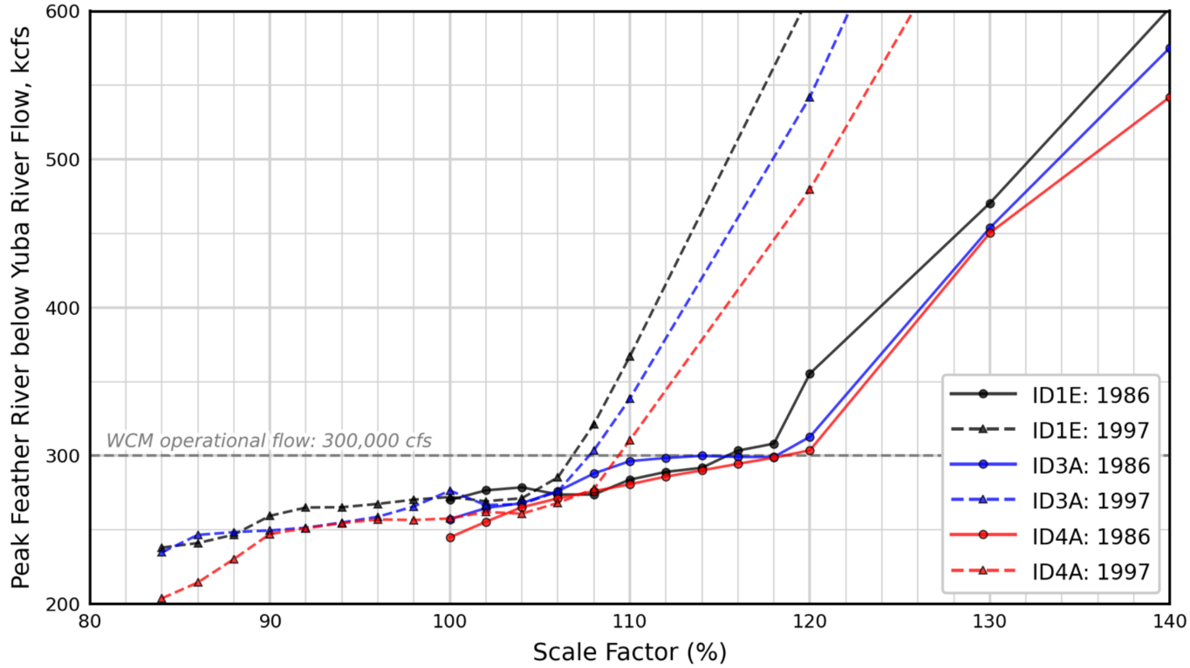


Figure 4-3. *Peak flows for Feather River below Yuba River for the HEFS scalings of the 1986 and 1997 flood events.*

For the Feather River below Yuba River case (objective flow 300,000 cfs), the findings show:

- For the 1986 event, the objective flow can be achieved for scale factors through 118 percent for ID3A and ID4A, compared to 114 percent for ID1E.
- For the 1997 event, the objective flow can be achieved for scale factors through 108 percent for ID3A and ID4A, compared to 106 percent for ID1E.
- For both the 1986 and 1997 events, peak flows for ID3A and ID4A are lower than ID1E once the objective flow is exceeded.

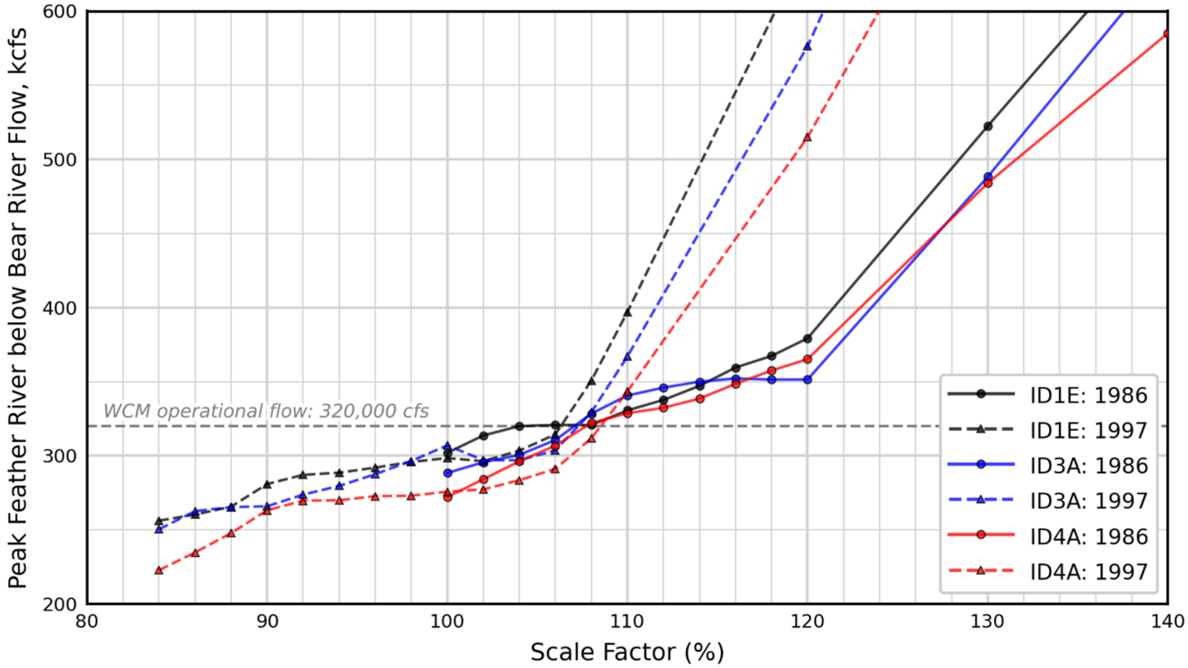


Figure 4-4. *Peak flows for Feather River below Bear River for the HEFS scalings of the 1986 and 1997 flood events.*

For the Feather River below Bear River case (320,000 cfs objective flow), the findings show:

- For both the 1986 and 1997 events, the objective flow can be achieved for scale factors through 106 and 108 percent for ID3A and ID4A, respectively, compared to 106 percent for ID1E.
- For both the 1986 and 1997 events, peak flows for ID3A and ID4A are lower than ID1E once the objective flow is exceeded.

Reviewing maximum flow results at the key locations provides limited context for performance metrics. Flow hydrographs provide a more complete understanding of system performance in the Yuba-Feather system where the timing of releases and local flows is critical to successful water management. Figure 4-5 and Figure 4-6 provide a better description of system performance for the 1986 event scaled to 116 percent and the 1997 event scaled to 106 percent, respectively. These events were selected for demonstration, as they are the largest events that can be managed with ID1E without exceeding the top of gross pool at ORO. The larger event magnitudes can illustrate a full range of operational regimes in the FIRO alternatives, including FIRO advanced releases, release capacity limitation, cutbacks for downstream constraints, emergency operations, and event recovery. These plots include ORO and NBB outflows in addition to the flows at the control points downstream (Table 4-1).

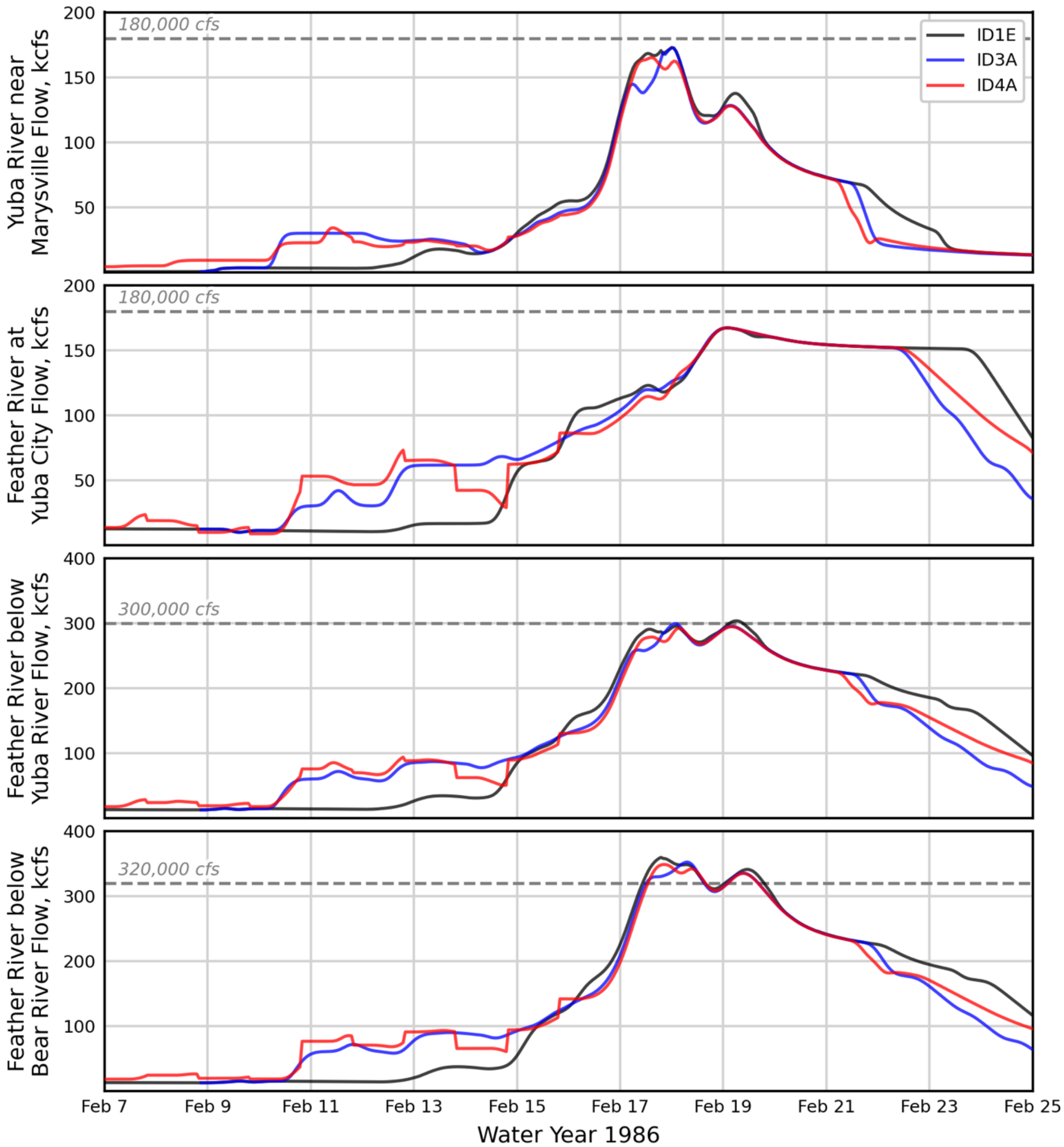


Figure 4-5. *System flows for ID1E, ID3A, and ID4A for the 116 percent scaling of the 1986 flood event.*

For the 116 percent scaling of the 1986 flood event, the findings show:

- Pre-releases from both ORO and NBB under ID3A and ID4A result in higher downstream flows earlier in the flood event that are still below the maximum objective flows at key downstream locations.
- Peak downstream flows for ID3A and ID4A are at or below maximum objective levels for all locations except Feather River below Bear River. These peaks fall below peak flows for ID1E at all locations.
- Reservoir releases for ID3A and ID4A are cut back earlier than ID1E once the peak has passed.

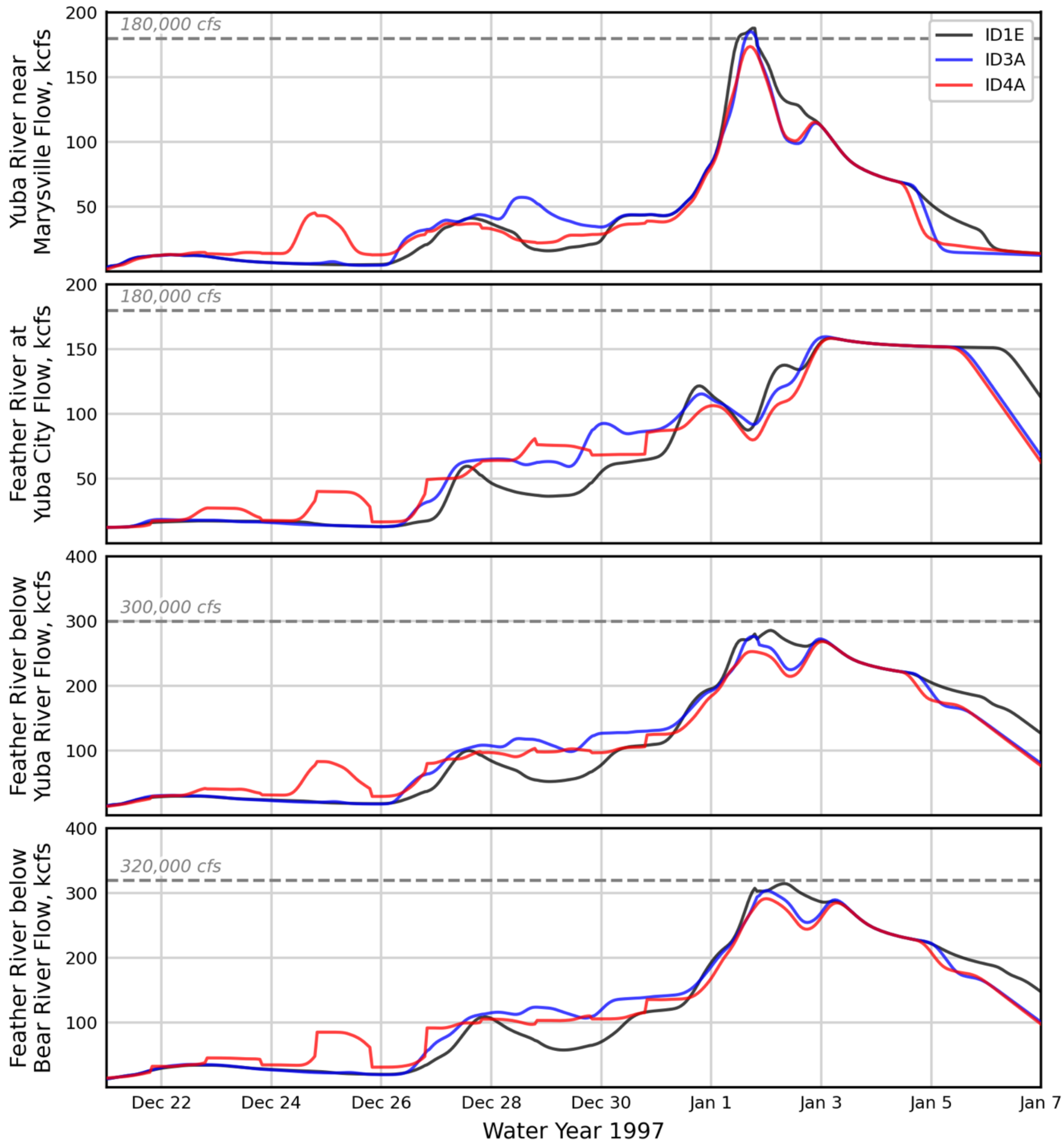


Figure 4-6. *System flows for ID1E, ID3A, and ID4A for the 106 percent scaling of the 1997 flood event.*

In the 106 percent scaling of the 1997 event, the findings show:

- Pre-releases from both ORO and NBB under ID4A are earlier than ID3A but are still below the maximum objective flows at key downstream locations.
- Peak downstream flows for ID3A and ID4A are at or below flows for ID1E at all locations.
- Reservoir releases for ID3A and ID4A are cut back earlier than ID1E once the peak has passed.

Appendix A provides additional graphics (like Figure 4-5 and Figure 4-6) for all scaled events simulated per Table 3-8.

The key takeaways for the downstream control point metrics are:

- ID3A and ID4A provide benefits by achieving the objective flows at the four downstream control points while utilizing the USACE Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) system balance operation.
- The alternatives perform similarly because the HEC-ResSim model configuration attempts to keep control points at or below the maximum objective releases and utilizes all available channel capacity in doing so.
- Improvements in FRM outcomes are attributable to using forecasts, activating FIRO Space in the water conservation pool, and operating the planned ARC Spillway at NBB.

4.1.2 Reservoir Metrics

From Table 3-7, the reservoir metrics of interest are the peak water surface elevation (and storage) and the peak release associated with the range of scaled 1986 and 1997 events. More broadly, however, the goals are to (1) avoid exceeding the top of gross pool (i.e., water on the emergency spillway), (2) limit releases greater than the maximum objective releases (ORO: 150 kcfs; NBB: 50 kcfs), and (3) to emerge from the event with more stored water than baseline operations. It is important to remember that the "points" in Figure 4-7 through Figure 4-10 are taken from multiday simulations that cover the period before, during, and after the peak inflow.

Figure 4-7 provides a graphical summary of the ORO WCP alternatives (ID3A and ID4A) and the baseline (ID1E) for the peak reservoir elevation metric for each scaled 1986 and 1997 hindcast event, measured using the National Geodetic Vertical Datum of 1929 (NGVD 29).

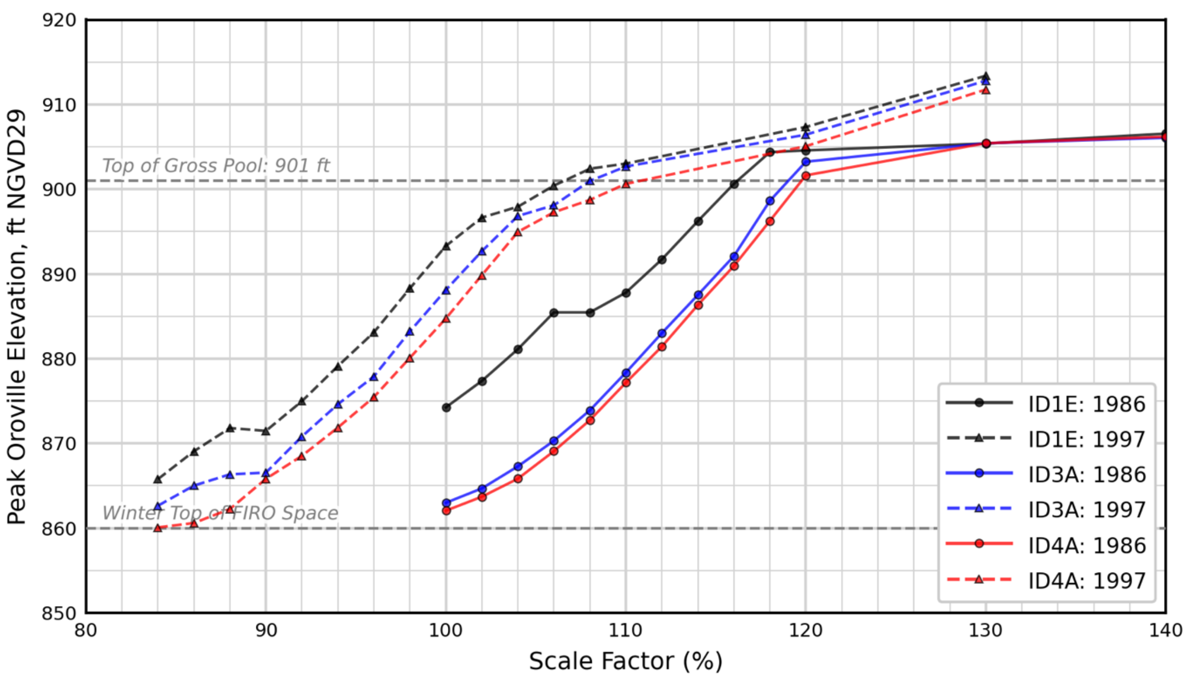


Figure 4-7. *ORO WCP performance of maximum pool elevation for HEFS scalings of the 1986 and 1997 flood events.*

The findings in Figure 4-7 show:

- The 1986 event can be managed without exceeding the top of gross pool through scale factors of 118 percent for both ID3A and ID4A, compared to 116 percent for ID1E.
- The 1997 event can be managed without exceeding the top of gross pool through scale factors of 108 percent for ID3A and 110 percent for ID4A, compared to 106 percent for ID1E.
- ID3A and ID4A consistently provide lower maximum reservoir elevations than ID1E.

Figure 4-8 provides a graphical summary of 1986 and 1997 HEFS scaling performance of the NBB WCP alternatives (ID3A, ID4A) and baseline (ID1E) for the peak reservoir elevation metric.

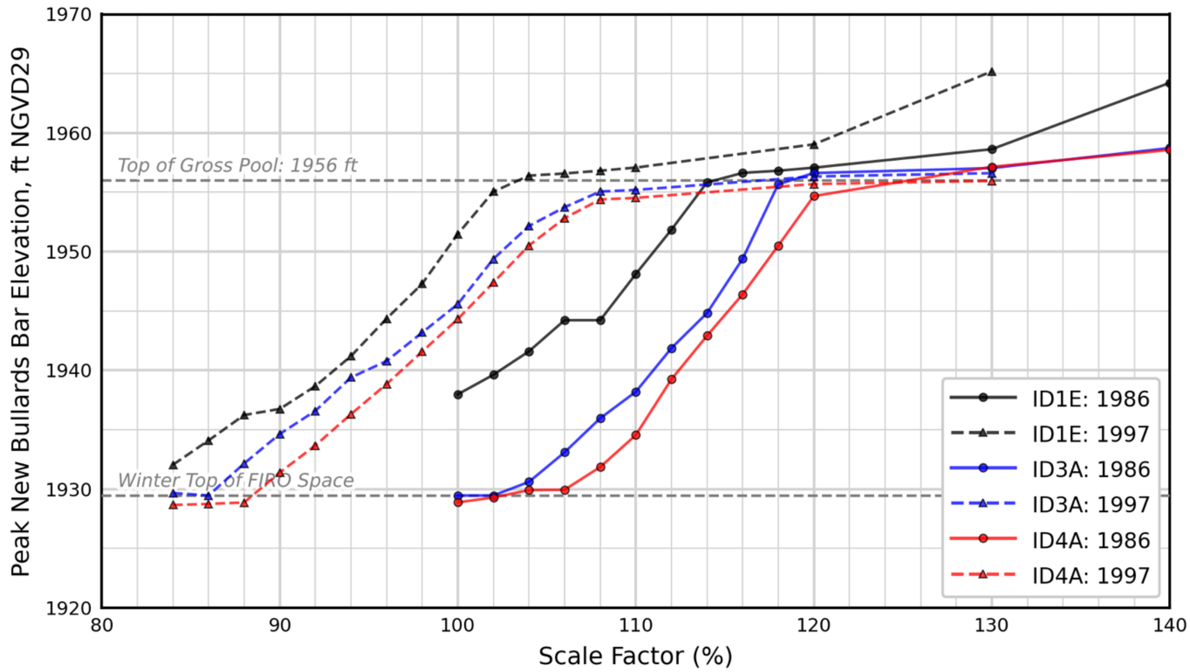


Figure 4-8. *NBB WCP performance of maximum pool elevation for HEFS scalings of the 1986 and 1997 flood events.*

The findings in Figure 4-8 show:

- The 1986 event can be managed without exceeding the top of gross pool through scale factors of 118 percent for ID3A and 124 percent for ID4A, compared to 112 percent for ID1E.
- The 1997 event can be managed without exceeding the top of gross pool through scale factors of 116 percent for ID3A and 130 percent for ID4A, compared to 102 percent for ID1E.
- ID3A and ID4A consistently provide lower maximum reservoir elevation than ID1E.

Figure 4-9 provides a graphical summary of 1986 and 1997 HEFS scaling performance of the ORO WCP alternatives (ID3A, ID4A) and baseline (ID1E) for the peak reservoir release metric.

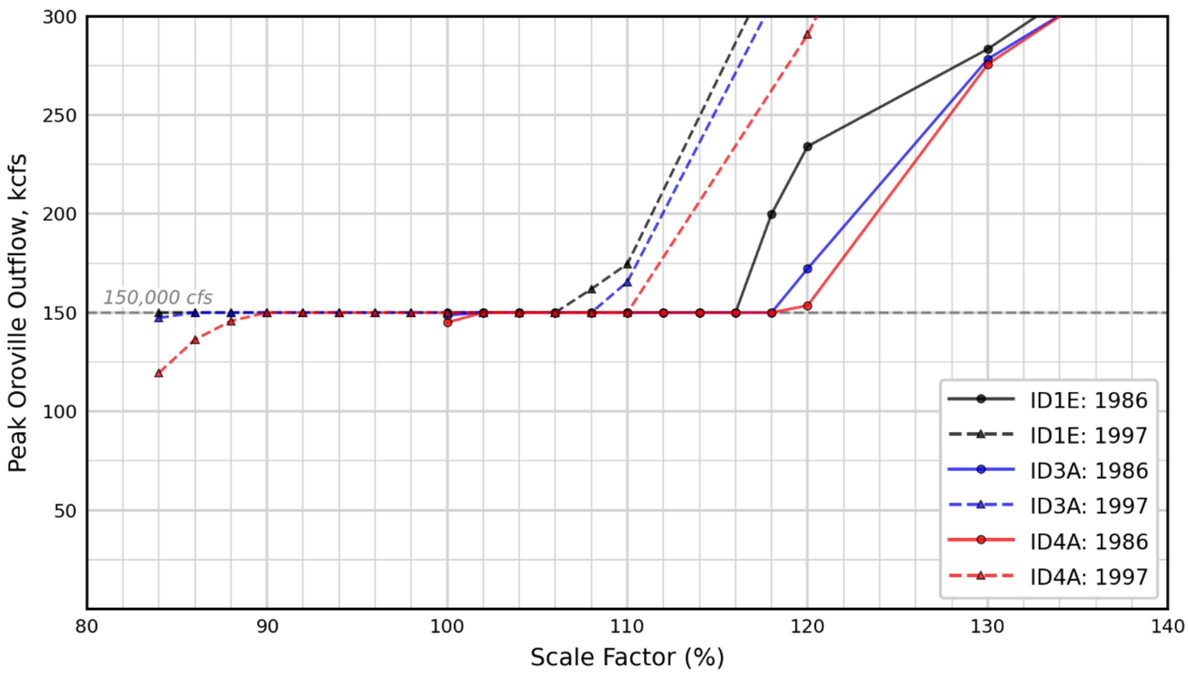


Figure 4-9. *ORO WCP performance of maximum release for HEFS scalings of the 1986 and 1997 flood events.*

The findings in Figure 4-9 show:

- For both the 1986 and 1997 patterns, releases greater than the maximum objective of 150,000 cfs take place for ID1E at lower scale factors than ID3A or ID4A.

Figure 4-10 provides a graphical summary of 1986 and 1997 HEFS scaling performance of the NBB WCP alternatives (ID3A, ID4A) and baseline (ID1E) for the peak reservoir release metric.

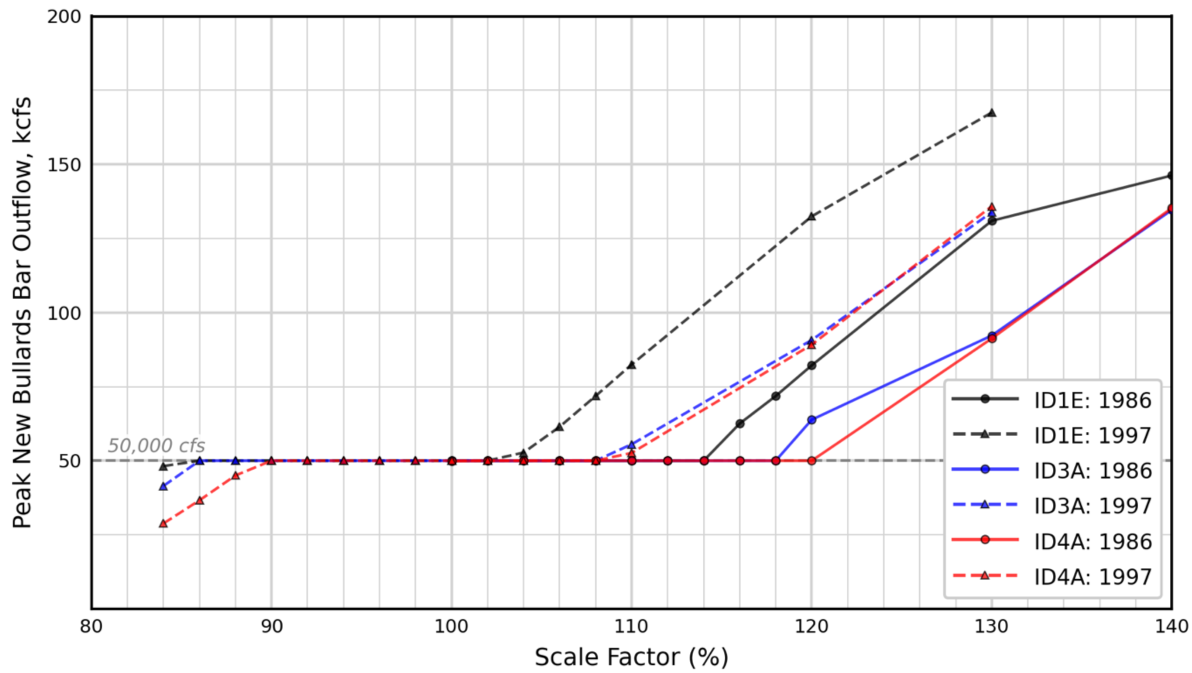


Figure 4-10. *NBB WCP performance of maximum release for HEFS scalings of the 1986 and 1997 flood events.*

The findings in Figure 4-10 show:

- For both the 1986 and 1997 patterns, releases greater than the maximum objective release of 50,000 cfs take place for ID1E at lower scale factors than either ID3A or ID4A.

The key takeaways from Figure 4-7 through Figure 4-10 are:

- ID3A and ID4A provide lower maximum reservoir storages and lower peak releases than ID1E at both ORO and NBB.

Assessing the individual scaled events provides insight into how each WCP handles the forecast information and attempts to meet FIRO's operational objectives. Figure 4-11 and Figure 4-12 show the ORO operation for the 1986 event scaled to 116 percent and the 1997 event scaled to 106 percent, respectively. Appendix A provides additional graphics for all scalings of the 1986 and 1997 events for ORO.

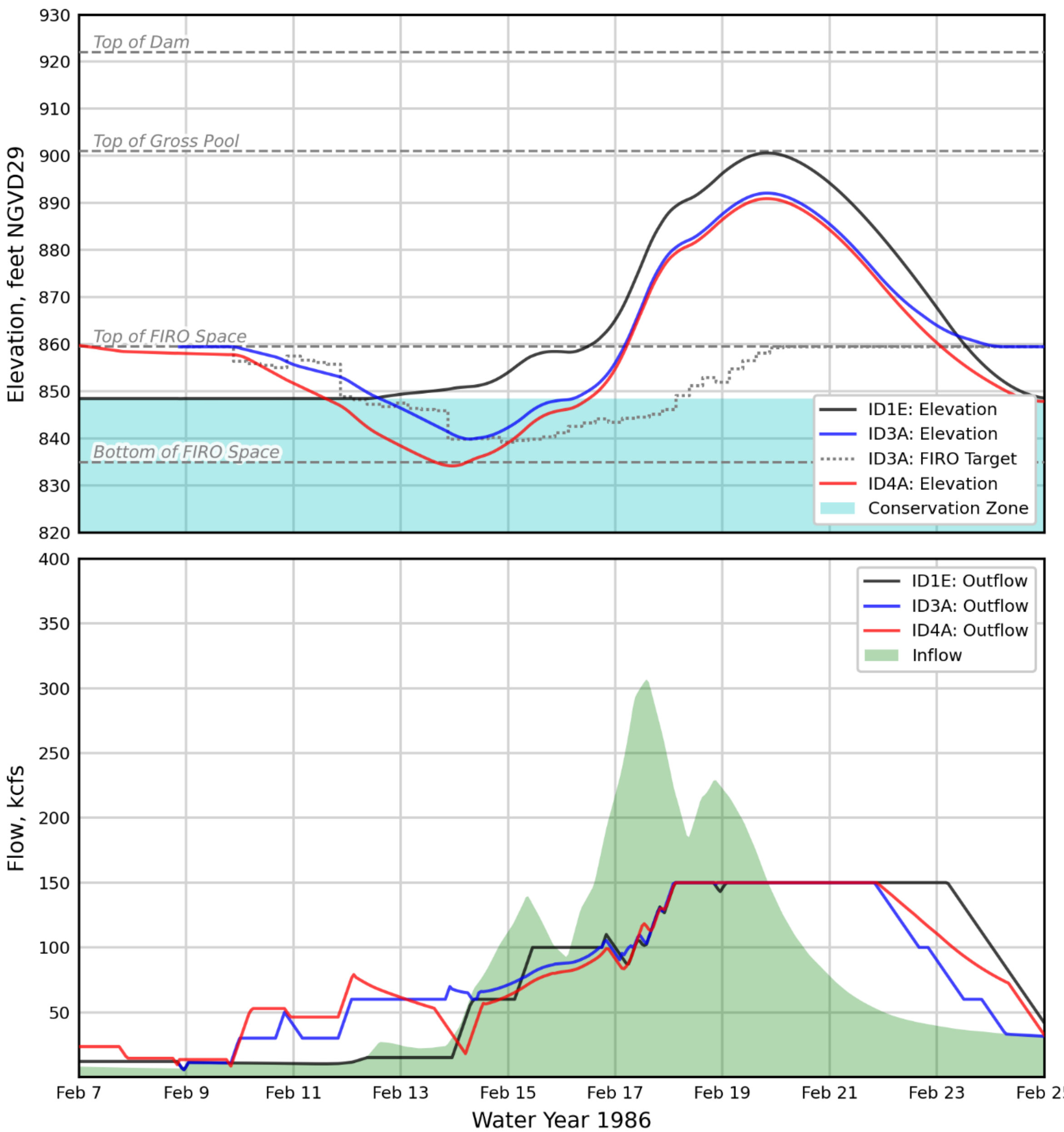


Figure 4-11. *ORO operations for the 116 percent scaling of the 1986 flood event.*

Figure 4-11 illustrates the following:

- ID3A and ID4A begin and end the simulation at a greater storage than ID1E because of the FIRO Space application. (Note that the return of ID4A to the top of conservation at the end of this event is likely an artifact of HEC-ResSim conflicts with external release overrides and would not happen in actual operations. The phenomenon does not consistently occur.)
- ID4A drafts into the conservation pool sooner and more deeply than ID3A.
- ID1E reaches the top of the gross pool while ID3A and ID4A do not.

- All alternatives limit the ORO release to 150,000 cfs. The duration of releases at 150,000 cfs is shorter for ID3A and ID4A than for ID1E.

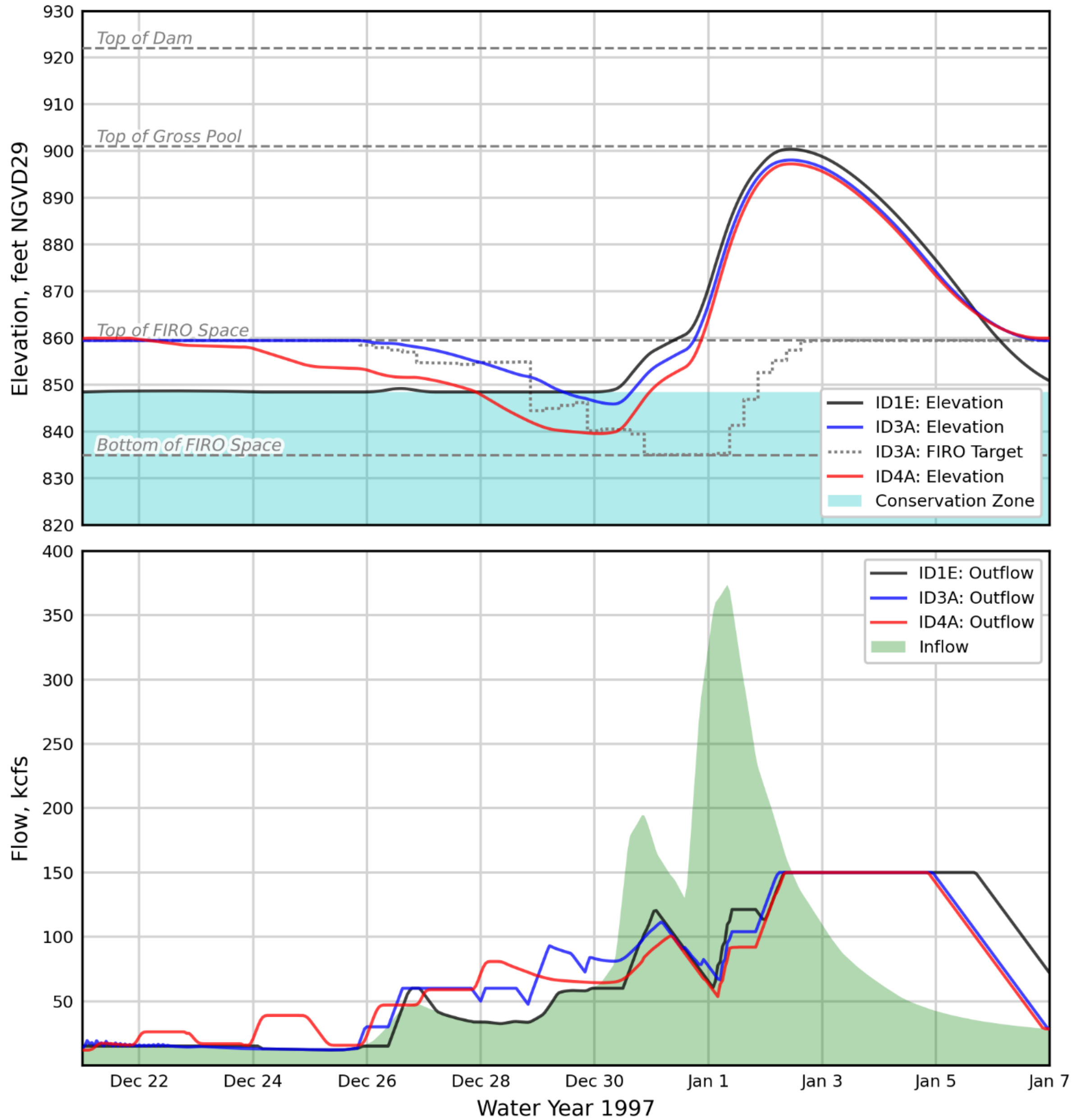


Figure 4-12. *ORO operations for the 106 percent scaling of the 1997 flood event.*

Figure 4-12 illustrates the following:

- ID3A and ID4A begin and end the simulation at a greater storage than ID1E because of the FIRO Space application.
- ID4A drafts into the conservation pool sooner and more deeply than ID3A.
- ID1E reaches the top of the gross pool while ID3A and ID4A do not.

- All alternatives limit the ORO release to 150,000 cfs. The duration of releases at 150,000 cfs is shorter for ID3A and ID4A than for ID1E.

Figure 4-13 and Figure 4-14 show the NBB operation for the 1986 event scaled to 116 percent and the 1997 event scaled to 106 percent, respectively. Appendix A provides additional graphics for all scaled 1986 and 1997 events for NBB.

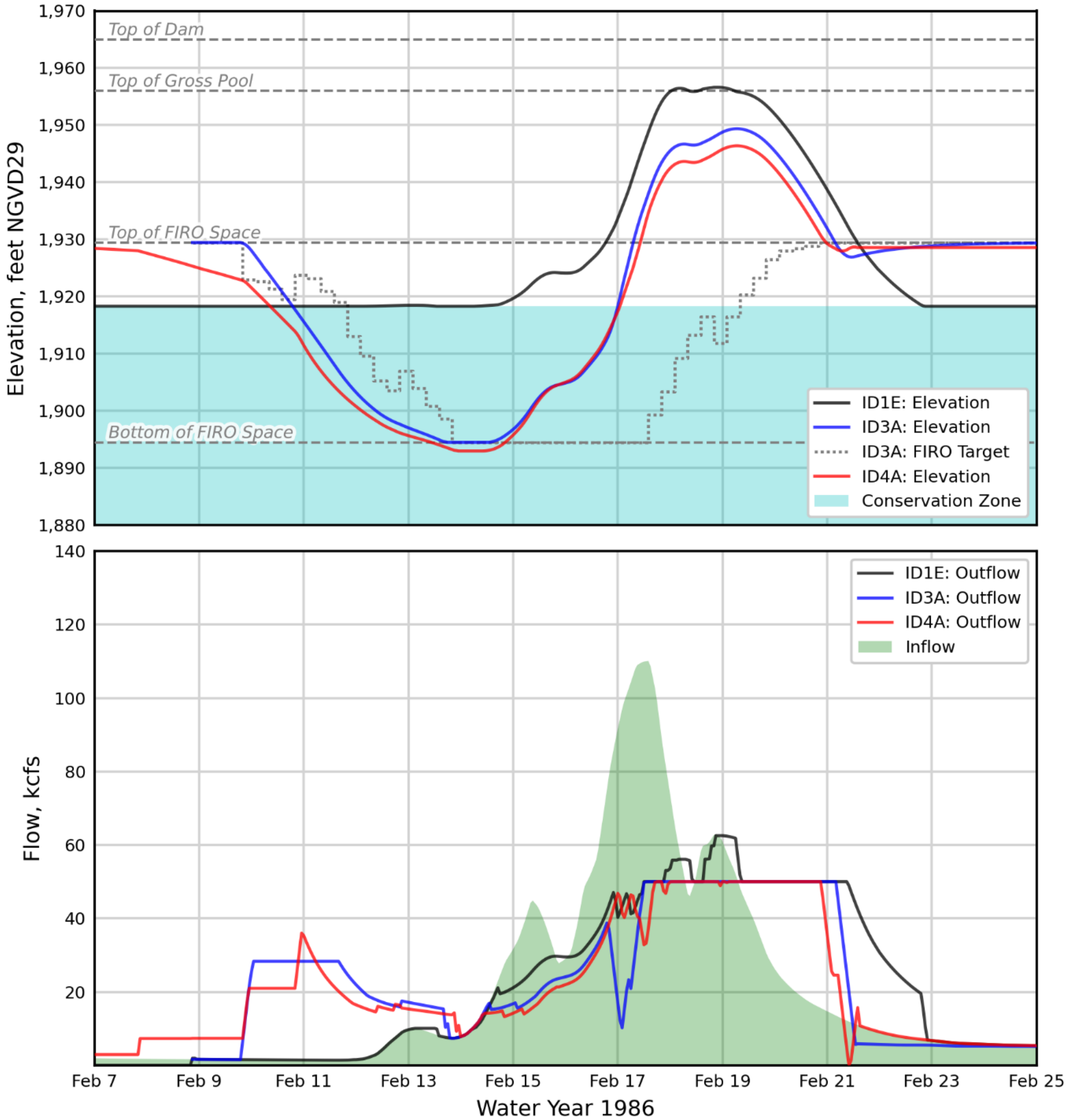


Figure 4-13. *NBB operations for the 116 percent scaling of the 1986 flood event.*

Figure 4-13 illustrates the following:

- ID3A and ID4A begin and end the simulation at a greater storage than ID1E because of the FIRO Space application.

- ID4A drafts into the conservation pool sooner and more deeply than ID3A.
- ID1E exceeds the top of gross pool while ID3A and ID4A do not.
- ID3A and ID4A limit the NBB release to 50,000 cfs. A larger release is required by the Emergency Spillway Release Diagram (ESRD) for ID1E.

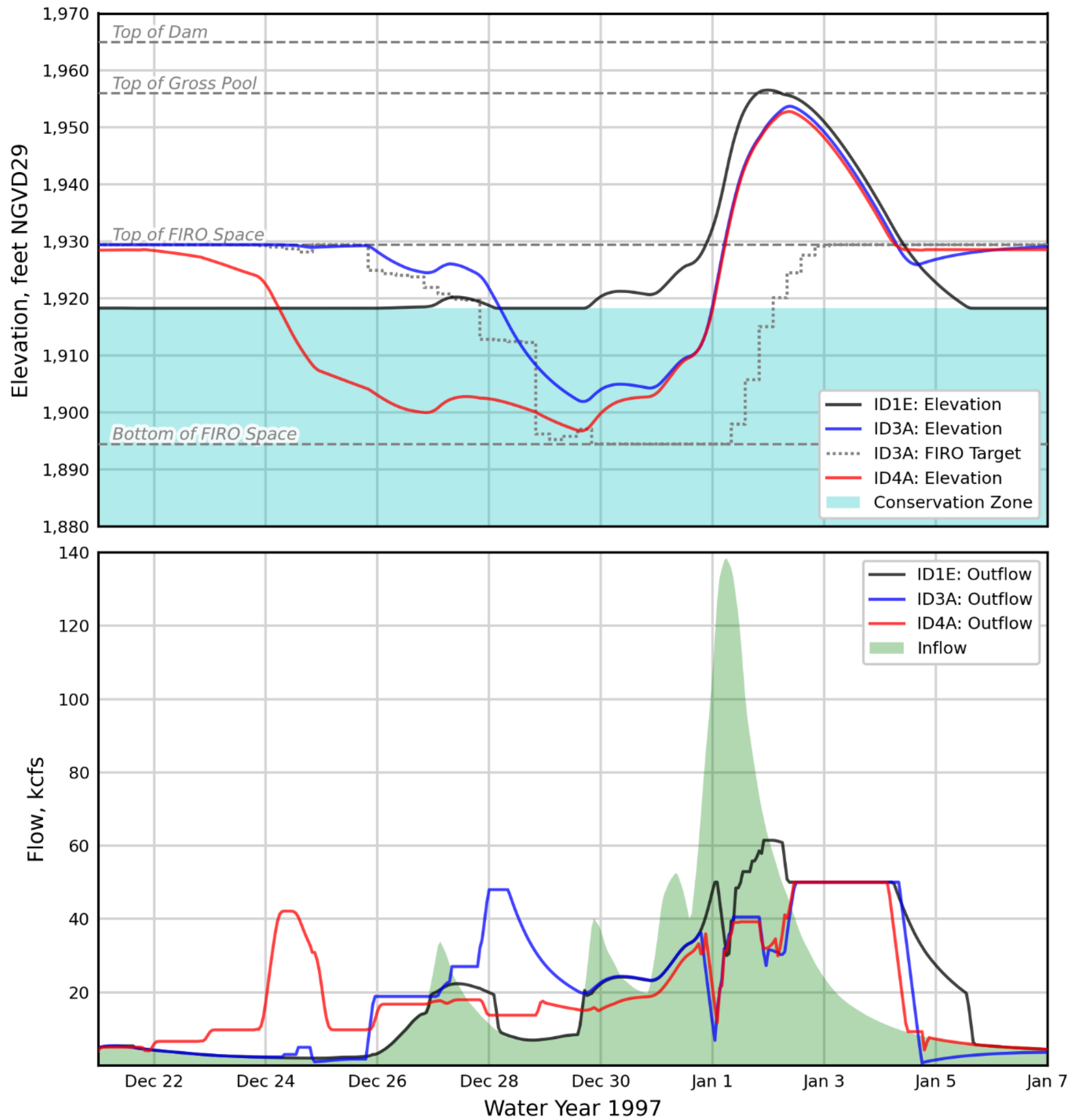


Figure 4-14. *NBB operations for the 106 percent scaling of the 1997 flood event.*

Figure 4-14 illustrates the following:

- ID3A and ID4A begin and end the simulation at a greater storage than ID1E because of the FIRO Space application.
- ID4A drafts into the conservation pool sooner and more deeply than ID3A.

- ID1E exceeds the top of gross pool while ID3A and ID4A do not.
- ID3A and ID4A limit the NBB release to 50,000 cfs. A larger release is required by the ESRD for ID1E.

Figure 4-15 summarizes minimum and maximum event storage values for the ORO and NBB reservoirs for the scaled 1986 and 1997 events. This figure illustrates the key differences in how the ID3A and ID4A FIRO alternatives propose to augment the existing flood reserve using a portion of the water conservation space.

Note that:

- The FIRO alternatives (ID3A and ID4A) consistently draft into the conservation storage, and the degree of the draft increases as the scaling factor increases.
- ID4A is slightly more effective at using the FIRO Space within the conservation storage, most likely because it utilizes forecasts with longer lead times than ID3A (14 versus seven days), even though forecast skill beyond seven days is arguably quite limited.

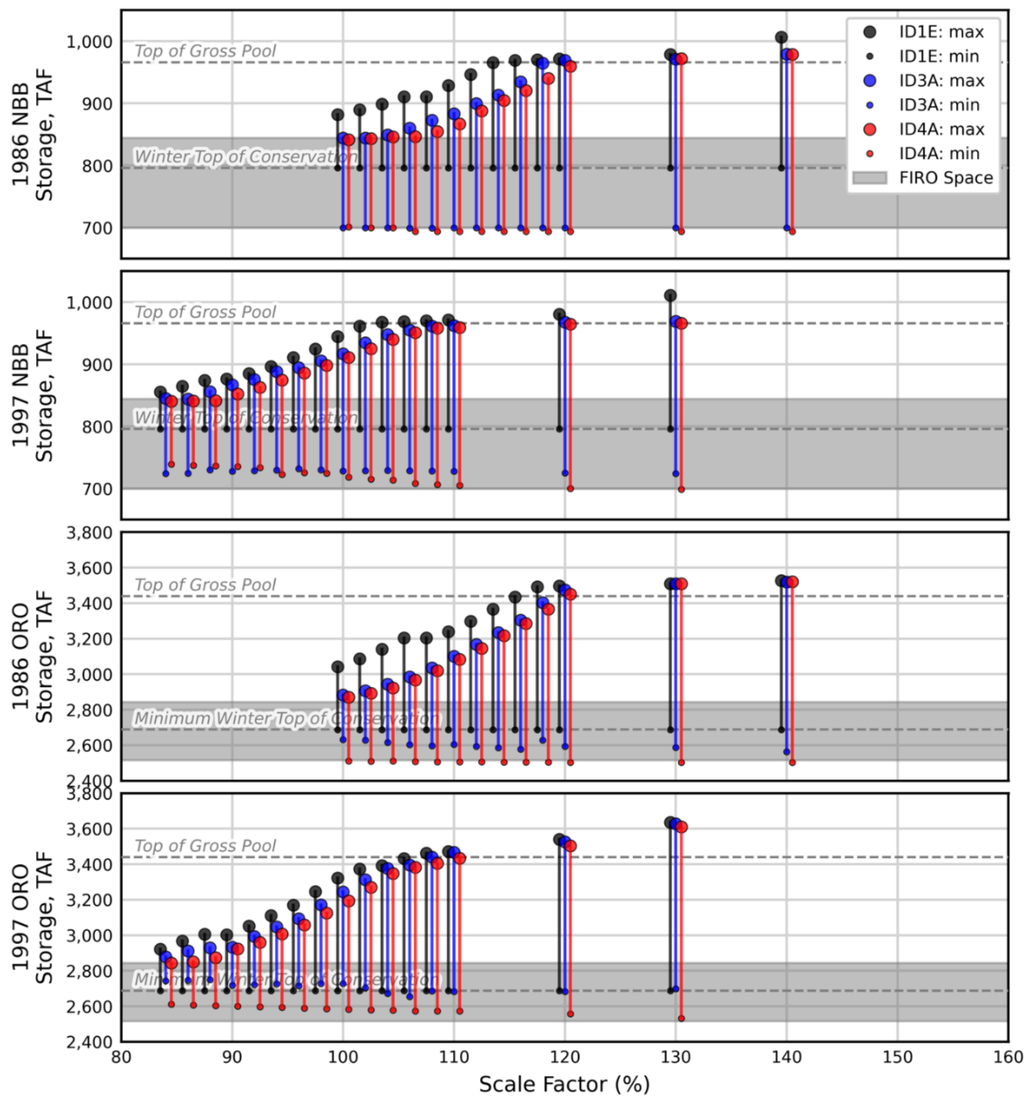


Figure 4-15. *Storage utilization at NBB and ORO, measured in thousands of acre-feet (TAF).*

4.2 Water Supply Availability Metrics

The water supply availability metrics (IDs M6 and M7 from Table 3-7) are the post-event water storage in both ORO and NBB. These metrics, along with the frequency of HEFS hindcasts that would trigger a pre-release into the conservation pools, allow for an indirect assessment of water supply availability impacts.

Figure 4-16 provides a conceptual picture of how a FIRO WCP can improve water supply availability at an individual-event scale. The key element is the designation of the FIRO Space that includes some portion of the flood control reservation (above top of conservation). As shown here, pre- and post-event storage are allowed to encroach into the flood control reservation to an extent demonstrated to be safe given the skill of the forecasts and the ability of the dam to release the excess water in advance of a forecast event.

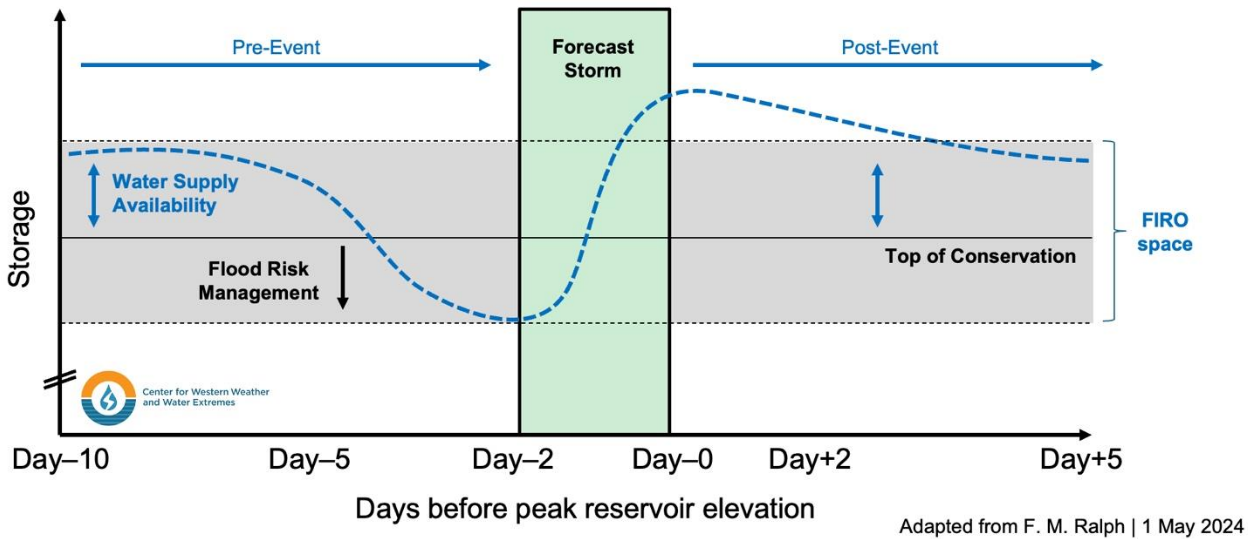


Figure 4-16. *Conceptual FIRO operation that shows the potential for improvements in FRM before storm events and water supply availability after storm events.*

The event simulations conducted as a part of this study consistently confirm the pattern shown in Figure 4-16. Thus, FIRO WCP alternatives that leverage FIRO Space have the potential to positively impact water supply availability due to higher post-event reservoir storage levels.

The studies conducted under the Final Viability Assessment also confirm the findings of the Preliminary Viability Assessment in that the forecast-informed pre-release of reservoir storage is consistently recaptured during the flood event. More conclusive statements on the effect of FIRO on water supply availability are expected to be available during the WCM update process (NEPA), where the full period of record evaluation will be conducted.

4.3 Transfer of Benefits to Downstream Control Points

In the scaled event routings, ID3A and ID4A consistently produced lower peak reservoir elevations compared to ID1E. This reduction in peak storage volume affords operational flexibility for different FRM objectives. An alternative way to characterize the FRM benefits is to determine the lowest levels at which downstream flows can be maintained while allowing the reservoirs to fill up to the peak reservoir storage of the ID1E baseline. This technique allows the potential storage reduction benefit by the FIRO alternative to be shifted to a downstream peak flow and stage reduction benefit.

Figure 4-17 through Figure 4-22 illustrate two sets of ID3A FIRO event simulations (1986 and 1997 100 percent) configured to induce each reservoir to fill to a level approaching the ID1E baseline while targeting lower maximum flows at key joint operational locations downstream of the reservoirs. Note that, while the lower target cannot always be maintained for the duration of the event, a reduced target results in lower peak flows in the Feather River below Yuba River and Feather River below Bear River. The stage reduction for the 1986 × 100 percent hindcast event ranges from 0.7 to 1.7 feet for Feather River below Yuba River (for the flow/stage rating curve at Boyd’s Landing) and 0.4 to 1.2 feet at Feather River below Bear River (Nicolaus).

For the 1997 × 100 percent hindcast event, the ID3A FIRO alternative results in slightly higher flows, though still significantly below the existing downstream maximum objective flows. For the reduced target simulations, the stage reduction ranges from 0 to 0.8 feet for Feather River below Yuba River and 0 to 0.3 feet for Feather River below Bear River. These simulations are shown in Figure 4-20 through Figure 4-22.

These events effectively demonstrate that FIRO enhances operational flexibility to provide more options for operators in managing ORO and NBB, as well as the downstream floodway as a system. Note that the simulations were made for specific downstream targets and do not represent the maximum downstream flow reductions possible if the reservoirs were allowed to fill to some agreed-upon maximum elevation (e.g., top of the gross pool).

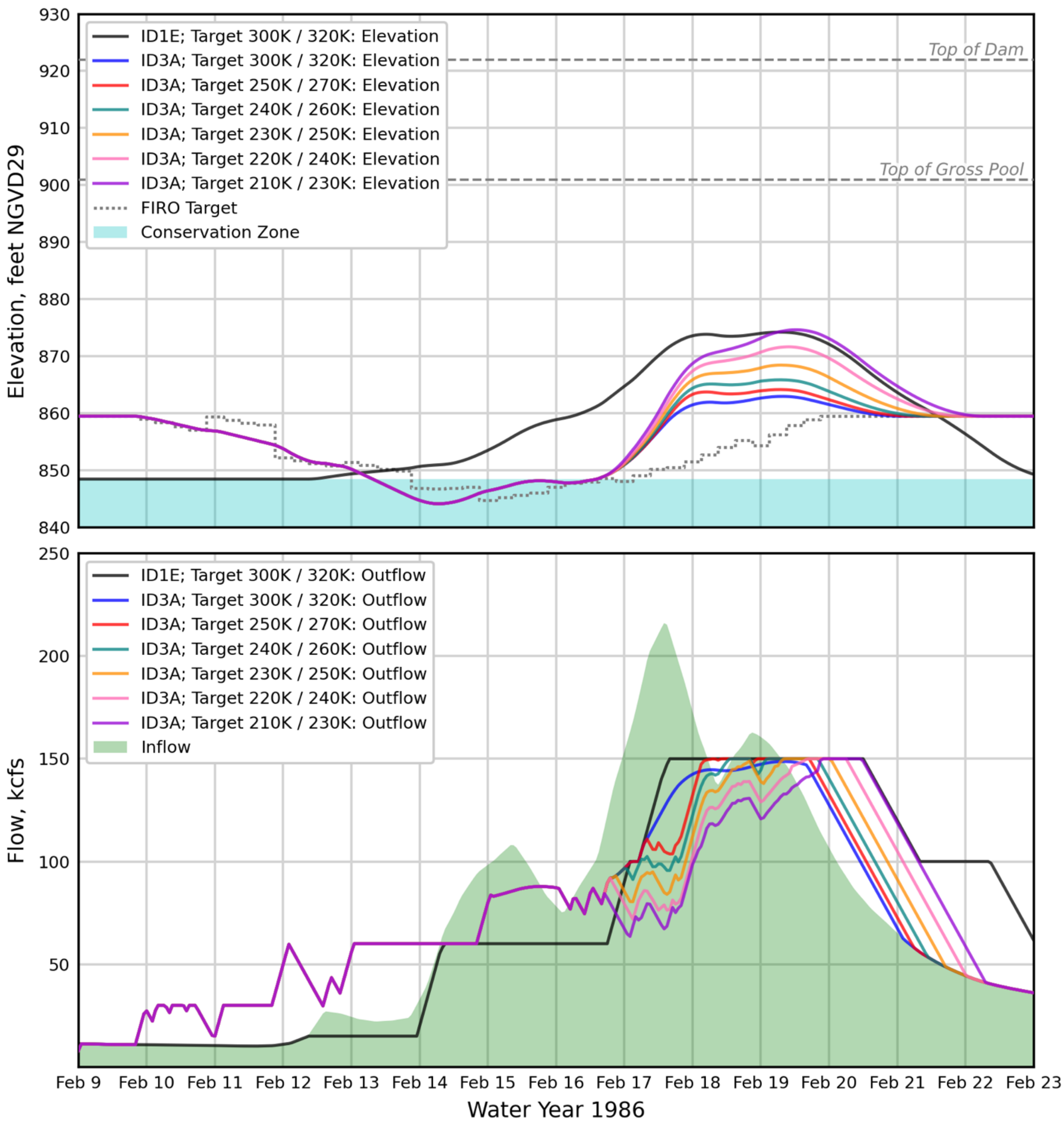


Figure 4-17. *ORO operations for an example range of reduced downstream control flow targets for the 1986 × 100 percent scaled hindcast event.*

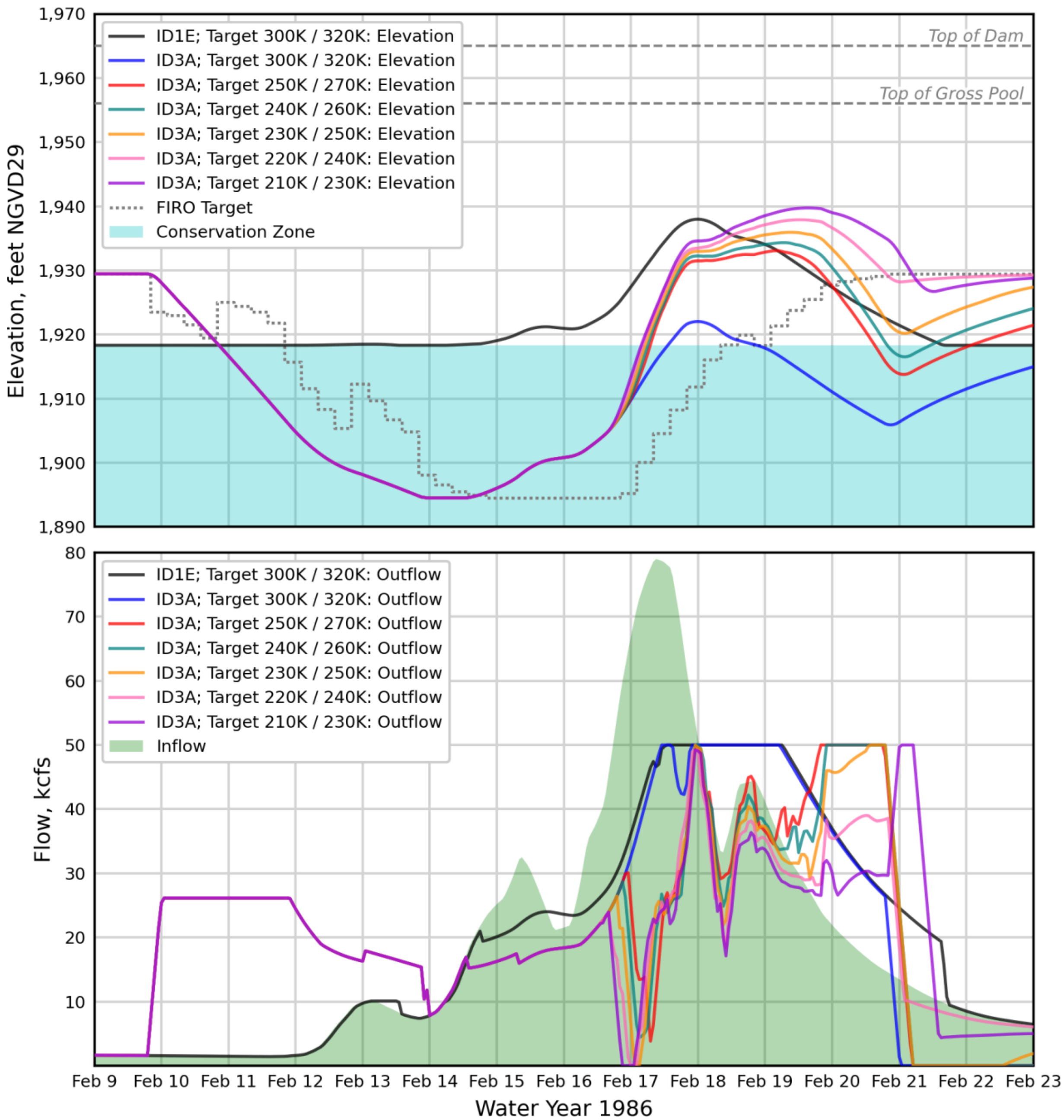


Figure 4-18. *NBB operations for an example range of reduced downstream control flow targets for the 1986 × 100 percent scaled hindcast event.*

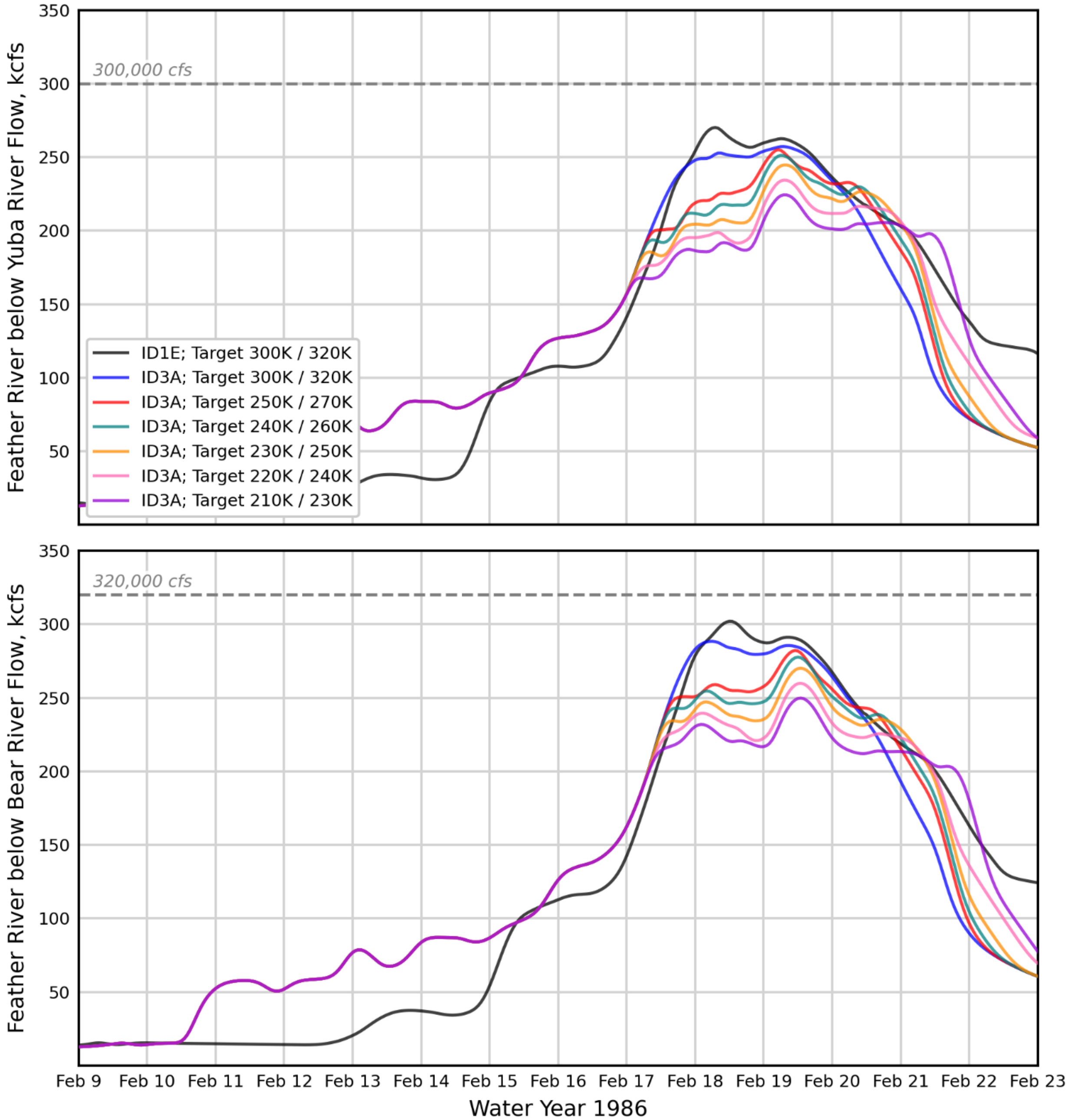


Figure 4-19. *Feather River below Yuba River and Feather River below Bear River flows for an example range of reduced downstream control flow targets for the 1986 × 100 percent scaled hindcast event.*

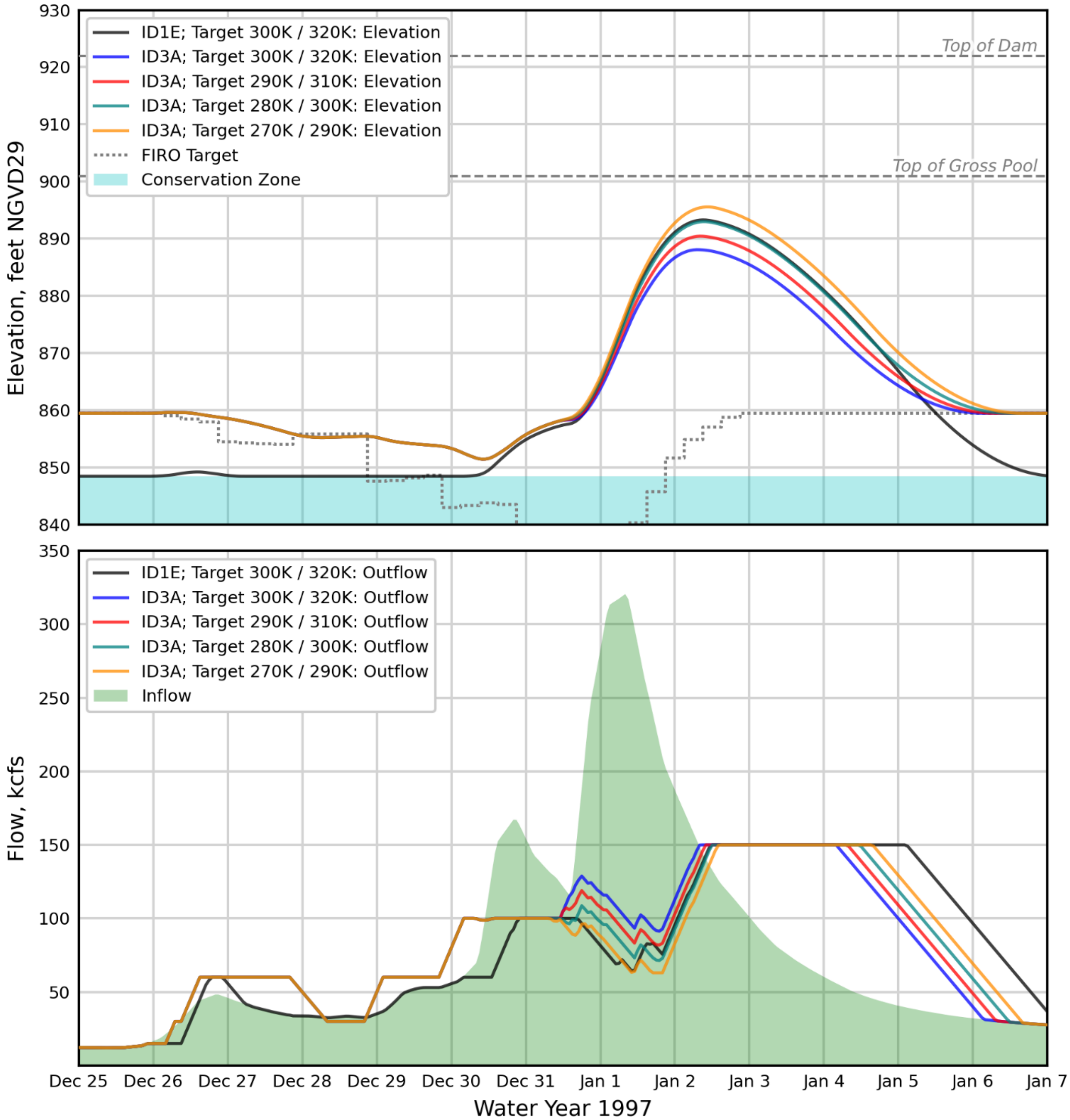


Figure 4-20. *ORO operations for an example range of reduced downstream control flow targets for the 1997 × 100 percent scaled hindcast event.*

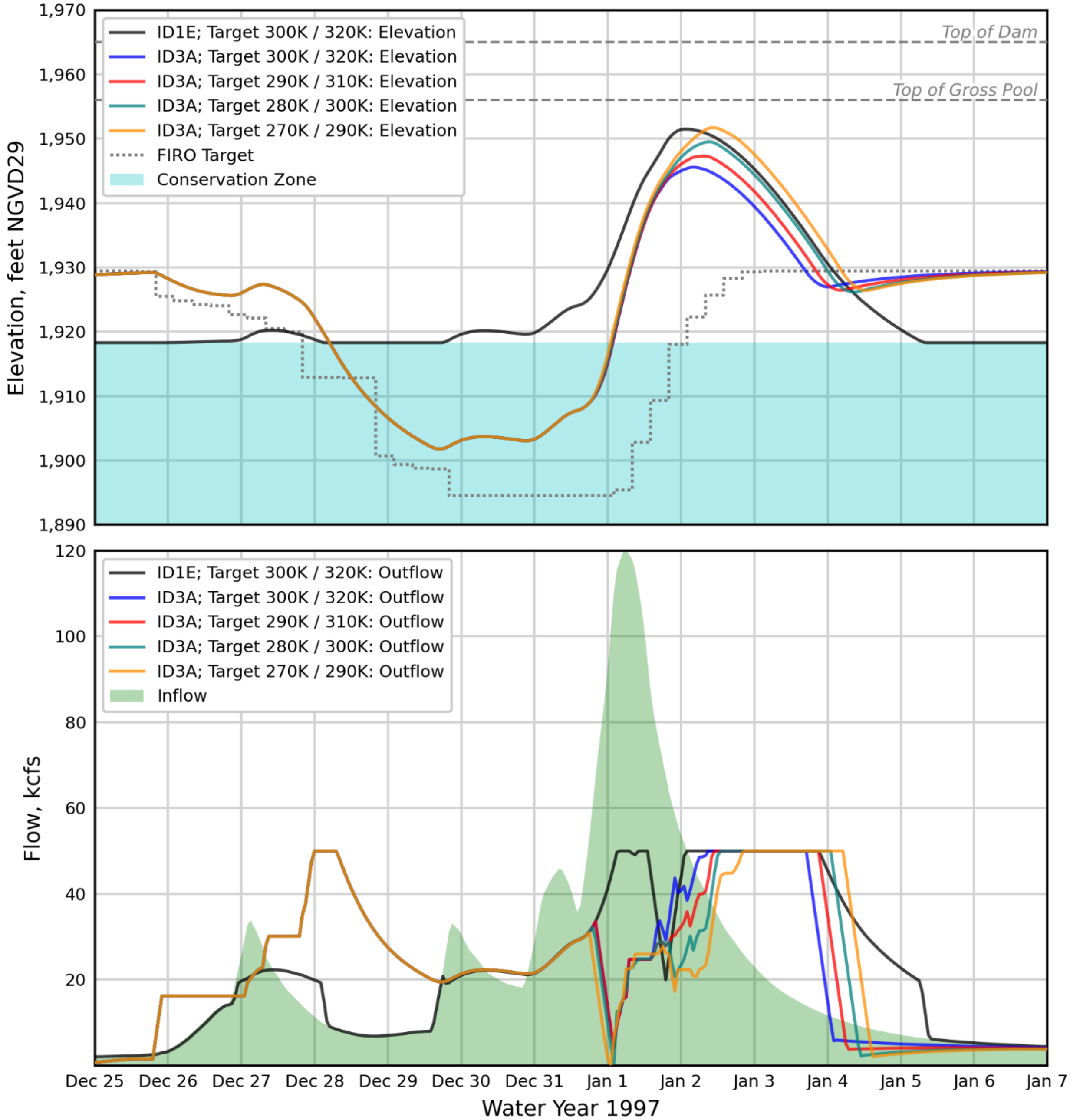


Figure 4-21. *NBB operations for an example range of reduced downstream control flow targets for the 1997 × 100 percent scaled hindcast event.*

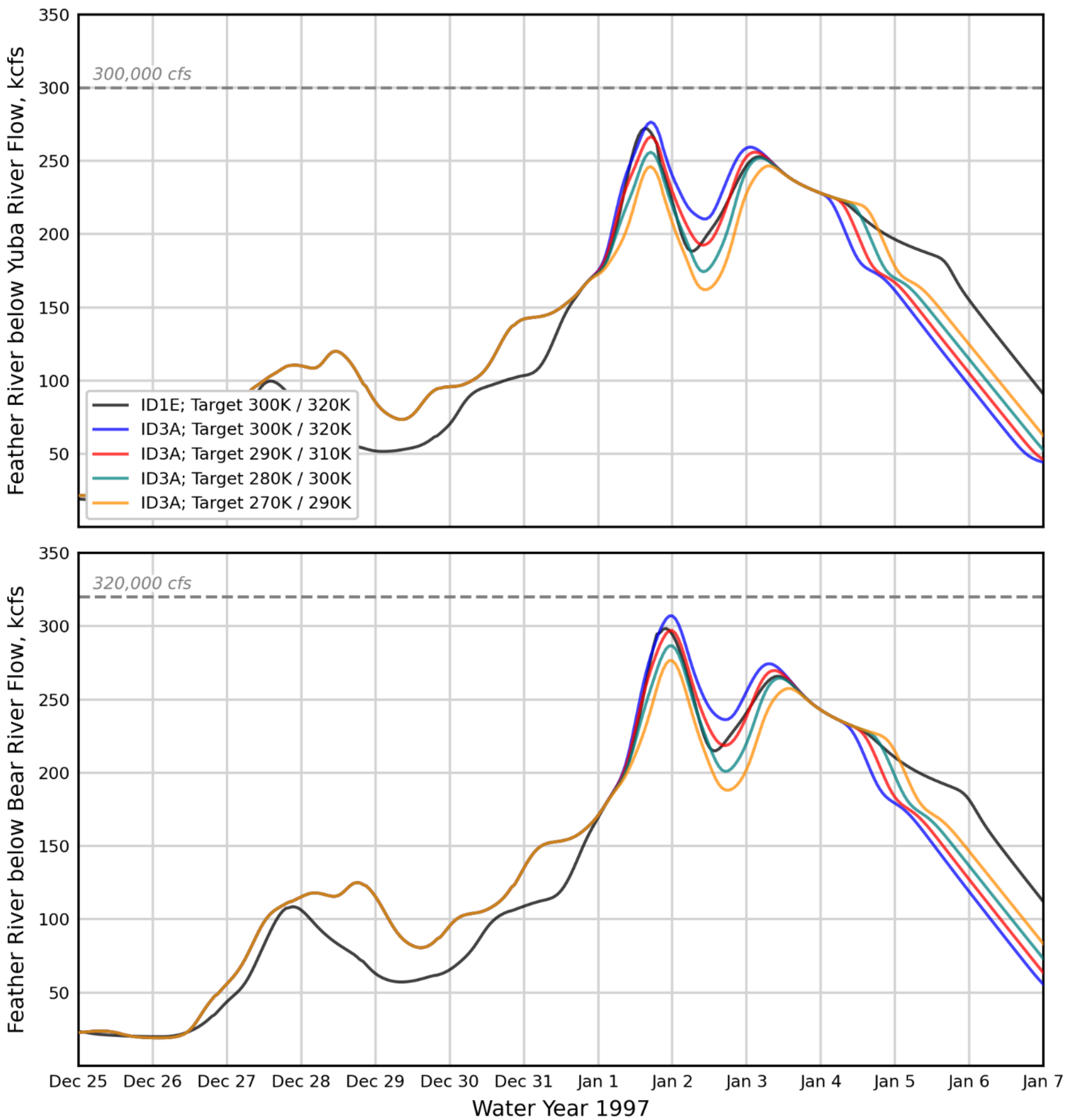


Figure 4-22. *Feather River below Yuba River and Feather River below Bear River flows for an example range of reduced downstream control flow targets for the 1997 × 100 percent scaled hindcast event.*

In addition to demonstrating flexibility that can be leveraged by operators in real-time F-CO collaboration, this illustrates the potential to utilize multiple simulations to inform a beneficial operation given changing priorities throughout the Yuba-Feather system. This concept is explored in greater detail in Section 4.4.

4.4 Demonstration of System Operations Alternatives

4.4.1 Explicit System Target Approach (S3)

The alternative system operation described in this section is flexible depending on the factors that would affect the goals of the operation. As described in Section 3.5.3.1, this operation takes the ensemble forecast and utilizes model simulations of every ensemble member for a range of joint downstream flow constraints, tributary constraint distributions, and reservoir release order priority. Every ensemble member produces a potential release pattern.

At this point, ensemble performance metrics are computed for every potential outcome in the next 120 hours. A set of performance metrics were identified at a WRE team workshop as the following:

- ORO flood space utilization.
- NBB flood space utilization.
- ORO outflow channel utilization.
- Feather River at Yuba City channel utilization.
- Yuba River near Marysville channel utilization.
- Feather River below Yuba River channel utilization.
- Feather River below Bear River channel utilization.

Each of these seven metrics is then assigned a weight based on its relative importance. The combined score considering each weighted metric is then used to determine which downstream targets to adhere to until the next forecast is released.

To demonstrate how the weighted metrics affect the operation, three examples were run for the 1997 100 percent scaled CNRFC HEFS hindcast. The weights for each metric, for the three example weight schemes, are shown in Table 4-3.

Table 4-3. *Example weight schemes.*

Metric	Weight Scheme		
	Balanced	Reservoir Favored	Downstream Favored
ORO flood space utilization	25%	50%	0%
NBB flood space utilization	25%	50%	0%
ORO outflow channel utilization	6.25%	0%	0%
Feather River at Yuba City channel utilization	6.25%	0%	0%
Yuba River near Marysville channel utilization	12.5%	0%	0%
Feather River below Yuba River channel utilization	12.5%	0%	0%
Feather River below Bear River channel utilization	12.5%	0%	100%

The simulation was run with HEFS hindcasts from December 30 through January 3 for the 1997 event scaled to 100 percent. Figure 4-23 shows the combinations of joint downstream constraints (CMCs), reservoir independence, and tributary constraint distributions that were used for this example. These 12 alternatives are only example models for this algorithm; they are just a subset of the combinations that could be considered. Additional gradation in the CMC or flow splits could be modeled to make a more precise decision.

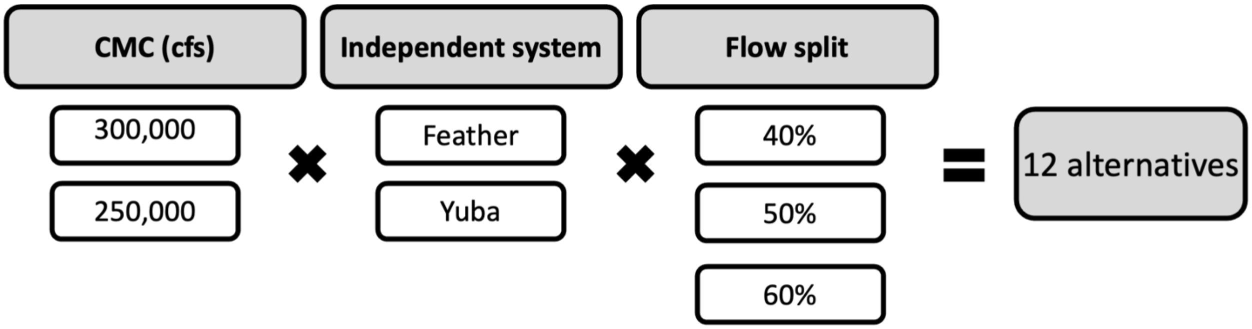


Figure 4-23. *Model system balance variables in an example simulation.*

Based on the weighted peak metrics for every ensemble member in the hindcast, a decision was made about how to balance reservoir and downstream objectives for the next 24 hours. That decision is applied to the model and the "simulated historical" series is then run to represent what would happen in real time. The resulting operation is shown in the following figures. There are three simulations displayed on each figure: the blue solid line is the operation with balanced weights, the red dashed line is the operation with downstream-favored weights, and the purple dotted line is the operation with reservoir-favored weights. Figure 4-24 is for the ORO operation and Figure 4-25 is for the NBB operation.

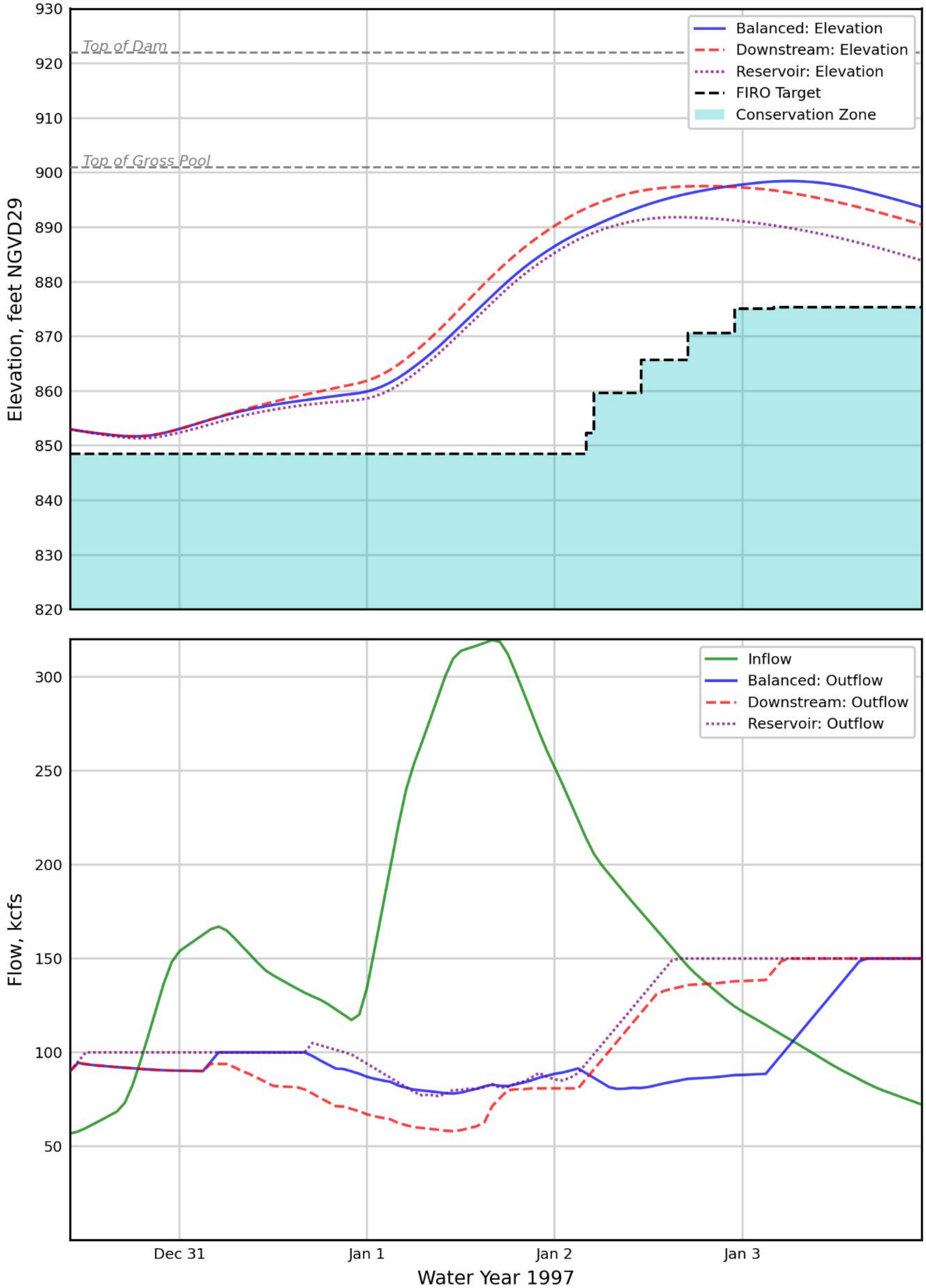


Figure 4-24. *ORO comparison operations for varied weight schemes for the 1997 × 100 percent scaled simulated historical event.*

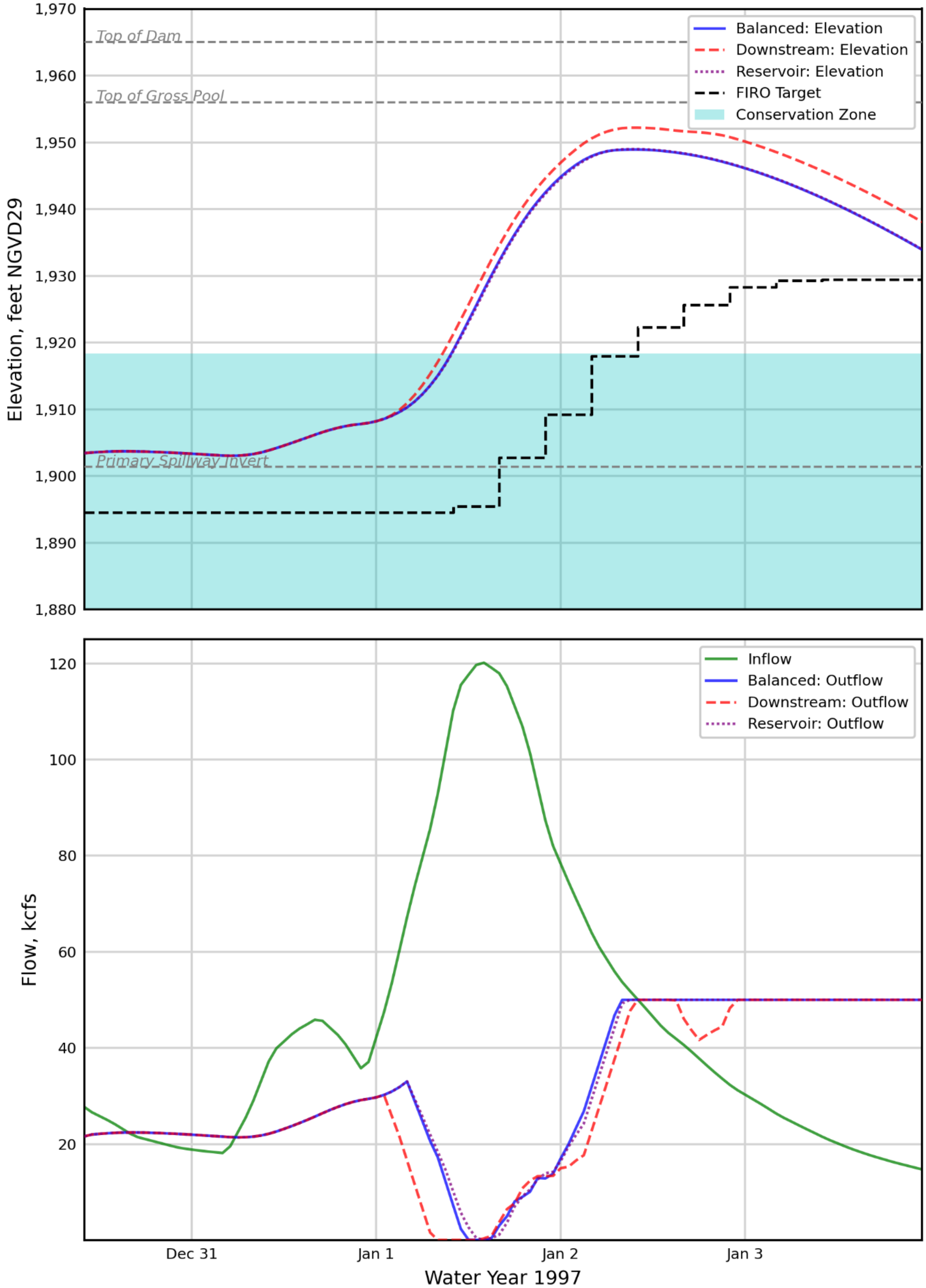


Figure 4-25. *NBB comparison operations for varied weight schemes for the 1997 × 100 percent scaled simulated historical event.*

On the ORO operations plot in Figure 4-24, the reservoir-favored alternative shows a much lower elevation compared to the other two. As shown in Figure 4-25, the NBB elevation is lower for the balanced and reservoir-favored alternatives compared to the downstream-favored alternative. As expected, the downstream alternative favors lower downstream flows compared to reservoir elevations.

Figure 4-26 shows the flows at the downstream control points.

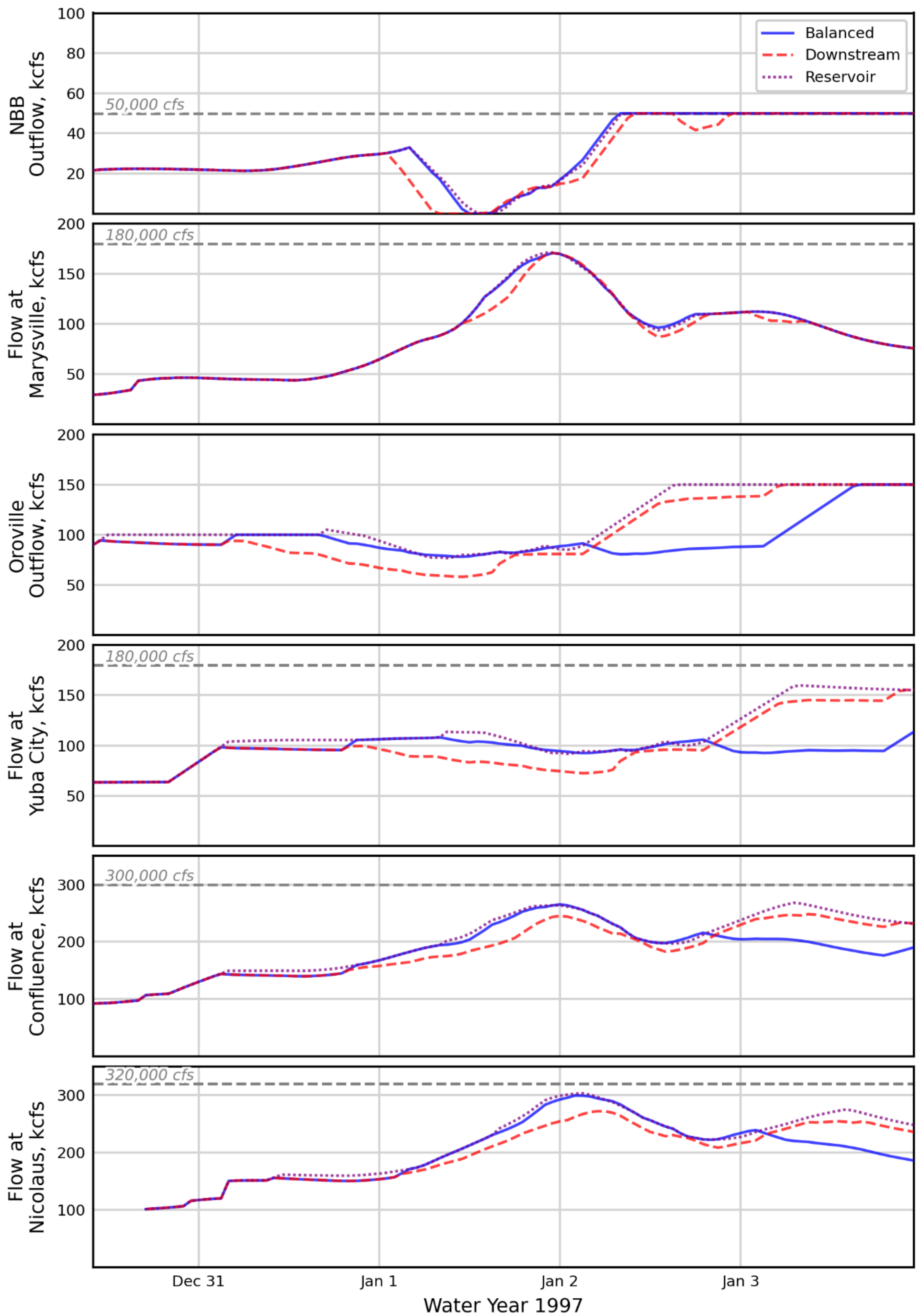


Figure 4-26. *Downstream flow comparison for varied weight schemes for the 1997 × 100 percent scaled simulated historical event.*

All three alternatives can meet the downstream flow constraints, but the downstream-favored alternative results in lower or equal peak flows at all locations. For this event, the weighted metrics from the entire ensemble hindcast indicate this balance between both reservoirs and downstream objectives as the "best" option, given the provided range of reduced downstream targets and tributary flow distribution.

This method was developed to build off the current F-CO process and guide operators' decisions more effectively according to the ensemble forecasts. The explicit system target approach can be built into the modeling algorithm to disambiguate the downstream flow targets and utilize all the available forecast information.

4.4.2 Ensemble Forecast Operations System Approach (S4)

The methodology for the ensemble forecast operations (EFO) system is described in Section 3.5.3.2. The approach attempts to mitigate the risk of exceeding the downstream flow objectives by balancing the "intolerable" storage risk equally between ORO and NBB. Figure 4-27 and Figure 4-28 show the application of S4 for ORO and NBB, respectively, for the 1997 event scaled to 100 percent. These simulations do not use HEC-ResSim and are therefore not subject to codified constraints or challenging HEC-ResSim idiosyncrasies. As such, there is no comparison of ID4 with a representation of the F-CO system operations.

Figure 4-27 and Figure 4-28 show that with the 100 percent scaling of the 1997 event, storage in ORO and NBB is held well below the gross pool even as compromises in risk tolerance are made to keep the control points of the confluence and Feather River at Nicolaus at or below their objective flows. For this simulation, the EFO model scheduled the releases to minimize flooding downstream of the confluence and balance forecasted "intolerable" storage risk between the reservoirs, which placed a greater burden on NBB to mitigate control point flows downstream in the time surrounding the peak inflow to the reservoirs.

Figure 4-29 shows the simulated hydrographs for the four control points for the 100 percent scaling of the 1997 event. Note that the confluence and Feather River at Nicolaus were held to their objective flows, while Feather River at Yuba City and Yuba River at Marysville remained below their objective flows.

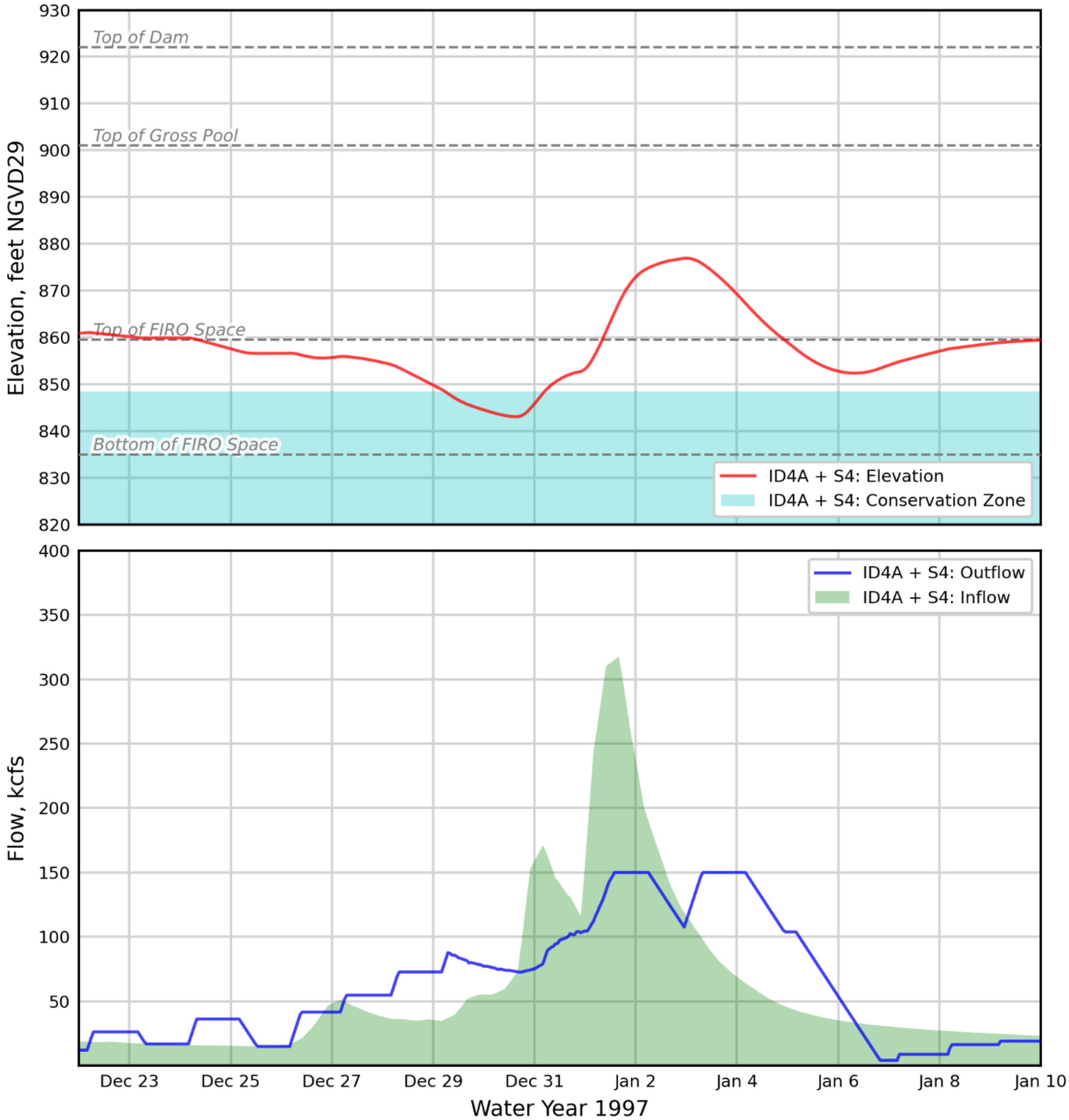


Figure 4-27. *ORO operations for S4 alternative with 1997 × 100 percent scaled simulated historical event.*

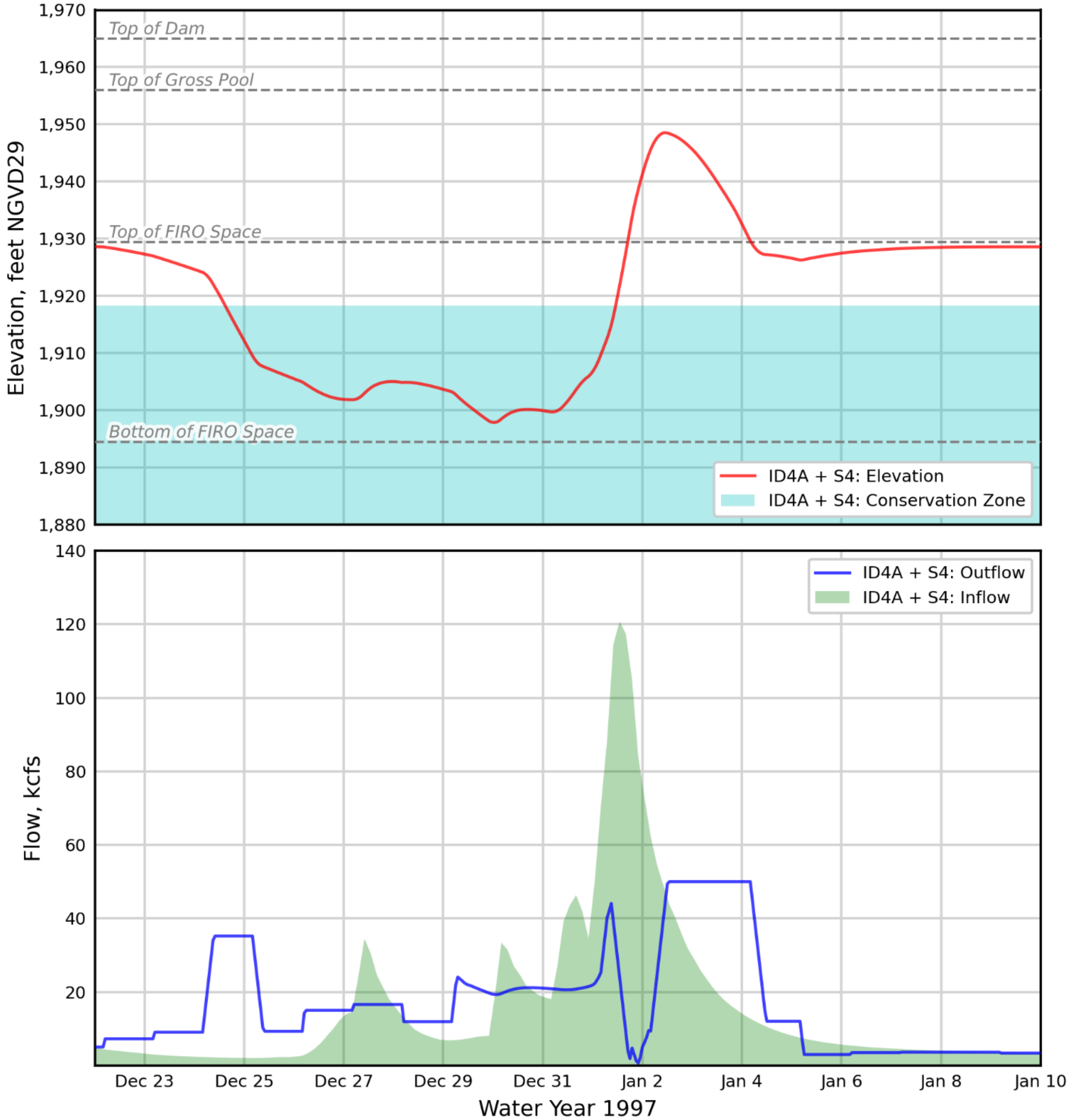


Figure 4-28. *NBB operations for S4 alternative with 1997 × 100 percent scaled simulated historical event.*

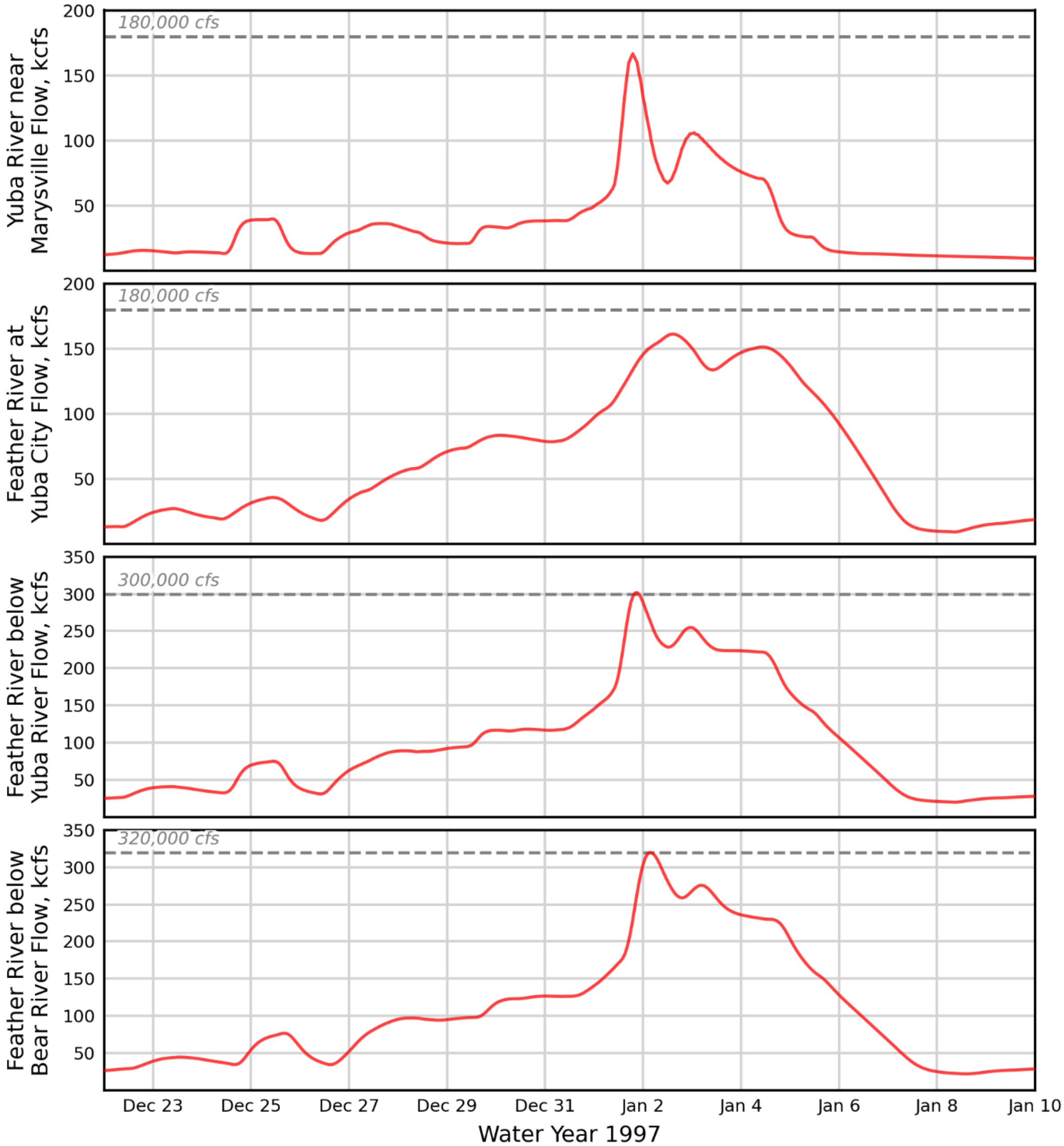


Figure 4-29. *Downstream flow hydrographs for S4 alternative with 1997 × 100 percent scaled simulated historical event.*

4.4.3 System Operations Discussion

S3 and S4, as described in Section 3 and briefly demonstrated in Section 4.4, serve as examples of how system operations in the Yuba-Feather system could be developed and enhanced over time.

4.5 Conclusions

Engineering Process

1. The models and processes described in Section 3 were successful in simulating ORO and NBB operations across a range of scaled HEFS extreme events for the baseline (ID1E) and prescriptive (ID3A) and iterative (ID4A) alternatives with F-CO system operations.
2. Refined or enhanced system operations that more fully leverage the uncertainty in the local flows below ORO and NBB were demonstrated. Local flows in the system impact reservoir operations, and accounting for these flows and their associated uncertainties is critical for system operations performance.
3. The use of HEC-ResSim as a modeling framework was effective; however, challenges were encountered related to evaluating and implementing the FIRO strategies as envisioned given current HEC-ResSim capabilities.

Flood Risk Management

1. FIRO WCP alternatives (ID3A and ID4A) were effective at reducing both maximum reservoir elevation and downstream peak flows compared to baseline operations (ID1E).
2. FIRO WCP benefits are naturally realized as reductions in peak reservoir storage. These reductions can be effectively traded for reduced downstream peak flows.
3. Demonstrated alternative system operations (S3 and S4) have the potential to improve FRM outcomes but require additional refinement.
4. Improvements in FRM outcomes are attributable to: (1) the use of forecasts, (2) the application of FIRO Space in the top of the water conservation pool for both ORO and NBB (Figure 3-1 and Figure 3-2), and (3) the contributions of the planned ARC Spillway at NBB that can more effectively pre-release water in advance of an extreme event.

Water Supply Availability

1. Flood routings of winter season scaled events demonstrate recovery to the top of FIRO Space, which means increased storage after the event compared to baseline operations. Increased storage suggests a benefit to water supply availability. Some refinements may be required for spring operations.
2. The potential for improved water supply availability was inferred through the FIRO process rather than definitively demonstrated. The period of record assessment conducted as a part of the WCM updates is expected to clarify the potential impacts.

4.6 Recommendations

1. Modify HEC-ResSim to allow for separate time series for both observed flow routing and the forecast flows used to make computational decisions. HEC-ResSim currently assumes perfect foresight for local flows downstream of dams but lacks a mechanism to include forecast uncertainty in the timing and magnitude of those flows.
2. Implement a FIRO Space concept in HEC-ResSim that enables representation of rules that smoothly transition from flood space to conservation space.

3. Evaluate seasonally specific forecast skill to better inform how FIRO should be applied when transitioning from winter to spring.
4. Continue enhancing HEC-ResSim to leverage ensemble forecasts and their associated uncertainty more explicitly.
5. Continue developing system operations concepts that will balance risk between ORO, NBB, and downstream control points during a large flood event. Continue to refine these concepts for inclusion in the F-CO program.

Section 5. Studies, Research, and Development in Support of the FVA

5.1 Overview and Purpose

The Yuba-Feather Final Viability Assessment (FVA) stands on a foundation of extensive meteorological and hydrological research, enhancements and expansions to hydrometeorological observations, weather and water forecast verification, and analysis of economic benefits. This work has focused on the atmospheric river (AR) storms that produce most of the Yuba River and Feather River watersheds' precipitation—driving both beneficial water supply and flood hazards.

5.2 Meteorology

Section Lead Author: J. M. Cordeira

Section Contributing Authors: C. Hecht, J. Rutz, A. Wilson, C. Castellano, A. Sengupta, B. Kawzenuk, S. Bartlett, S. Roj, M. Steen, M. Zheng, and P. Loikith

5.2.1 Introduction

Meteorology studies, research, and development activities in support of the Preliminary Viability Assessment (PVA) in the upper Yuba and Feather River watersheds previously characterized watershed precipitation and its association with landfalling ARs. Among the characteristics investigated were AR intensity and duration, as well as mesoscale features such as the presence of mesoscale frontal waves, barrier jets, narrow cold frontal rainbands, or variable freezing levels that strongly influence precipitation and streamflow variability and predictability within the watersheds. (For the purposes of this report, "freezing level" is defined as the altitude at which the air temperature reaches 0 degrees Celsius.)

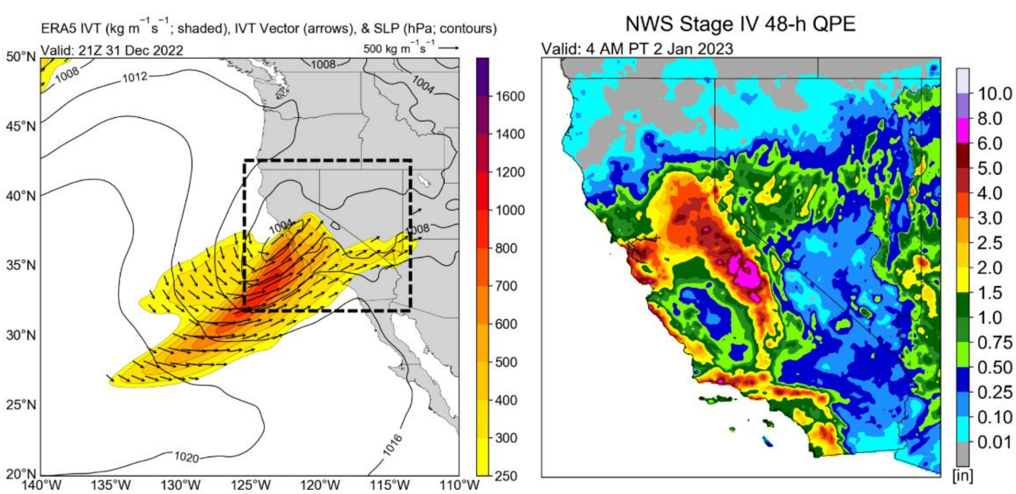


Figure 5-1. *Left: integrated vapor transport (IVT), shaded according to scale in kilogram per meter per second (kg $m^{-1}s^{-1}$); IVT vectors; and sea-level pressure (SLP) in hectopascals (hPa), shown with contours. Right: 48-hour quantitative precipitation estimate ending at 4:00 a.m. Pacific Time on January 2, 2023.*

The primary goal of the current activities in support of the FVA was to further investigate characteristics of landfalling ARs that are associated with precipitation extremes, uncertainty, and challenges to hydrometeorological prediction. An example of the type of storms studied in this effort included a storm in late December 2022 that occurred during a three-week period featuring nine landfalling ARs in California (Figure 5-1**Figure 5-1**). This storm featured all the abovementioned mesoscale characteristics and extraordinary challenges to short-term (one- to two-day) precipitation prediction over Northern California.

5.2.2 Methods and Analysis

The meteorological studies, research, and development for the FVA were guided by eight tasks recommended by the PVA. These tasks can be broadly grouped as "studies and research" in Tasks 1–4 (focusing on the prediction of landfalling ARs and their precipitation) and "development" in Tasks 5–8 (focusing on CW3E's West-WRF model and advanced prediction capabilities using machine learning [ML] and artificial intelligence [A.I.]). Many of these tasks were accomplished using a diverse set of observational, reanalysis, and forecast datasets and leveraged the period from late December 2022 through January 2023 that featured nine landfalling ARs in California (i.e., the "AR onslaught").

The eight tasks are as follows:

- **Task 1.** Build a catalog of landfalling ARs; identify storm-based precipitation characteristics driven by physical processes; evaluate quantitative precipitation forecast (QPF) skill as a function of storm characteristics.
- **Task 2.** Evaluate how well numerical weather prediction (NWP) models resolve mesoscale processes within ARs, such as representation of narrow cold frontal rainbands (NCFRs), the Sierra Barrier Jet (SBJ), and freezing level.
- **Task 3.** Investigate the impact of AR Reconnaissance (AR Recon) observations on QPF and other forecast metrics over the Yuba and Feather watersheds.
- **Task 4.** Prepare a report summarizing the lead time predictability of high-impact ARs affecting the Yuba and Feather watersheds.
- **Task 5.** Evaluate the reliability and skill of the Western Weather Research and Forecasting (West-WRF) ensemble for QPF over the Yuba and Feather watersheds.
- **Task 6.** Use ML techniques, trained on historical data, to improve the forecast skill of West-WRF forecasts.
- **Task 7.** Maintain and update existing tools/develop new tools leveraging West-WRF and its ensemble to better visualize Yuba-Feather QPF and mesoscale processes.
- **Task 8.** Explore and develop novel A.I./ML methods to improve AR, ridge, precipitation, and freezing level forecasts and aid in the improvement of AR forecast lead times.

5.2.3 Meteorological Highlights

Below, meteorological highlights are organized thematically by task or groups of tasks. In some cases, the subsections below refer to more information available elsewhere in Section 5 and/or in Appendix B.

5.2.3.1 Precipitation and AR Catalog

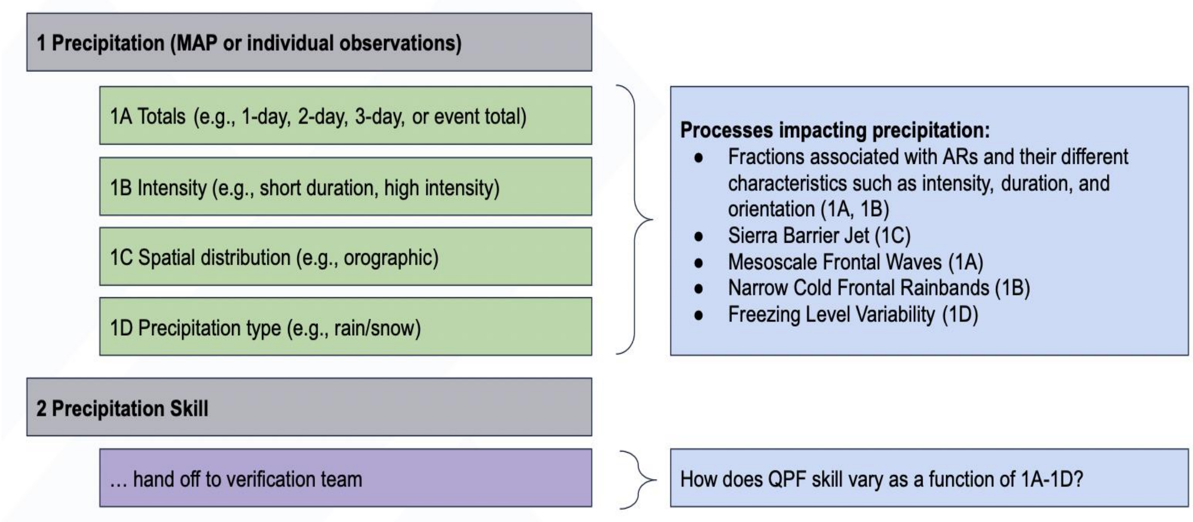


Figure 5-2*. Schematic of the approach to building a precipitation-based catalog to study the influence of ARs (and other features) on precipitation forecast skill.*

A 20-water-year (WY), 2003–2022 catalog of precipitation, AR characteristics, and forecast verification statistics over the Yuba and Feather River watersheds was developed to further the understanding of the mechanisms that lead to precipitation and their predictability (Figure 5-2). This catalog focused on two categories of events: three-day precipitation events and discrete (or event-total) precipitation events. Both categories used mean areal precipitation (MAP) from the Stage IV quantitative precipitation estimates (QPEs) within the eight-digit hydrologic unit code (HUC-8) boundaries of the Yuba River and aggregate HUC-8 boundaries of the Feather River, combining the North Fork (NFF), East Branch North Fork (EBNFF), and Middle Fork (MFF). Several meteorological and AR-related parameters were subsequently derived for each precipitation event from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5 (ERA5) reanalysis and observational datasets (e.g., IVT characteristics, AR scale, occurrence of an SBJ, freezing level).

In concert with the FVA verification efforts (Section 5.5), forecast information was combined with the event-based precipitation catalog to contextualize and identify systematic sources of error as a function of lead time and physical process (e.g., how does precipitation forecast error vary as a function of AR characteristics?). The forecast information included mean areal QPFs and IVT forecasts from CW3E's West-WRF reforecast dataset and the National Centers for Environmental Prediction's (NCEP's) Global Ensemble Forecast System (GEFS) model for lead times up to 48 hours. Several analyses, including the influence of landfall position error of ARs on QPF error, were examined using the Method for Object-based Diagnostic Evaluation (MODE) tool (see Section 5.5). More information on the AR and precipitation catalog can be found in Appendix B.1.

5.2.3.2 Evaluation of Physical and Mesoscale Processes

i. Heavy precipitation days in the upper Yuba are driven by ARs

Storm types or atmospheric patterns associated with the five days leading to heavy precipitation days in the upper Yuba (90th percentile; October–March, 1980–2022) were grouped into nine clusters using a method called self-organizing maps, or SOMs (Loikith et al. 2017; Aragon et al. 2020). All nine clusters produced AR-like features with narrow corridors of enhanced IVT directed at the upper Yuba; however, there is a considerable variability in evolution and range of IVT strength, orientation, and length of the IVT corridors. One prominent mode of variability illustrated within the SOM was whether the landfalling AR contained moisture of subtropical or extratropical origin. This study demonstrated that heavy precipitation days in the upper Yuba are driven by ARs and their IVT, but that different "flavors" of ARs are present from storm to storm and season to season. (Details are available in Appendix B, Section B.2.1.)

ii. Upslope water vapor flux along ARs drives variability in precipitation

Many studies have demonstrated that heavy precipitation in Northern California is often associated with landfalling ARs. Comparing the relationship between storm total MAP and projected time-integrated IVT at the mouth of the Yuba River watershed (i.e., rotated onto 225 degrees to produce upslope IVT) shows that time-integrated IVT explains 91 percent (r^2 = 0.912) of the variability in storm total MAP. In other words, there is a strong relationship between upslope water vapor flux and MAP over the upper Yuba watershed. (Details are available in Appendix B, Section B.2.2.)

iii. Precipitation generally increases with elevation in the upper Yuba

Upslope water vapor flux generally produces increasing precipitation with elevation in the upper Yuba. During WY2003–2022, the average total water year MAP in the lower and upper portions of the upper Yuba was 882 mm (34.7 inches) and 1552 mm (61.1 inches), respectively. Overall, about 29 percent of the total precipitation fell in the upper 25 percent of the upper Yuba, whereas only 16 percent of the total precipitation fell in the lower 25 percent of the upper Yuba. The relative contributions from the upper and lower portions of the upper Yuba to the total water year precipitation are anti-correlated (i.e., WYs with greater contribution from the lower portion of the upper Yuba are characterized by less contribution from the upper portion of the upper Yuba, and vice versa), with a correlation coefficient of −0.67. (Details are available in Appendix B, Section B.2.3.)

iv. Precipitation varies spatially across the Feather sub-basins

Climatologically, the NFF is the wettest sub-basin, followed by the MFF. The EBNFF is substantially drier, because it is located on the leeward side of the main crest of the Sierra Nevada, where rain shadowing is common. During WY2003–2022, the average total water year MAPs in the NFF, MFF, and EBNFF sub-basins were 1,162 mm (45.7 inches), 1056 mm (41.6 inches), and 714 mm (28.1 inches), respectively. Overall, 39 percent of the total precipitation fell in the NFF, 40 percent of the total precipitation fell in the MFF, and only 20 percent of the total precipitation fell in the EBNFF. Note that the relative contribution from the MFF is slightly higher than the relative contribution from the NFF because the MFF is larger in area. The relative contribution from the NFF to the total water year precipitation is anti-correlated ($r = -0.66$) with the relative contribution from both the MFF and the EBNFF to the total water year precipitation. These results suggest that certain storm characteristics determine whether the heaviest precipitation falls in the NFF or the MFF. (Details are available in Appendix B, Section B.2.4.)

v. The SBJ is responsible for a portion of Feather sub-basin precipitation variability

Previous research by Neiman et al. (2013) found that the SBJ, often present during a landfalling AR, can enhance precipitation amounts at the northern end of the Sacramento Valley and in the western portion of the Feather basin due to enhanced low-level southerly moisture transport. Here, we investigate the sensitivity of the spatial distribution of precipitation within the Yuba-Feather system to SBJs by comparing event precipitation at two stations, one at Four Trees in the NFF and one at Alleghany in the upper Yuba; both are susceptible to upslope flow from southwest-oriented water vapor transport, but Four Trees is more exposed to southerly water vapor transport along the SBJ. Compared to events without an SBJ, as event precipitation increases, the relative increase in precipitation at Four Trees is much larger than the relative increase in precipitation at Alleghany when both an AR and an SBJ are present. Interestingly, events with an SBJ but no AR do not exhibit the same behavior, which suggests that both an AR and an SBJ must be present to produce this precipitation effect. (Details are available in Appendix B, Section B.2.5.)

vi. Landfalling ARs are often accompanied by large snow-level rises

Because ARs are typically associated with the warm sector of an extratropical cyclone (Ralph et al. 2017), AR-related storms tend to involve higher snow levels than non-AR-related ones (Kim et al. 2013). Analysis of large (> 200-meter) snow-level changes from precipitating periods observed at Downieville (DLA), New Bullards Bar (NBB), and Oroville (ORO) confirm that the greatest snow-level changes (rises or falls) tend to be rises at all sites. With a focus on data from ORO, snow-level rises tend to coincide with periods of higher hourly IVT magnitudes and occur more often when IVT magnitudes are near 250 kg $m^{-1}s^{-1}$ and integrated water vapor (IWV) values are near 20 millimeters. Changes in snow level are often correlated with changes in the IVT and IWV: rising when IVT/IWV are increasing and falling when IVT/IWV are decreasing. (Details are available in Appendix B, Section B.2.6.)

vii. Maximum hourly precipitation rates are higher with landfalling ARs than with non-ARs

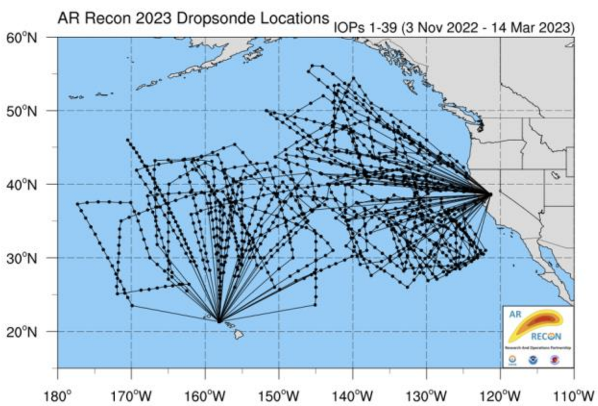
On average, the maximum observed hourly precipitation rates during precipitation events is almost double during AR-related precipitation vs. non-AR-related precipitation across all watersheds. Comparing non-AR events to AR events shows a 92 percent increase in the NFF, a 79 percent increase in the EBNFF, a 111 percent increase in the MFF, and a 93 percent increase in the upper Yuba, which averages out to 94 percent across the four watersheds. As AR intensity on the Ralph et al. (2019) AR scale increases from AR1–2 to AR3–5, the maximum hourly precipitation rates increase by about 50 percent across stations in each watershed. There is a 41 percent increase in the NFF, a 42 percent increase in the EBNFF, a 56 percent increase in the MFF, and a 40 percent increase in the upper Yuba, which averages out to 45 percent across the four watersheds. (Details are available in Appendix B, Section B.2.7.)

viii. Extreme hourly precipitation rates are not necessarily driven by NCFRs

An analysis of 49 extreme hourly precipitation events in the Yuba-Feather watersheds identified that about 10 (18 percent) were likely associated with NCFRs. While this fraction appears to assign a relatively low overlap between NCFRs and extreme hourly precipitation in the Yuba-Feather watersheds, the real headline is that extreme precipitation here does not necessarily require an NCFR—orographic enhancement and other processes play key roles in most events. What this study does not answer is how often extreme hourly precipitation occurs when an NCFR is present. Answering that question is beyond the scope of this study: it requires radar analysis of all precipitation events to determine how many NCFRs are not associated with extreme hourly precipitation. (Details are available in Appendix B, Section B.2.8.)

5.2.3.3 AR Recon

AR Recon activities over the North Pacific began on November 1, 2022, and continued for 21 weeks through March 31, 2023 (Figure 5-3). In January 2023, the Air Force's 53rd Weather Reconnaissance Squadron and the National Oceanic and Atmospheric Administration (NOAA) flew 13 consecutive days to sample a family of ARs affecting California (DeFlorio et al. 2023). In addition to other observations over the North Pacific (see Appendix B), radiosondes were launched throughout California, including at Marysville, California, in support of Forecast Informed Reservoir Operations (FIRO) activities in the Yuba and Feather River watersheds. All AR Recon dropsonde and radiosonde data were distributed for assimilation in real time into Global Forecast System (GFS), ECMWF, and Navy Global Environmental Model (NAVGEM) operational forecast models, among others.



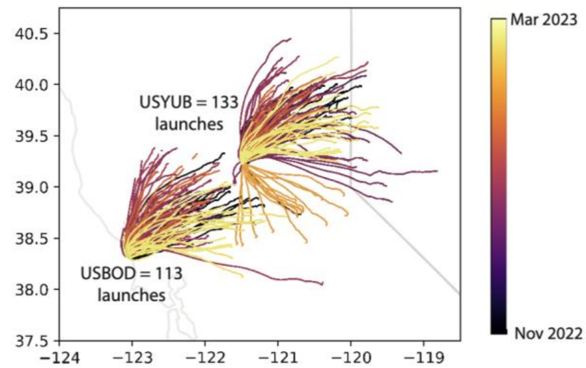


Figure 5-3. *Left: flight tracks and locations of all AR Recon 2023 dropsonde data over the North Pacific. Right: balloon tracks of all radiosondes over Northern California during WY2023.*

Assessing the impact of AR Recon observations on model precipitation forecasts has become a regular and important part of the program in collaboration with NCEP. Highlights relevant to northern and central California include the following:

- Observations from consecutive AR missions during January 6–18, 2023, systematically reduced California precipitation forecast errors in the GFS model by about 20–25 percent for thresholds over 1 inch.
- Case studies of individual precipitation events in central California demonstrate that observations from AR Recon can increase forecast lead time on the order of days in the GFS model as compared to forecasts without these observations.
- Observations from AR Recon improve ECMWF and GFS model forecasts of both IVT and precipitation at several FIRO watersheds, including the Yuba-Feather system (Figure 5-4) (DeHaan et al. 2023).
- More detail on AR Recon is provided in Appendix B.2.3.

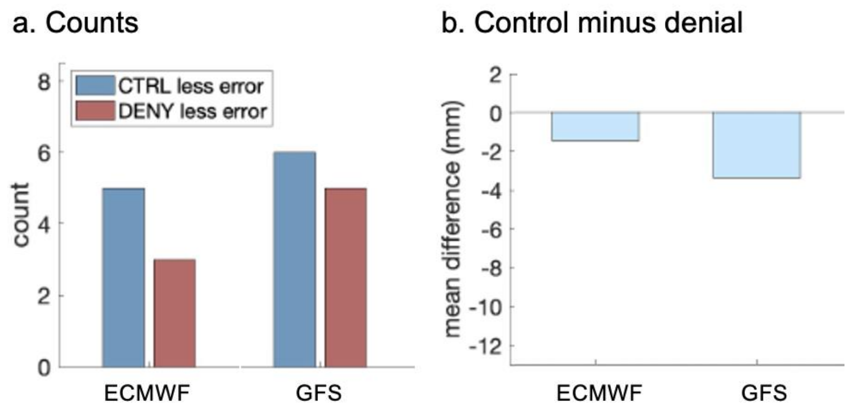


Figure 5-4. *(a) Counts of instances (valid days and lead times) where each of the control and denial forecasts had a smaller watershed intensity error magnitude for the Yuba-Feather system, and (b) the mean difference (control – denial) in the magnitude of the error for those instances. The counts are limited to cases where the difference between control and denial is greater than 1 mm/24 hours. Image adapted from DeHaan et al. (2023).*

5.2.3.4 Lead Time Prediction of Landfalling ARs

The lead time prediction of landfalling ARs in coastal California using an ensemble probability-over-threshold approach (i.e., the "AR landfall tool"; Cordeira and Ralph 2021) from the NCEP GFS ensemble model is illustrated in Section 5.5 for the landfalling ARs during the deep-dive period from December 2022 through January 2023. This section describes part of that methodology, as applied to all storms ranked AR2 or stronger for October 2016 through January 2023. The chosen analysis location is a coastal point at 37.5°N near San Francisco; the chosen metric is the event-average lead time at which the ensemble probability of IVT magnitudes over 250 kg $m^{-1}s^{-1}$ increased above 66 percent (i.e., 2:1 odds) and stayed above 66 percent for the entire period up to verification (Figure 5-5). On average, the GFS ensemble can predict landfalling ARs with 2:1 odds at a lead time of five days in the California Bay Area with a standard deviation of 1.6 days. Several of the better forecast events contained lead times over seven days (e.g., December 2022) and several of the worse forecast events contained lead times under three days (e.g., February 2019). More details are provided in Appendix B, Section B.2.4, and Section 5.5.

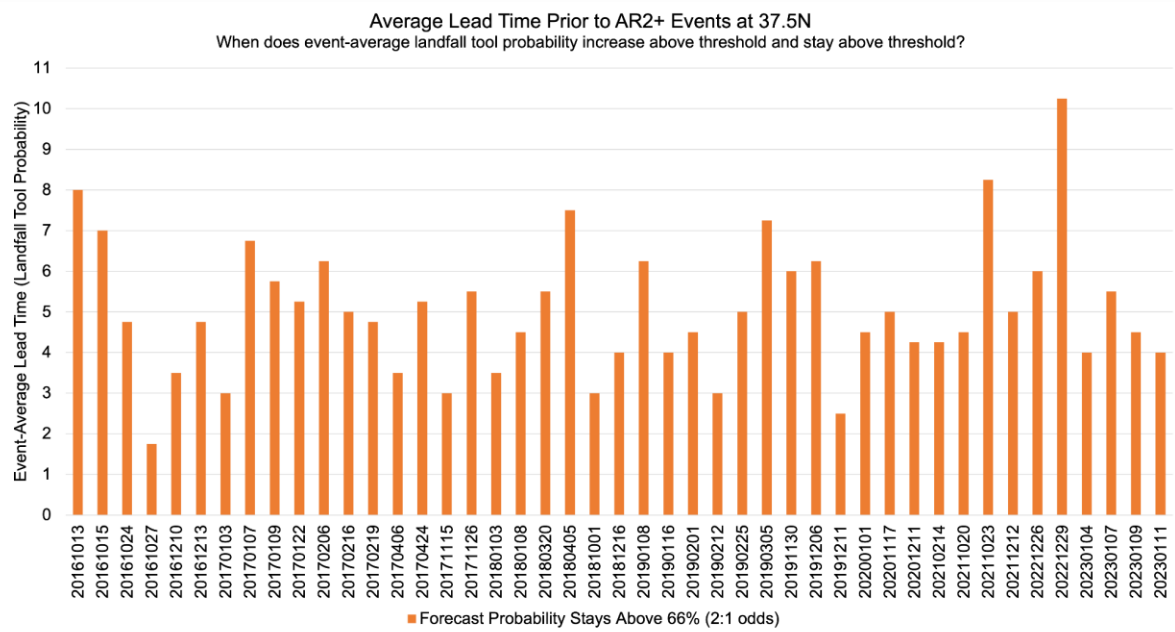


Figure 5-5. *Event-average lead time prediction of landfalling ARs ranked AR2+ near San Francisco for October 2016 through January 2023 from the GFS Ensemble model using a probability over threshold methodology set at 66 percent.*

5.2.3.5 West-WRF and Its Skill: ML and A.I.

NWP QPF and IVT forecasts provide crucial information to water managers for mitigating urban, riverine, and flash flood risks. These forecasts, however, are often contaminated by errors in initial conditions, numerical approximations, incomplete understanding of underlying physical processes, and the inherent chaotic nature of the atmosphere. Recent investigations have demonstrated that a significant portion of NWP model errors can be recovered in a post-processing framework leveraging recent advancements in A.I. and ML.

Advancements in using ML to improve prediction of precipitation and IVT for the Yuba and Feather River watersheds include a deep learning framework based on a convolutional neural network called "U-Net" has been developed for post-processing deterministic West-WRF predictions of precipitation and generating zero- to five-day probabilistic forecasts of daily accumulated precipitation. For the 2016–2017 winter period, the U-Net model (red line in Figure 5-6) closely follows the observed precipitation throughout the year and its prediction for the year-round total precipitation is more accurate than those in other baseline forecasts. The West-WRF model post-processed with deep learning (West-WRF + U-Net) has now been implemented operationally into CW3E's near real-time operational forecast system (Figure 5-6b).

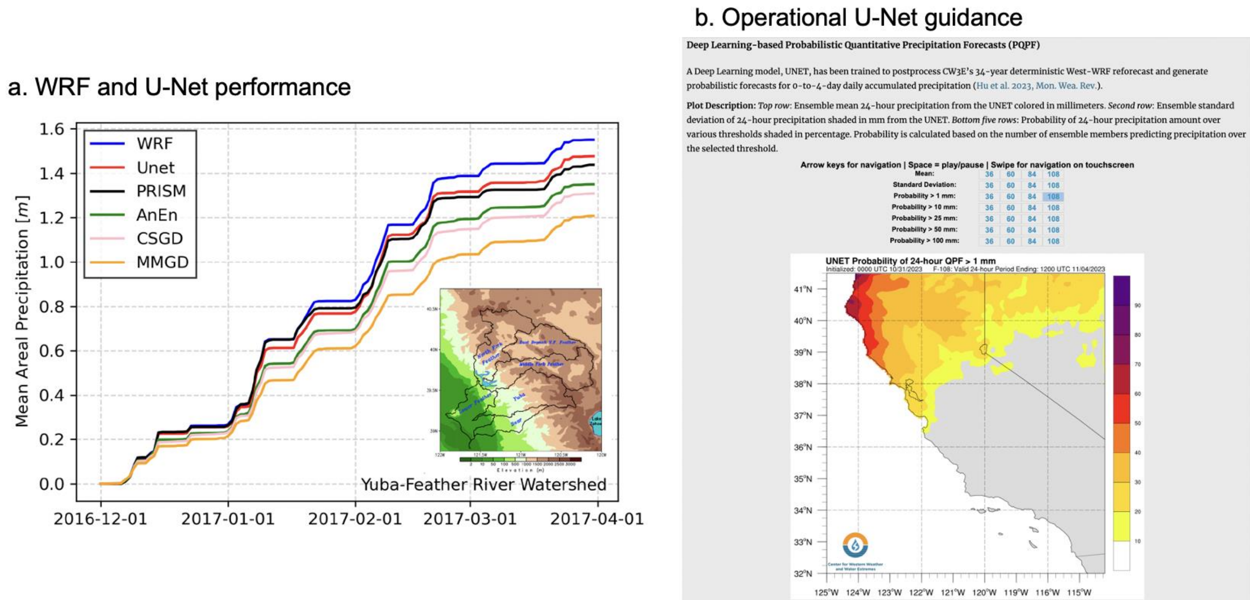


Figure 5-6. *(a) MAP over the Yuba-Feather watersheds in WY2017: proposed U-Net vs. West-WRF and other traditional post-processing methods. PRISM is used as the observational ground-truth dataset. (b) Associated near real-time forecast product generating probabilistic QPFs operationally throughout the water year via CW3E's near real-time operational system.*

A second advancement includes using deep learning to improve CW3E's West-WRF 200-member ensemble, run in support of decision making and scientific research of extreme weather events over the Western United States. The deep learning application involves using an artificial neural network (as in Ghazvinian et al. 2022) to generate post-processed, high-resolution, probabilistic precipitation forecasts for lead times up to seven days. The application of the deep learning technique is shown to improve the skill of the raw forecast and maintains the high precipitation event probabilities while reducing the locational biases. For the Yuba-Feather watersheds, the deep learning post-processed West-WRF forecast outperforms all other reference benchmarks, including the ECMWF and the raw West-WRF for the period of assessment (December 2021–March 2022), from a lead time of one to six days. Details on the forecast skill improvements are also documented in Section 5.5.5.

Additional advancements in the prediction of IVT and precipitation using artificial intelligence and ML are described in Appendix B. These include advancements in the deterministic prediction of IVT using convolutional neural networks (Chapman et al. 2019) and in the probabilistic prediction of IVT using deep learning techniques (Chapman et al. 2022). Details are provided in Appendix B, Section B.2.5.

5.2.3.6 West-WRF and Its Ensemble: Forecast Tool Development

CW3E maintained, updated, and provided near real-time decision support tools that leverage West-WRF and its ensemble, using them to visualize atmospheric processes, including ARs, and their resulting impacts on the Yuba and Feather River watersheds.

The watershed precipitation forecasting tool was updated to include additional reservoir catchments, additional models, optimized timing/availability, and updated visualizations. The tool now includes the ORO, NBB, and Englebright Reservoir catchment areas and forecasts from the GFS, ECMWF, NOAA Weather Prediction Center (WPC), National Blend of Models, GEFS, ECMWF Ensemble Prediction System (EPS), California Nevada River Forecast Center (CNRFC), and West-WRF (two deterministic versions and the 200-member ensemble). Updated visualizations include additional model-to-model comparisons for all the models.

Several key ensemble model IVT forecasts were upgraded to enhance the reliability and timing of these products, as well as expand all models (GEFS, ECMWF EPS, and West-WRF) to three transects along the U.S. West Coast, one which transects the Yuba and Feather River watersheds. Probabilistic and percentile-based forecast maps from the West-WRF ensemble are generated to provide more insight into forecasted quantities of precipitation, snowfall, winds, and temperature over the U.S. West Coast. Point-based forecast tools are also generated to add details and insight to forecasts from individual ensemble members within the West-WRF.

Forecast diagnostics were developed to provide insight into the potential likelihood for narrow cold frontal rainbands and synoptic-scale forcing for rising motion that can cause short-duration/high-intensity precipitation and large-scale precipitation, respectively, that is not necessarily tied to orographic features, and upstream events that may introduce forecast uncertainty downstream. Details can be found in Appendix B, Section B.6.

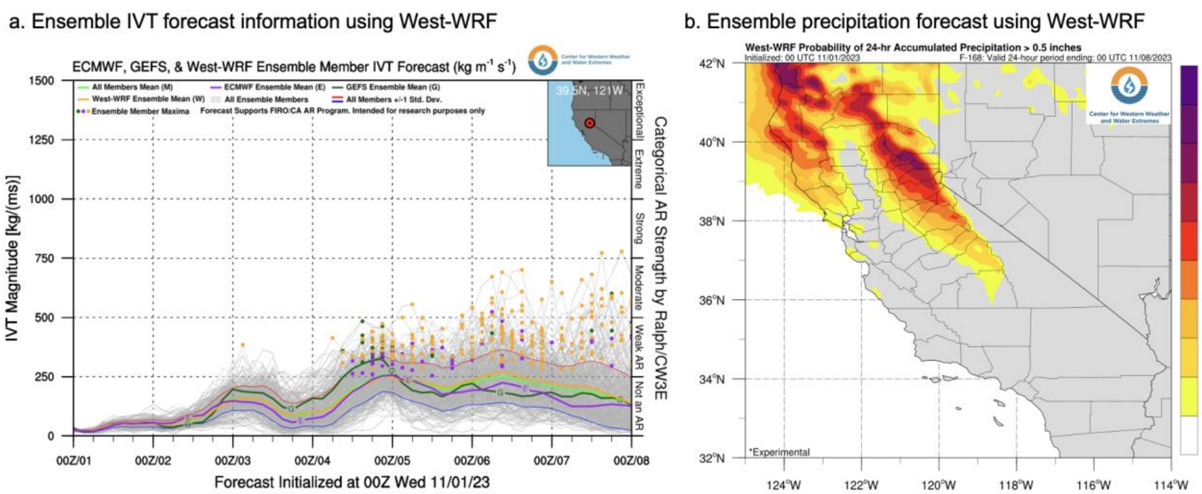


Figure 5-7. *(a) Seven-day forecast of IVT (kg $m^{-1}s^{-1}$) from the GEFS, ECMWF EPS, and West-WRF ensemble from each ensemble member (thin gray lines), the ensemble means (dark green for GEFS, purple for ECMWF EPS, orange for West-WRF, and light green for all members), and plus or minus one standard deviation from the ensemble mean (red and blue lines and gray shading) at 39.5°N, 121°W. (b) Probability of 24-hour precipitation above 0.5 inches from the West-WRF ensemble. Probability is calculated from the number of ensemble members predicting precipitation above 0.5 inches at each grid point.*

Meteorological Highlights: Summary

- Heavy precipitation days in the upper Yuba are driven by ARs.
- Upslope water vapor flux along ARs drives variability in precipitation.
- Precipitation generally increases in elevation in the upper Yuba.
- Precipitation varies spatially across the Feather sub-basins.
- The SBJ is responsible for a portion of the Feather sub-basin precipitation variability.
- Landfalling ARs are often accompanied by large snow-level rises.
- Maximum hourly precipitation rates are higher with landfalling ARs than with no-AR storms.
- Extreme hourly precipitation rates are not necessarily driven by NCFRs.
- AR Recon improves forecasts of precipitation over the Yuba-Feather basin.
- Landfalling ARs are predicted using ensemble methods with leads times of about five to seven days.
- ML and A.I. methods applied to CW3E's West-WRF model improve precipitation forecast skill.

5.2.4 Recommendations

- Continue AR Recon field campaigns yearly, including assessing AR Recon's impact on forecast skill over the Yuba-Feather basin.
- Leverage AR Recon and field observations to evaluate model forecasts of mesoscale processes during landfalling ARs with a focus on the vertical profiles of water vapor flux, freezing levels, orographic precipitation gradients, the SBJ, and NCFRs.
- Further evaluate forecast skill improvements of precipitation and freezing level over the Yuba-Feather basin afforded by advanced technologies including ML, A.I., and West-WRF.

5.2.5 References

Aragon, C. M., Loikith, P. C., McCullar, N., & Mandilag, A. (2020). Connecting local-scale heavy precipitation to large-scale meteorological patterns over Portland, Oregon. *International Journal of Climatology*, *40*(11), 4763–4780. https://doi.org/10.1002/joc.6487

Chapman, W. E., Subramanian, A. C., Delle Monache, L., Xie, S. P., & Ralph, F. M. (2019). Improving atmospheric river forecasts with machine learning. *Geophysical Research Letters*, *46*(17–18), 10627–10635. https://doi.org/10.1029/2019GL083662

Chapman, W. E., Delle Monache, L., Alessandrini, S., Subramanian, A. C., Ralph, F. M., Xie, S.-P., Lerch, S., & Hayatbini, N. (2022). Probabilistic predictions from deterministic atmospheric river forecasts with deep learning. *Monthly Weather Review*, *150*(1), 215–234. https://doi.org/10.1175/MWR-D-21-0106.1

Cordeira, J. M., & Ralph, F. M. (2021). A summary of GFS ensemble integrated water vapor transport forecasts and skill along the U.S. West Coast during water years 2017–20. *Weather and Forecasting*, *36*(2), 361–377. https://doi.org/10.1175/WAF-D-20-0121.1

DeFlorio, M. J., Sengupta, A., Castellano, C. M., Wang, J., Zhang, Z., Gershunov, A., Guirguis, K., Luna Niño, R., Clemesha, R. E. S., Pan, M., Xiao, M., Kawzenuk, B., Gibson, P. B., Scheftic, W., Broxton, P. D., Switanek, M. B., Yuan, J., Dettinger, M. D., Hecht, C. W., … Anderson, M. L. (2024). From California's extreme drought to major flooding: Evaluating and synthesizing experimental seasonal and subseasonal forecasts of landfalling atmospheric rivers and extreme precipitation during winter 2022/23. *Bulletin of the American Meteorological Society*, *105*(1), E84–E104. https://doi.org/10.1175/BAMS-D-22-0208.1

DeHaan, L. L., Wilson, A. M., Kawzenuk, B., Zheng, M., Monache, L. D., Wu, X., Lavers, D. A., Ingleby, B., Tallapragada, V., Pappenberger, F., & Ralph, F. M. (2023). Impacts of dropsonde observations on forecasts of atmospheric rivers and associated precipitation in the NCEP GFS and ECMWF IFS models. *Weather and Forecasting*, *38*(12), 2397–2413. https://doi.org/10.1175/WAF-D-23-0025.1

Ghazvinian, M., Zhang, Y., Hamill, T. M., Seo, D.-J., & Fernando, N. (2022). Improving probabilistic quantitative precipitation forecasts using short training data through artificial neural networks. *Journal of Hydrometeorology*, *23*(9), 1365–1382. https://doi.org/10.1175/JHM-D-22-0021.1

Hu, W., Ghazvinian, M., Chapman, W. E., Sengupta, A., Ralph, F. M., & Delle Monache, L. (2023). Deep learning forecast uncertainty for precipitation over the western United States. *Monthly Weather Review*, *151*(6), 1367–1385. https://doi.org/10.1175/MWR-D-22-0268.1

Kim, J., Waliser, D. E., Neiman, P. J., Guan, B., Ryoo, J.-M., & Wick, G. A. (2013). Effects of atmospheric river landfalls on the cold season precipitation in California. *Climate Dynamics*, *40*(1–2), 465–474. https://doi.org/10.1007/s00382-012-1322-3

Loikith, P. C., Lintner, B. R., & Sweeney, A. (2017). Characterizing large-scale meteorological patterns and associated temperature and precipitation extremes over the northwestern United States using self-organizing maps. *Journal of Climate*, *30*(8), 2829–2847. https://doi.org/10.1175/JCLI-D-16-0670.1

Neiman, P. J., Hughes, M., Moore, B. J., Ralph, F. M., & Sukovich, E. M. (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*(12), 4211–4233. https://doi.org/10.1175/MWR-D-13-00112.1

Ralph, F. M., Iacobellis, S. F., Neiman, P. J., Cordeira, J. M., Spackman, J. R., Waliser, D. E., Wick, G. A., White, A. B., & Fairall, C. (2017). Dropsonde observations of total integrated water vapor transport within North Pacific atmospheric rivers. *Journal of Hydrometeorology*, *18*(9), 2577–2596. https://doi.org/10.1175/JHM-D-17-0036.1

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*(2), 269–289. https://doi.org/10.1175/BAMS-D-18-0023.1

5.3 Hydrology

The FVA hydrology work generated (1) ensemble hindcasts, including scaled events, and (2) flow frequency estimates. Both provide the baseline data for assessing FIRO viability. These products are needed to understand forecast uncertainties, to develop and test reservoir operation strategies, and to assess the achievement of water management goals like flood protection and water supply. The FIRO Hydrology subgroup adopted and provided feedback on flow frequency curves developed by the U.S. Army Corps of Engineers (USACE) specifically for the Water Control Manual (WCM) updates. Based on those statistics, the CNRFC used a suite of state-of-the-art programs to compute current and future streamflows at a series of flow points in the Yuba River and Feather River watersheds.

Accomplishments

- Provided ensemble streamflow hindcasts spanning 1990–2019 (and January–March 1986) and scaled events based on GEFSv12.
- Collaborated on the flow frequency analysis being conducted concurrently by USACE as part of the WCM updates for Oroville Dam and New Bullards Bar Dam.
- Provided scaled historical streamflow simulations for evaluation by the water resources engineering team.
- Coordinated on deterministic and probabilistic forecast verification of inflows at New Bullards Bar and Oroville within the verification task.

5.3.1 Streamflow Forecasting

Streamflow forecasts for reservoir inflows and the local contributing areas to key control points downstream were provided by the CNRFC. In operations, the CNRFC provides both a deterministic five-day forecast and an ensemble-based 30-day probabilistic forecast.

5.3.1.1 Deterministic Streamflow Forecasts

Figure 5-8 shows the CNRFC's deterministic forecast process.

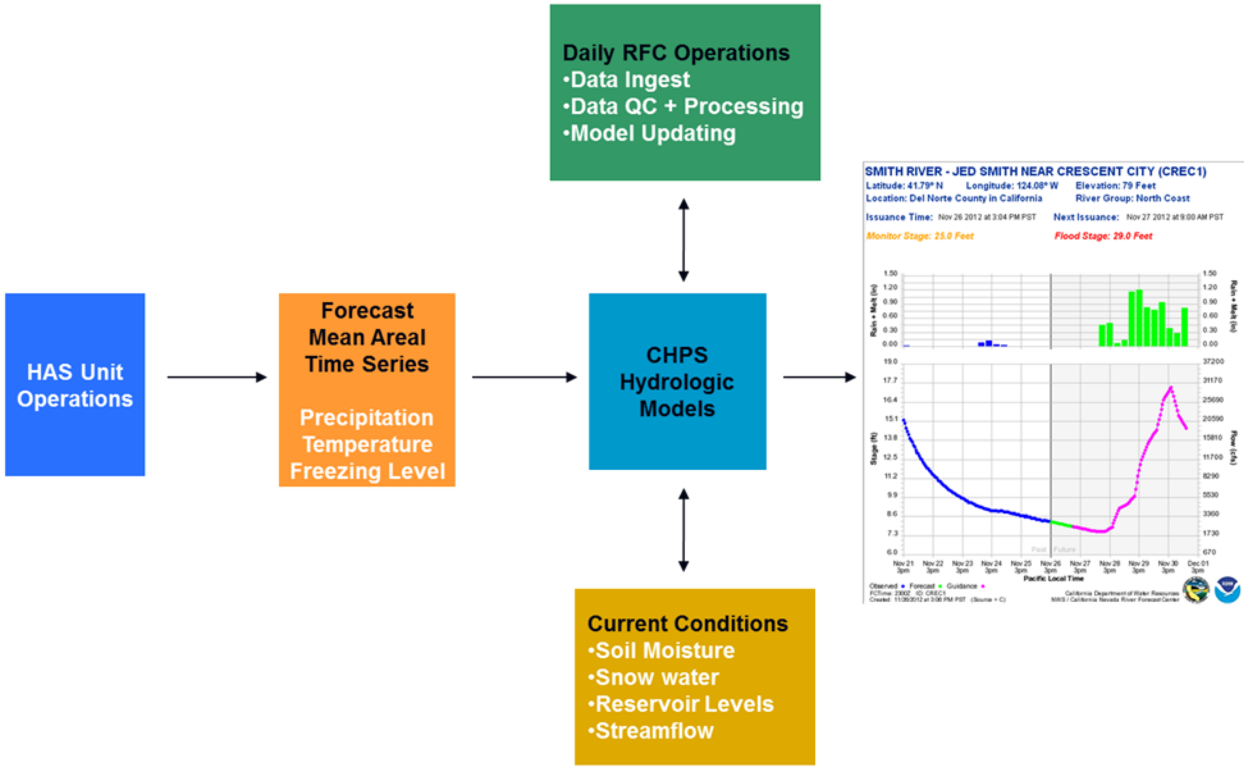


Figure 5-8. *Generalized forecast process used by the CNRFC to generate five-day deterministic streamflow forecasts.*

The CNRFC model topology for simulating and forecasting the Feather River, Yuba River, and Bear River watersheds is shown in Figure 5-9.

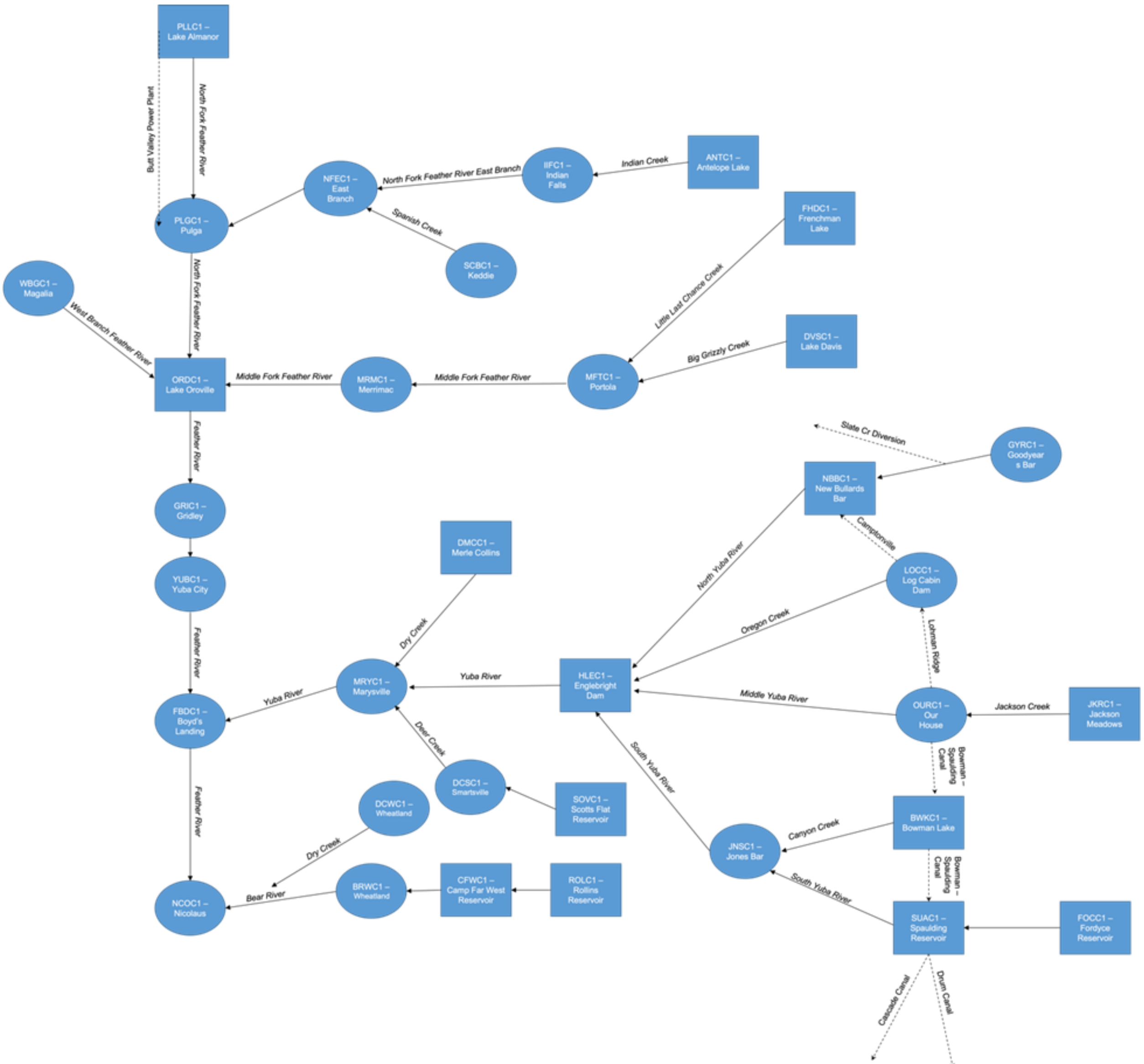


Figure 5-9. *CNRFC Community Hydrologic Prediction System (CHPS) model topology for the Yuba-Feather System.*

5.3.1.2 Ensemble Streamflow Forecasts

Ensemble streamflow forecasts are generated using the same models and model states as the deterministic process but instead create a set of equally likely streamflow outcomes that attempts to represent the uncertainty of flows in the future. The National Weather Service's (NWS's) Hydrologic Ensemble Forecasting System (HEFS), described in Figure 5-10, is used to create the ensemble streamflow forecasts.

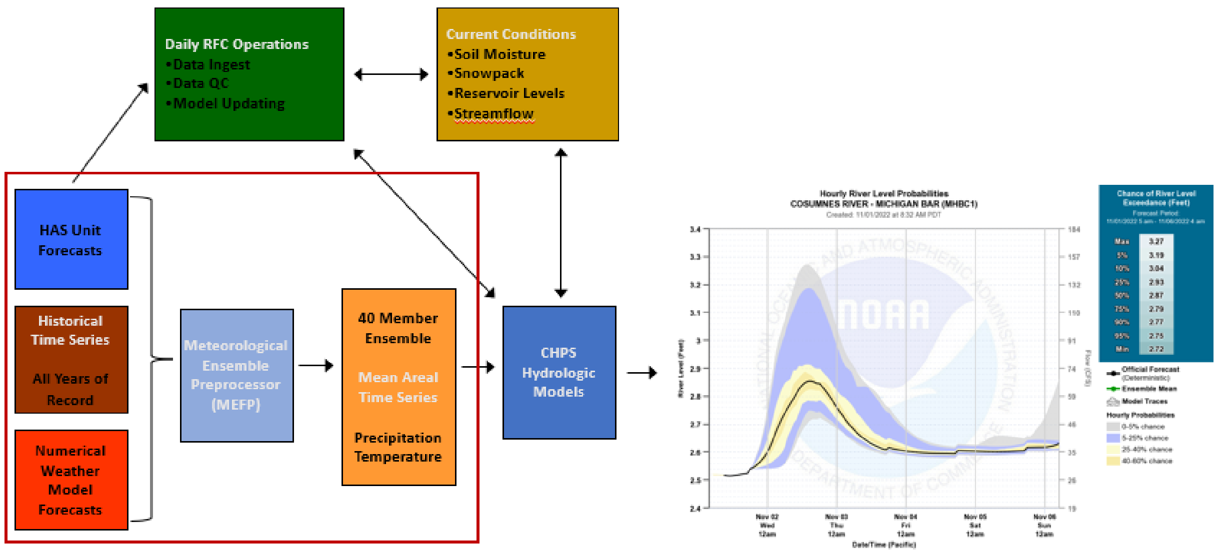


Figure 5-10. *CNRFC operational ensemble streamflow forecast generation process (HEFS).*

HEFS generates hydrologic forecasts that provide information about forecast uncertainty. It achieves this by issuing an ensemble of possible values of the forecast variables (precipitation and temperature). Unlike a single-valued or "deterministic" forecast—which comprise a single estimate of the forecast variable at each time and location—an ensemble forecast provides a set of possible values. HEFS translates an ensemble of meteorological inputs through hydrologic models to provide an ensemble of outputs (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 previously are physically based, and the meteorological forecast uncertainties are produced through statistical modeling. Meteorological ensembles are generated using a statistical model called the Meteorological Ensemble Forecast Processor (MEFP), which relies on historical observations to identify forecast errors. This requires statistical modeling of the relationship between 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 for MEFP used at the CNRFC are the River Forecast Center (RFC) precipitation forecasts and the mean GEFSv12 temperature and precipitation forecasts.

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 reforecast datasets (precipitation and temperature) and the corresponding observations. For the FVA, the MEFP parameters were based on the 2000–2019 GEFSv12 reforecast datasets (precipitation and temperature). 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 MEFP are fed as inputs through the physically-based hydrologic models one ensemble pair at a time. Figure 5-11 shows the overall flow of HEFS from parameter estimation to the final streamflow ensemble output.

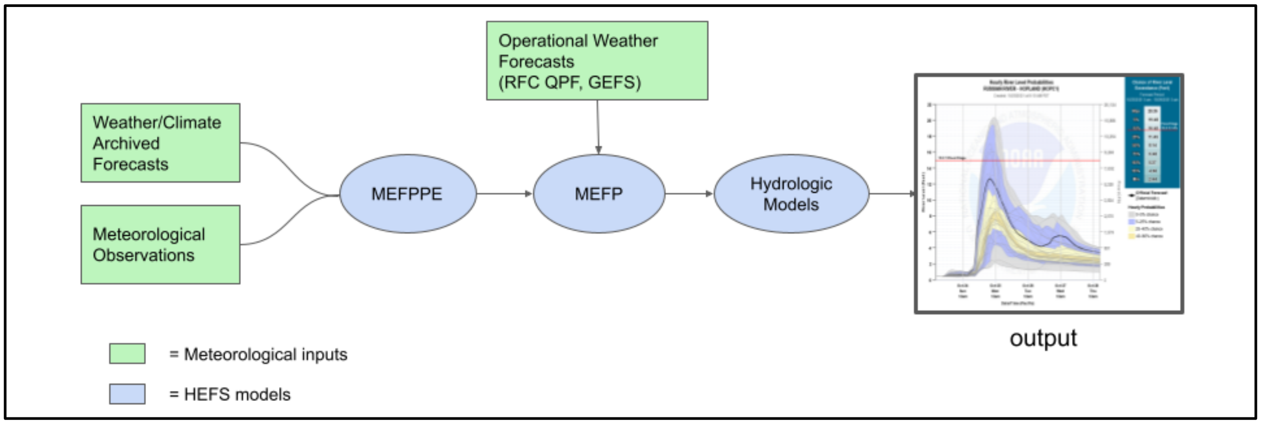


Figure 5-11. *The HEFS process.*

5.3.2 Ensemble Streamflow Hindcasts

Unscaled ensemble streamflow hindcasts were generated by the CNRFC for the Yuba-Feather system in 2022. These ensembles were produced using HEFS and used as the basis for the Yuba-Feather PVA assessment of FIRO WCP alternatives.

5.3.2.1 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 Appendix C for details). The inputs to 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. (GEFSv10 is no longer run by NCEP, so GEFSv12 is used for current operations. An assessment of forecast skill for the two versions of the model suggests they are essentially the same.)

The hindcast process follows the general flow of operational HEFS forecasting single source meteorological forecasts are fed to 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 result is a set of equally likely streamflow ensemble forecasts reflective of the watershed conditions at that time. For the Yuba-Feather hindcasts, the GEFSv12 was used as the single source for both temperature and precipitation. The RFC precipitation forecasts were not used due to limited record length. The GEFSv12 hindcast dataset (also used in MEFPPE) covers the 1990–2019 period. However, the quality of the GEFSv12 reforecasts is somewhat different because the 1990–1999 period reforecasts were initialized by the Climate Forecast System V2 (CFSV2), but the 2000–2019 GEFSv12 reforecasts were initiated by the higher-quality Finite-Volume Cubed-Sphere Dynamical Core (FV3) GFS. Naturally, this is also the period that covers the Yuba-Feather HEFS hindcast effort. Only the higher-quality GEFSv12 reforecasts were used for MEFP parameterization (mentioned above), but the HEFS hindcast effort associated with the FVA spanned the entire 1990–2019 period and the January–March 1986 period. The HEFS hindcast covered the full range of GEFSv12 reforecasts because a lot of the large/extreme events occurred before 2000 (when the higher-quality GEFSv12 reforecasts started).

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 every day during the historical model simulation. For the Yuba-Feather hindcasts, the modeling period was 1983–2019: the historical simulation period starts earlier than the actual hindcast period 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, January 1986, GEFSv12 mean hindcast precipitation and temperatures are processed through MEFP, resulting in forcing ensembles for that day. The hydrology models are initiated using the appropriate antecedent conditions; then the MEFP ensembles are processed through the hydrology models, resulting in streamflow ensemble hindcasts for that day. This process is followed one day at a time until the end of the hindcast period (December 2019). The process yields a large collection of ensemble streamflow forecasts using consistent meteorological inputs and hydrology models spanning nearly 30 years. The HEFS streamflow hindcasts are not continuous from January 1986 through December 2019 because the GEFSv12 reforecasts only covered January–March 1986 and the continuous 1990–2019 period.

5.3.2.2 Scaled Events

To evaluate the performance of reservoir management alternative strategies for extreme events, set of ensemble streamflow hindcasts greater than what has been observed in the historical record is 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 was done for every scaling increment and every historical event selected for scaling. The GEFSv12 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, which when processed through the hydrology models resulted in scaled ensemble streamflow hindcasts.

The two largest historical events in the hindcast period, (1) February 1986 and (2) December 1996–January 1997, were chosen as the basis for the winter 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 C. The FVA also analyzed two spring flooding scenarios, March 1995 and May 1995. The scaling methodology used for the winter events also applied to the spring events.

5.3.3 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, which result mainly from precipitation events. The determination of these flood frequencies at various index locations provides the basic information for scaling hindcasts and the assessment of candidate reservoir operation sets.

Unregulated flow frequency estimates were generated for the following locations:

- Feather River at ORO Dam.
- Feather River above Yuba City.
- Feather River at Yuba River confluence.
- Feather River at Bear River confluence.
- North Yuba River at NBB Dam.
- Yuba River above Marysville.

Final frequency curve information was provided by USACE during the FVA for comment and use in the hindcast scaling process described in Section 5.3.3. Similarly, preliminary statistical estimates of maximum duration flows during the spring refill months (March, April, and May) were adopted. The month-based frequency curves were used to scale the events of March and May 1995 to a magnitude that approximates the decrease in flood threat that is assumed during the transition to the dry summer period in the Central Valley.

5.3.4 Conclusions and Recommendations

The Yuba-Feather FVA used the latest GEFS reforecast information (v12) along with the most current CNRFC hydrology models. This information should also be used during further alternative analysis within the NBB and ORO WCM update process. Currently, there are several efforts going on within the HEFS research community that are attempting to improve the forecast quality associated with extreme events (systematic low bias). The Office of Water Prediction is actively bringing new methods into the MEFP software that should be operationalized into a new release (HEFSv2) within a year. Parallel efforts funded by the Cooperative Institute for Research to Operations in Hydrology are also attempting to address this problem. Depending on the timelines of these research efforts, the WCM update studies should attempt to leverage MEFP/HEFS software improvements in the form of updated streamflow hindcasts as well as possible without compromising the WCM update schedule.

There is also ongoing research spearheaded by Cornell University (Brodeur and Steinschneider) related to synthetic ensemble forecasting. These methods could provide additional ensemble hindcasts outside the GEFSv12 reforecast window (1990–2019). They could also provide many different plausible scenarios of extreme events within and outside the GEFSv12 reforecast window (i.e., 1997, 1986, 1955, etc.). This additional information could assist with robustness testing of alternative operational plans.

Recommendations

- Encourage and leverage improvements in HEFS related to MEFP, ensemble post-processing, and the explicit ensemble modeling of forecast freezing level.
- Sharpen the process for developing scaled historical hindcast events.
- Leverage efforts in synthetic ensemble forecast generation to create more robust testing datasets for WCP evaluations.

5.4 Observations

5.4.1 Introduction

The assessment of FIRO viability in the Yuba River and Feather River watersheds included enhancements and expansions to the existing observational network. These improvements were focused on bolstering real-time monitoring capabilities, aligning with FIRO objectives, and addressing pertinent research questions. Additions to the observational network were informed by the network evaluation conducted as part of the Yuba-Feather FIRO PVA and were developed in close collaboration with project partners and coordination across FIRO technical teams. The monitoring network is integral to atmospheric and hydrologic models: it improves our process-based understanding and improves model initial conditions. The monitoring network and additions made through FIRO are essential to the validation of models and forecasts, offer valuable situational awareness by monitoring antecedent watershed conditions, and facilitate the evaluation of watershed responses to precipitation events. In support of the FVA objectives, this section summarizes the work of the observation team including concluding the first monitoring network evaluation with a survey of operators in the region, summarizing additions made to the monitoring network, evaluating missing high-elevation precipitation data, leveraging new observations for assessing freezing level, and developing QPE products.

Accomplishments

- Currently collecting and disseminating near real-time hydroclimatic observations on multiple public platforms.
- Added 12 stations to existing monitoring network over the course of the PVA and FVA, with another three stations planned for 2024.
- Filled identified gaps in soil moisture data and observations that support freezing level identification.
- Now carrying out a radiosonde launch campaign at Marysville, California.
- Leveraged CW3E observations to evaluate freezing level forecasts.
- Developed CW3E QPE tools and implemented machine learning methods to improve gridded precipitation products.

5.4.2 Methods and Analysis

5.4.2.1 Network Survey and Evaluation

The PVA provided the initial evaluation of the monitoring network, which summarized the distribution of observations of interest, summarized the representation of landscape characteristics by the monitoring network, and highlighted spatial and temporal gaps in data. The FVA concludes the first network evaluation with a survey of network operators about data quality and reliability as well as notes on data availability and additional metadata.

The network survey covered known station operators in the watersheds and was distributed as a Google Form for operators to fill out. There have been some delays in responses due to the increased strain on operations from winter 2023, and staff will continue to collate information from operators as responses are received. (Appendix D, Section D.1, summarizes agencies surveyed and responses received so far.)

The survey focused on the data reliability and dissemination for surface meteorological stations, particularly those that measure precipitation, soil moisture, or snow. Streamflow was not its focus, as streamflow observations were evaluated as part of the Forecast-Coordinated Operations (F-CO) program.

Key outcomes from the survey responses thus far include:

- Many respondents already have most of their networks' stations available on the California Data Exchange Center (CDEC) or another online platform.
- Stations not available online included canal sites, and streamflow and groundwater for a couple of different agencies.
- Partners suggested more interactive observation plots for the CW3E website.
- Some agencies quality-control their data but most data on CDEC are raw data.

The next monitoring network evaluation will be conducted as a post-FVA activity and will focus on summarizing gaps filled by CW3E and partners during and after the initial FIRO process. Streamflow will also be considered in future network evaluations as we move toward FIRO implementation.

5.4.2.2 Updates to the CW3E Monitoring Network

Leading up to the PVA, CW3E added 10 stations to the observation network and a radiosonde launch site. Two additional stations were installed during the FVA (see Appendix D, Section D.2, for station metadata). The new and planned stations' locations (highlighted in Appendix D, Figure D-2) were informed by findings from the PVA. Since the PVA, where installations were more frequent in the Yuba, the focus has been to address gaps in soil moisture and precipitation data identified in the Feather River watershed. Stations planned by partner agencies are also detailed in Appendix D, Section D.2.

FIRO station types include streamflow measurements, surface meteorology with soil moisture (SMOIL), surface meteorology with Micro Rain Radar (snow level), disdrometers (precipitation phase), and GPS (measuring IWV) (Rad Met hereafter). Additionally, a disdrometer was installed at FIRO's highest elevation site in the Yuba watershed (Lower Bath House [LBH], at 5,512 feet) to target phase changes within storm events to help identify the rain–snow transition as called for in the work plan. (That station is hereafter referred to as Disdro Met.) All SMOILs and Rad Mets have precipitation measurements, and three stations have all-weather precipitation via heated tipping buckets. All seven SMOIL stations have soil moisture and temperature sensors at six depths, up to 1 meter deep or as deep bedrock (see Appendix D.2, Table D-2, for details). Most SMOIL and Rad Met sites are telemetered in near real time and are available on CDEC, and telemetry installation is planned for all remaining sites. More information on the radiosonde sampling from the Marysville launch location is provided in Appendix D, Section D.3, and in Section 5.2.

CW3E stations that are telemetered and online in near real time are available for inclusion in forecasting and modeling products via The Hydrometeorological Automated Data System (HADS) and the Meteorological Assimilation Data Ingest System (MADIS). NWS RFCs across the United States produce a gridded QPE as part of their hydrologic operations across their individual areas of responsibility. This precipitation product is constructed using a multi-sensor approach that incorporates radar, gauge, and satellite estimates of precipitation, manually QC'ed by RFC hydrologists. The CNRFC tracks when individual gauges are excluded from the QPE analysis, providing information on the scenarios in which gauges, including CW3E-maintained gauges, tend to provide erroneous precipitation estimates. Post-FVA, CW3E plans to further investigate the scenarios in which its gauges are dropped from the QPE product and plan for ways to mitigate those instances.

5.4.2.3 High-Elevation Precipitation

Both the Yuba and Feather watersheds have extensive snow observational capacities (Table 5-1 shows all stations that measure snow water equivalent [SWE]; more information is available in Appendix D, Section D.4), but quantifying precipitation of all phases is challenging at high elevations. The PVA identified the highest precipitation forecast errors along the Sierra Nevada crest. Observations of SWE, snow depth, and precipitation accumulation are necessary to get a comprehensive representation of high-elevation precipitation. Rain gauges are known to perform especially poorly during frozen precipitation because of wind-induced under-catch (Sevruk 1982), and better quantifying the gauges available above the rain–snow transition and their performance in winter events supports efforts to improve gridded precipitation products.

To ensure all precipitation gauges in the region (available on CDEC) were included and gauge types correctly reported, a survey was sent to operators (60 percent of whom responded). Lower elevations and lower precipitation areas have mostly tipping buckets which cannot accommodate frozen precipitation unless heated. The identified weighing rain gauges, which perform well in freezing conditions, are distributed in the higher elevations of the watersheds and the areas of high precipitation climatologically (Figure 5-12).

Gauges were classified as "high-elevation" by, and evaluated at and above, a cutoff of 1,400 meters—approximately the lower end of the climatological rain–snow transition (Cui et al. 2020). This subset of gauges was evaluated for missing data during AR events, and missing data were summarized by individual sites and by gauge type: tipping buckets, heated tipping buckets, weighing gauges, and unidentified gauge types. Gauges were evaluated over the last five water years based on the stations with the shortest periods of record. This analysis did not discern whether data were missing in real time and then backfilled. Nine out of the 14 snow stations have co-located precipitation measurements, which offer a more comprehensive representation of precipitation of all phases. Missing data during AR events during the last five water years were also summarized for these stations (Table 5-1). Missing data during AR events over the last five water years had no correlation with the elevation of the snow stations. Stations often had similar amounts of missing data for SWE and precipitation, which might indicate power or transmission issues rather than individual sensor measurement errors. Tipping buckets and unidentified gauge types are often located in the lower end of the elevation range, thus encountering less frozen precipitation and fewer adverse conditions for measuring data (i.e., high winds, station power issues). These conditions make it difficult to draw direct comparisons between gauge types and performance. Whether gauges use Alter shields was not summarized in this report but has implications for data quality—especially for freezing conditions, in which they can reduce effects of wind-induced under-catch (Sevruk 1982).

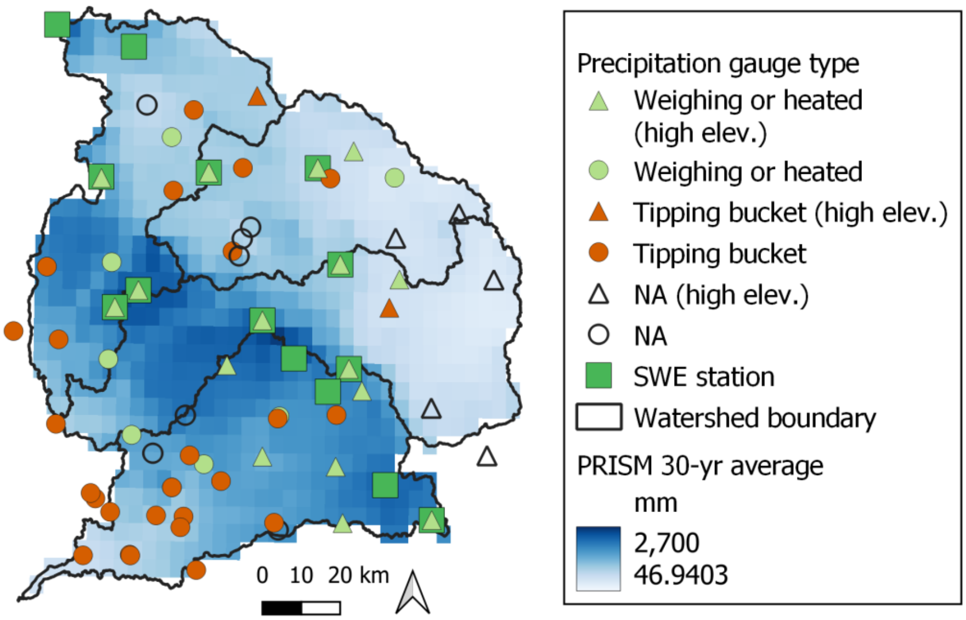


Figure 5-12. *All precipitation gauges available on CDEC. With gauge types where available (green = weighing gauge or heated gauge, orange = unheated tipping bucket, hollow = unknown). Gauges used in high-elevation precipitation analysis are marked as triangles. Stations with SWE measurements are marked with green squares.*

Table 5-1. *Percent of data missing during AR events for the last five water years for precipitation and SWE at stations that measure SWE. Some stations do not have precipitation gauges and are noted as "NA" for sites that have some precipitation data but had issues when processing.*

Station ID	Station Name	Watershed	Elevation (ft)	Missing SWE Data (%)	Missing Precipitation Data (%)
FOR	Four Trees	Feather	5.200	5.16	19.1
BKL	Bucks Lake	Feather	5.873	0.299	0.281
HRK	Harkness Flat	Feather	6.201	4.90	*NA*
RTL	Rattlesnake	Feather	6.211	0.0953	0.0774
SSM	Sunnyside Meadow	Yuba	6.300	28.5	*NA*
RCC	Robinson Cow Camp	Yuba	6.480	12.5	*NA*
HMB	Humbug	Feather	6.500	8.80	*NA*
GOL	Gold Lake	Feather	6.749	0.0626	0.0446
PLP	Pilot Peak	Feather	6.802	5.29	5.29
GRZ	Grizzly Ridge	Feather	6.900	0.511	0.511
CSL	Central Sierra Snow Lab	Yuba	6.900	9.33	8.39

Station ID	Station Name	Watershed	Elevation (ft)	Missing SWE Data (%)	Missing Precipitation Data (%)
MDW	Meadow Lake	Yuba	7.202	26.2	*NA*
KTL	Kettle Rock	Feather	7.300	5.40	5.40
LLP	Lower Lassen Peak	Feather	8.337	22.2	*NA*

5.4.2.4 Freezing Level Verification

The rain–snow transition at the surface can be difficult to quantify from freezing level forecasts and observations available at the surface. Broadly available measurements of temperature, relative humidity, precipitation, and snow depth can help identify changes in precipitation phase over the landscape but are limited as indirect measurements of precipitation phase. Disdrometers offer significant value to a monitoring network by providing real-time data on precipitation phase from measurements of fall velocity and drop size distribution of hydrometeors. This information can be leveraged to help validate freezing level forecasts and nearby observations of rain and snow (see the map of rain and snow observations in Appendix D, Figure D-4). A transect of three disdrometers was deployed in the Yuba River watershed at elevations of 2,075 to 5,530 feet in support of FIRO objectives. These locations fill in elevation gaps in the known range of freezing level observations in the Yuba River watershed (inverted triangles in Figure 5-13) where the existing snow pillows only covered a small portion of the higher elevation freezing levels.

The disdrometer observations were used to evaluate West-WRF forecasts of freezing conditions for select AR events that exhibited snowing or freezing conditions at two disdrometer locations: DLA (2,956 feet), and LBH (5,512 feet). The fraction of correctly forecasted snowing conditions (West-WRF freezing level below terrain and snow observed by disdrometer) at DLA is about 30 percent and increases slightly with higher spatial resolution (from 9 kilometers to 1 kilometer) using lead times of 24–45 hours (see Section 5.5). Forecasting snowing events (with subzero temperatures at the surface) remains challenging, given the relatively low percentage of correct forecasts at both DLA and LBH, and observations like those from disdrometers can help to continue validation and forecast improvement efforts.

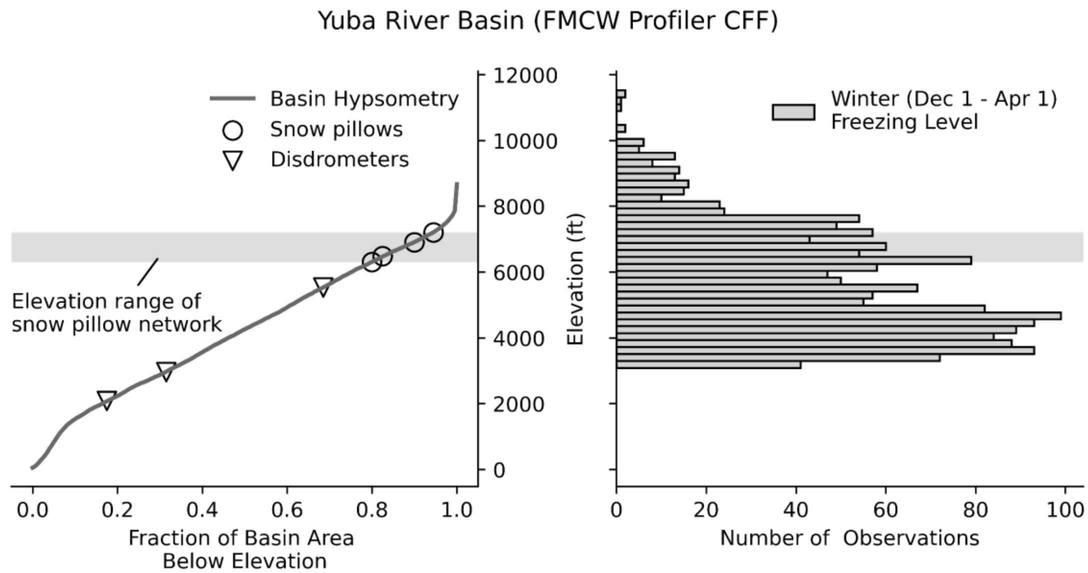


Figure 5-13. *Left: hypsometry of the Yuba River watershed with locations of snow pillows (circles) and CW3E radars and disdrometers (inverted triangles) plotted. Right: histogram of observed freezing levels from NOAA's FMCW (frequency-modulated continuous wave) radar in Colfax, California (2,113 feet elevation) over the last five winters binned by elevation.*

5.4.2.5 QPE

QPE is an important prerequisite of hydrological simulation and prediction, and it provides verification for meteorology applications. Existing QPE products use several methods to generate gridded precipitation products from precipitation gauge observations. Commonly used gridded products include CNRFC's Mountain Mapper (MM) algorithm QPE and PRISM. PRISM data are excluded from the QPE comparison because there is not a sub-daily product available.

CW3E has reproduced the six-hour CNRFC MM QPE to compare to other methods (see Appendix D, Section D.6 for methods). Additionally, an hourly QPE product was developed by a novel ML algorithm based on gauge measurements and topographic datasets over the CNRFC domain. Since topography is a significant factor influencing precipitation patterns, the proposed ML algorithm incorporates topographic variables as inputs. By considering the influence of terrain, we aim to improve the accuracy of precipitation estimation. Performance assessment metrics (see Appendix D, Section D.6) indicate that our ML algorithm outperforms other methods, particularly in situations where there is a substantial elevation difference between the target location and neighboring gauges. Notably, our algorithm demonstrates enhanced skill in scaling precipitation to match gauge measurements at test locations. Appendix D.6, Figure D-7, shows an example of the gridded six-hourly QPE, valid on January 27, 2021, at 1:00 p.m. All gauge stations are used to train the ML network and for interpolation. In this example, inverse distance weighting overestimates both the extent and the intensity of rain. MM produces a much more realistic representation of the precipitation extent due to the climatological scaling. However, it overestimates regions with high intensity when only a few gauge stations report higher values than their neighbors. Although ML overestimates the light rain extent to the northeastern Sierra Nevada, its estimation closely follows the general trend of gauge measurements while reflecting the detailed changes due to drastic topographic changes. CW3E plans to continue development of the ML QPE product, to produce QPE with short latency (same-day products), and to apply and test similar methodology for other variables such as air temperature and humidity to create additional gridded products.

5.4.3 Observational Highlights

- CW3E's ML-based QPE product can be used to estimate precipitation at ungauged locations and performs particularly well in areas with high-elevation gradients.
- Disdrometers help validate freezing level forecasts and fill spatial gaps in precipitation phase observations.
- Missing precipitation and SWE data from high-elevation stations during ARs might be due to transmission and power issues rather than sensor error.
- CW3E precipitation gauges are often included in CNRFC's QPE product and tracking is available to better quantify why gauges are sometimes dropped from the product.
- Multiple network operators expressed difficulty getting corrected and quality-controlled data onto online platforms.
- Surveyed operators suggested more interactive web pages for viewing observations for better use for decision support.

5.4.4 Recommendations

- Continue development of a one-hour ML QPE product with short latency.
- Create gridded air temperature and humidity products based on MM and ML frameworks to estimate temperature and humidity in ungauged locations.
- Deploy additional disdrometers in other relevant locations to enhance phase transition observations.
- Better quantify scenarios in which CW3E-maintained gauges are dropped from the CNRFC QPE product; plan network updates to mitigate issues when possible.
- Update the CW3E website to include more interactive plots for observation data.
- Continue annual network evaluations and seek feedback from partners to enhance network performance.

5.4.5 References

Cui, G., Bales, R., Rice, R., Anderson, M., Avanzi, F., Hartsough, P., & Conklin, M. (2020). Detecting rain–snow-transition elevations in mountain basins using wireless sensor networks. *Journal of Hydrometeorology, 21*(9), 2061–2081. https://doi.org/10.1175/JHM-D-20-0028.1

Sevruk, B. (1982). *Methods of correction for systematic error in point precipitation measurement for operational use*. World Meteorological Organization. https://community.wmo.int/en/bookstore/methods-correction-systematic-error-point-precipitation-measurement-operational-use

5.5 Weather and Water Forecast Verification

5.5.1 Introduction

The PVA provided evaluations of key aspects of ARs, precipitation, and inflows into the NBB and ORO reservoirs. These evaluations set the stage for establishing contextual knowledge about when forecasts of these characteristics *could* be leveraged for decision making. Leveraging forecasts is only one piece of the FIRO puzzle: it needs to be compared with, e.g., stipulations of the reservoir operations and capacity requirements/limitations. This section of the FVA describes CW3E's further work to evaluate forecasts of AR activity, and the resulting precipitation and river flows that can affect operations, by investigating state-of-the-art forecasts, comparing scales of forecast errors, identifying alternative observations for better verification, and modifying metrics to better reflect forecast errors that are more applicable to watershed scales.

5.5.2 QPF Error Tendencies

5.5.2.1 Introduction

Deterministic forecast evaluations of global and regional forecasts were provided in the Yuba-Feather PVA. In short, top 10 percentile events using 72-hour precipitation were shown to have skill metrics exceeding appropriate thresholds out to six to eight days' lead time. The West-WRF reforecast (the regional model) had better variance explained but had larger random errors, suggesting that some bias correction could be made to improve forecasts. Many of the statistics imply the overall skill of the weather modeling system but could be skewed based on the influence of a few key events. This section describes the frequency of forecast errors and how over-forecasts and under-forecasts contribute to the overall error patterns.

5.5.2.2 Methods and Data

This investigation uses the CW3E West-WRF reforecast (Cobb et al. 2022), which contains 34 years of precipitation forecast data at a 3-kilometer resolution over California, Oregon, and southern Washington. MAP is computed over the upper Yuba River and Feather River watershed at the HUC-8 level between December 1 and the following March 31 for lead times of one through five days. The forecasts are compared to observations from the Stage IV QPE from 2004 to 2018. Forecast errors are computed on 24-hour totals and the tendencies of total seasonal error, occurrences of overestimations and underestimations, and the percentage of error attributable to the top three bust forecasts to the total forecast error. For this report, only upper Yuba results are included as the Feather River results were very similar.

5.5.2.3 Verification Highlights

In summary, the QPF errors on average tend to be consistently more overestimated than underestimated over the upper Yuba River basin across all lead times (Figure 5-14) and the impact of the overestimated QPF is larger than the impact on underestimating QPF (Figure 5-15) with respect to total QPF error. This result is most robust at the two- and three-day lead times of total QPF error (where the black vertical lines do not overlap between the overestimations and underestimations) in the number of events and for one- and two-day lead times for total QPF error. At lead times where they do overlap, the data suggest that there are some water years where the overestimations and underestimations are more similar in frequency and impact. Understanding these error tendencies is a pivotal first step in the process of improving model forecasts. Trends in the model forecasts can be isolated, identified, and investigated for future model skill improvements.

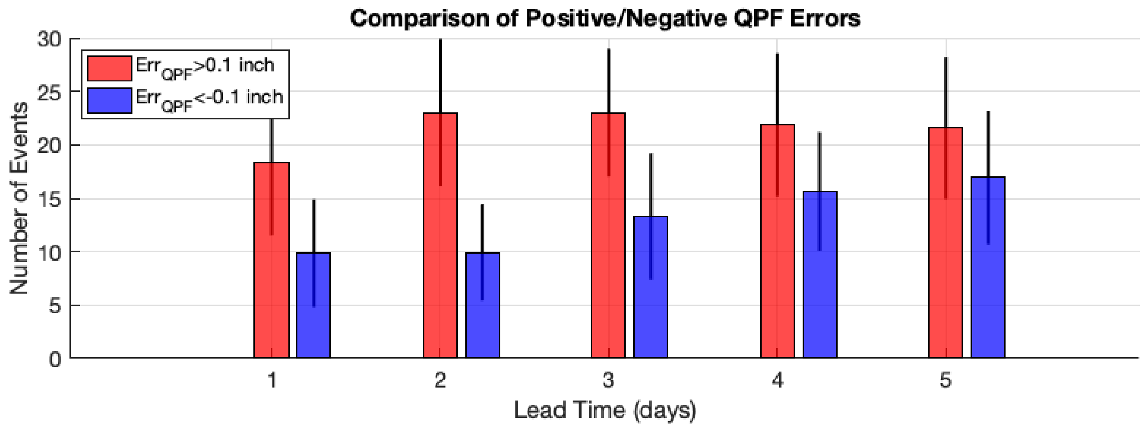


Figure 5-14. *Frequency of overestimated (red) and underestimated (blue) MAP QPF error over the upper Yuba basin as a function of forecast lead time (days). The height of the bars represents the average error of the winter season (December–March) over a 14-year period, and the black vertical lines represent one standard deviation around the mean.*

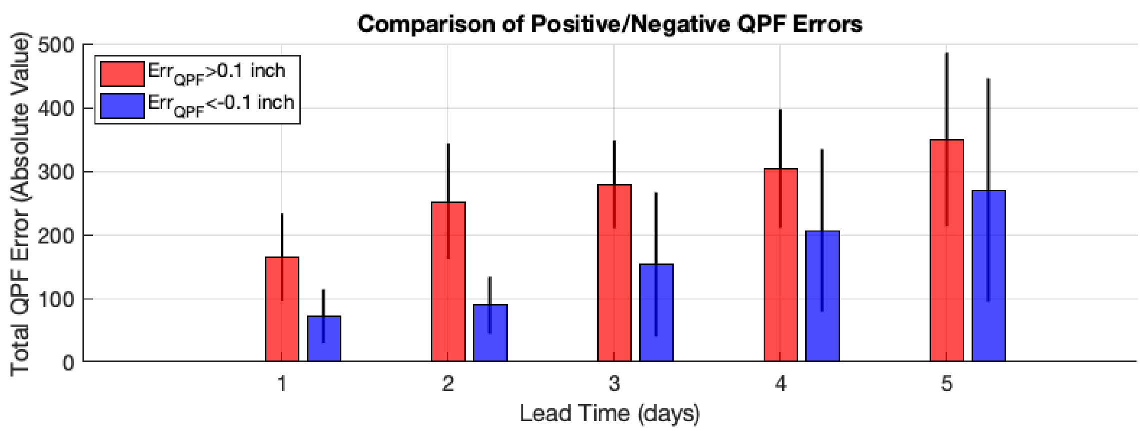


Figure 5-15. *Same as Figure 5-14 for MAP QPE total error over the winter season, December–March.*

5.5.3 Freezing level Evaluation

5.5.3.1 Introduction

The partitioning of rain and snow remains an important forecasting challenge for areas of the Sierra Mountains due to the hydrologic impacts on runoff generation and snowpack accumulation during precipitation events. Forecasting precipitation as frozen vs. liquid has significant implications for water management strategies. Freezing levels are often used as a proxy indicating where frozen precipitation might occur, as they explicitly represent the altitude of the 0°C isotherm of the vertical temperature profile. As reported in the PVA, Sumargo et al. (2020) found inflow volume uncertainties of under 10 percent to over 50 percent of the flood pool storages at ORO and NBB, depending on the freezing level, antecedent moisture condition, and precipitation event magnitude, using an average ±350-meter freezing level forecast error.

Forecasts of freezing level at ORO and Colfax were previously assessed during the Yuba-Feather PVA using archived near real-time CNRFC data and FMCW vertically profiling radars (Johnston et al. 2017). However, this assessment leveraged FMCW brightband heights, or altitude of the maximum radar reflectivity, as observations and thus only represented forecast skill of above-terrain freezing levels. It was recommended that forecasts correctly predicting freezing conditions at the surface should also be examined to convey the skill of snowing conditions.

The PVA did not address the discrepancy between the characteristics used to define partitioning of rain and snow (e.g., freezing level, brightband height, melting layer, snow elevation). Brightband heights, indicative of the altitude at which snowflakes partially melt and transition into rain, and offer insights into precipitation processes. Concurrently, the 0-degree isotherm delineates the boundary between freezing and non-freezing temperatures within the atmosphere. To make robust forecast skill assessments, one should compare the same physical measurements. Figure 5-16 shows a schematic of the different altitudes, and therefore variability, between brightband heights, freezing level, and melting layers. The 0°C isotherm is assumed to be above this layer to compensate for the time/depth of melt to occur and subsequent hydrometer makeup. For profiler observations to be used as a verification source for freezing level forecasts, the difference between the two measurements must be resolved because the observations, models, and physical representation of the rain/snow partitioning may all be different. Most importantly, these differences affect the level of precision achievable in freezing level forecast skill assessment.

This section describes the extensions to the PVA freezing forecast assessments that address:

- Correct forecasts of freezing conditions at the surface.
- The investigation of differences between brightband height and freezing level.

Investigations of the variability of freezing level across complex topography are summarized in Appendix E, Section E.1.

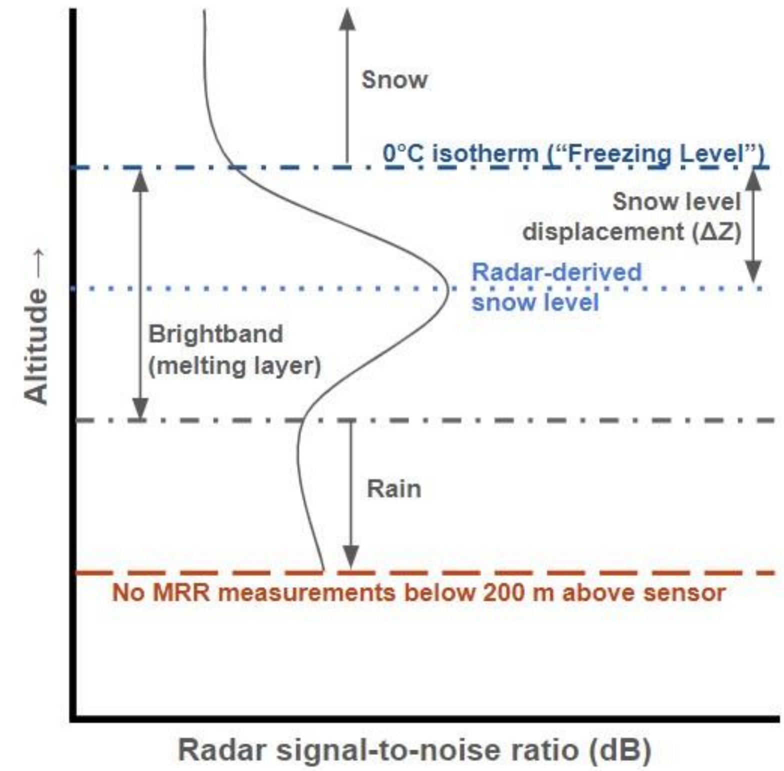


Figure 5-16. *Schematic of the height (altitude) 0°C isotherm (freezing level) brightband height ("radar-derived snow level") that is detected by the vertical profiler, melting layer, and the difference between the brightband height and 0°C isotherm (ΔZ). The black dot-dash line is a reference for missing reflectivity under 200 meters.*

5.5.3.2 Methods and Data

Correct forecasts of snowing/freezing conditions at the surface were evaluated during the WY2023 season to—for the first time possible—leverage several observation types and available high-resolution forecast data at the same time. We evaluated the skill of the forecasts that accurately predicted freezing conditions when snow was observed. The model forecasts were extracted from CW3E's West-WRF near real-time system, in which forecast predictions are made at three spatial resolutions within the Yuba-Feather region: 9 kilometers, 3 kilometers, and 1 kilometer. In this case, the deterministic forecast with initial and boundary conditions from the GFS model (West-WRF/GFS) was evaluated. The 1-kilometer data were produced for the first time during WY2023. The freezing level forecasts were compared to grid cell elevation within West-WRF to determine whether freezing conditions were observed at the surface. A buffer of 200 meters was used to account for the difference between freezing level height and the translation of fall speed and altitude of melting hydrometeors. Disdrometer data, from which precipitation phase can be derived from the distributions of drop size and fall velocity, were used to identify times of snowing conditions as a source for verification. This analysis was conducted for two locations: DLA (901 meters/2,956 feet) and LBH (1,680 meters/5,512 feet). Forecasts of snowing/freezing conditions at the surface were expressed with contingency table metrics (Dodge 2008, Figure 5-17).

- A forecast hit means that the West-WRF forecast predicted snow (≥ 0.5 millimeters), the forecasted freezing level was 200 meters or less above the grid cell elevation, and the disdrometer reported snow (> 0.5 millimeters).
- A forecast miss means that the West-WRF forecast did not predict snow but the disdrometer measured snow, or the forecast predicted snow but the forecasted freezing level was over 200 meters above the grid surface.
- A forecast false alarm means the West-WRF forecast predicted snow, the freezing level forecast was near (< 200 meters) or below elevation, but the disdrometer did not measure snow.
- A forecast correct negative means the West-WRF forecast did not predict snow, the freezing level is above terrain (≥ 200 meters), and the disdrometer did not measure snow.

Skill is expressed in terms of the critical success index, or CSI (hits ÷ [hits + misses + false alarms]) and probability of false alarms, or POFA (false alarms ÷ [false alarms + hits]). CSI and POFA range from 0 to 1; the best values are 1 for CSI and 0 for POFA.

		Disdrometer: Snow Observed	
		Yes	**No**
Forecast: Freezing level or Snow	**Yes**	Hit	False alarm
	No	Miss	Correct negative

Figure 5-17. *Contingency table scenario for forecasting freezing/snowing conditions at the surface.*

The investigation of the differences between brightband height and freezing level is a crucial undertaking in understanding atmospheric conditions during winter storms. The verification team was tasked with scoping a potential method for identifying the difference between the brightband height and freezing level with data specific for the Yuba-Feather region. We used a decade's worth of brightband data from FMCW snow-level radar (Johnston et al. 2017) at ORO and Micro Rain Radar at NBB and compared it to the CNRFC's publicly available freezing level observed grid (https://www.cnrfc.noaa.gov/fzlvl_guidance.php). The gridded observations represent freezing level instantaneous values at six-hourly intervals and are direct derivations of the 0-degree isotherm from the High-Resolution Rapid Refresh (HRRR) model analysis (Pete Fickenscher, CNRFC, personal communication). Essentially, this dataset contains the best source (long period of record, high spatial resolution) of 0-degree isotherm freezing level overlapping the periods of available profiler observations. The difference between the freezing level and brightband heights was computed by first pairing the median value of all 10-minute profile observations within one hour of the valid time of the gridded observed freezing level. The mean and standard deviations of all profiler-grid pairs were calculated for each water year between 2013 and 2023 and for all water years collectively.

5.5.3.3 Verification Highlights

i. Correct forecasts of freezing conditions at the surface

West-WRF forecast frequency analysis and skill scores of snowing/freezing conditions at DLA using snow observations from the disdrometer are given in Figure 5-18. The differing resolutions of the model are important because the terrain elevation resolved in the model affects how well forecasts represent a single-point observation. Snowing conditions at DLA were infrequent, given the large proportion of correct negatives within the forecast. There were proportionally more false alarms within the forecast, most noticeably at the 9- and 3-kilometer resolutions. CSI values for 9-kilometer forecasts across all lead times are only about 0.3, or a 30 percent success ratio, and the probability of false alarms is about 20 percent. CSI increases slightly as resolution increases (from 9 kilometers to 1 kilometer) using lead times of 24–45 hours. POFA also decreases. These two metrics together indicate some benefits of high-resolution forecasts. However, these findings suggest that correctly forecasting snowing events (with subzero temperatures at the surface) remains challenging, given the relatively low CSI. Similar results were seen at LBH.

Note that the grid cell elevation of the model terrain is often not the exact same as the altitude of the disdrometer. However, the goal for this analysis was to determine if the model's elevation/snow compatibility was representative of surface conditions at the point location. We found that the results can be sensitive to the sign of the difference between the grid cell elevation and the observation elevation—higher grid cell elevations can be disproportionately "more correct" because higher freezing levels are more frequent. This analysis suggests more in-depth studies are needed to affirm resolution impacts on freezing level forecast skill.

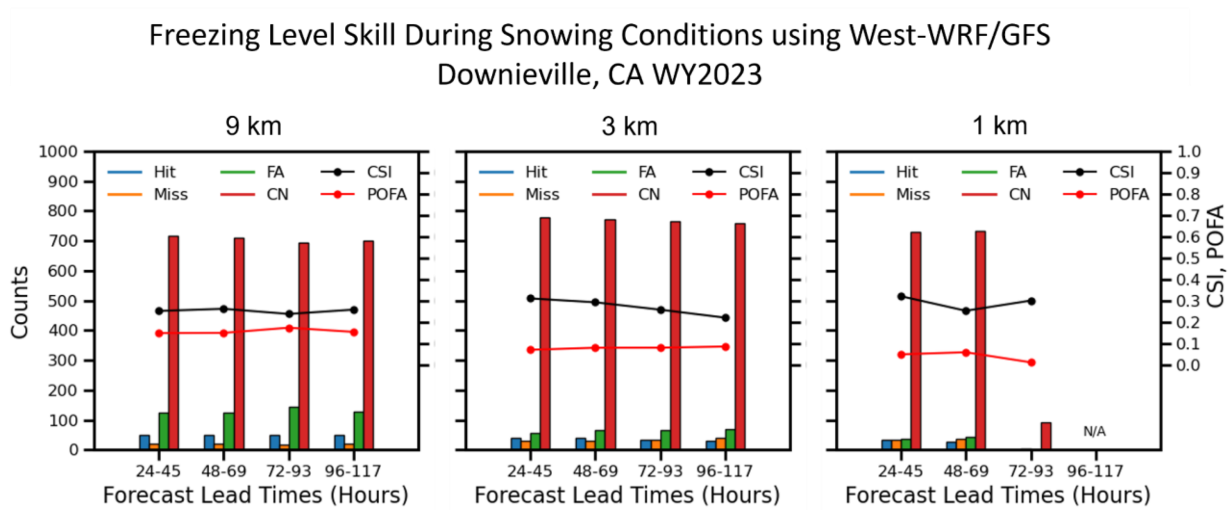


Figure 5-18. *Forecast skill of freezing level at DLA during WY2023: number of instances (counts) in which West-WRF forecasts are considered hits (blue bars), misses (orange bars), false alarms (green bars), and correct negatives (red bars), along with the forecast skill values of the CSI (black line) and POFA (red line) as a function of lead times using the 9-kilometer (left), 3-kilometer (middle), and 1-kilometer (right) forecasts. All three-hourly forecast–observation pairs with the same lead time (e.g., 24–45 hours) are evaluated together. The 1-kilometer forecast only extends out to 72 hours.*

ii. The investigation of differences between brightband height and freezing level

The goal of this assessment is to quantitatively determine the offset (Δz) between freezing level and brightband heights and ultimately remove it from either the observation or the forecast for a more robust comparison. The mean Δz will indicate average offset between the freezing level and brightband height, and the standard deviation of Δz will indicate whether the mean is representative of most data. In other words, if the standard deviation is small, then the mean value is an accurate representation of the offset. The mean and standard deviation of Δz at

ORO are given in Figure 5-19. Over all years examined, the mean Δz is -187.5 meters and the standard deviation 364.5 meters. This translates to a condition in which the actual offset can be as small as 0 meters or as large as 552 meters. This last value largely exceeds the value used in Sumargo et al.—meaning that the difference between freezing level and brightband height could represent an even larger proportion of uncertainty, and therefore a larger proportion of flood pool space, for runoff events.

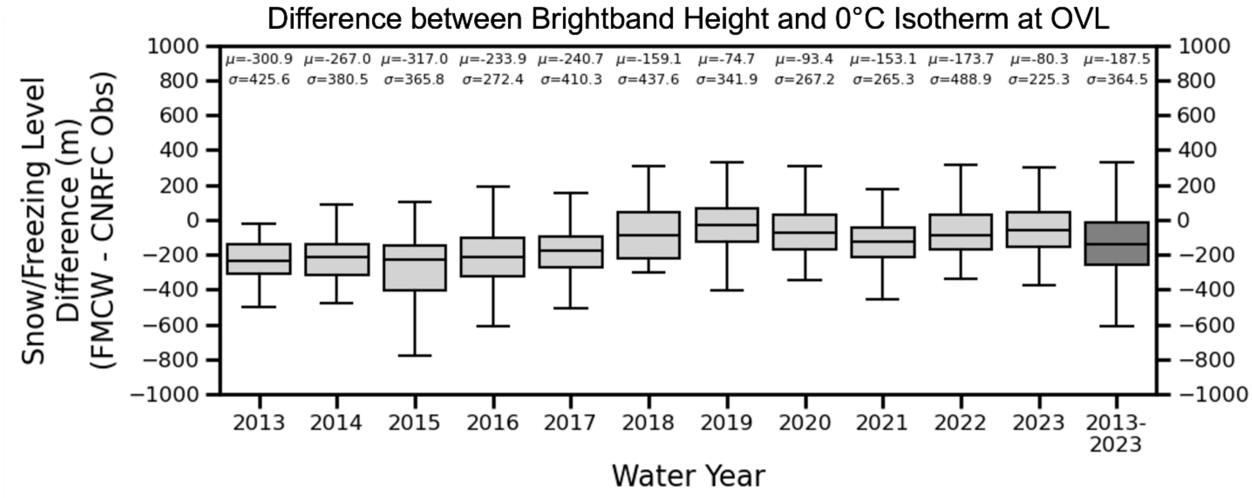


Figure 5-19. *Box plots of the differences (Δz, m) between the freezing level and brightband height from the FMCW at ORO (called "OVL" in this graph) as a function of water years between 2013 and 2023 (all water years are summarized in the last box plot). The mean (**μ**) and standard deviation (**σ**) of Δz are listed above each box plot. All data values are plotted as black dots, the edges of the box correspond to the interquartiles (25th, 75th percentile), and the whiskers correspond to the 5th and 95th percentiles of the data distribution.*

This analysis has several implications and generated recommendations for further research. The large spread between the differences in freezing level and brightband height at ORO could be the result of several factors including meteorological processes (e.g. isothermal layers), the resolution of the model vertical structure within the source data for the gridded observations (recall that this is the HRRR analysis), limited precision of the profiler observations, etc. To remove noise from the profiler data, the all-year **μ** and **σ** decreased to -137.8 meters and 209.5 meters, respectively. This important finding supports further post-FVA investigations including:

- Using IVT/QPE to contextualize differences, especially because latent heating can bend down the freezing level during intense precipitation.
- Comparing freezing level from radiosondes.
- Identifying times/depths of isothermal layers.
- Computing differences between hydrometeor concentrations in high-resolution model predictions as an alternative methodology for Δz determination.

It also creates an opportunity to address the uncertainty in freezing level estimates and potentially engineer a new rain/snow elevation, giving the CNRFC a more reliable estimate of rain/snow partitioning.

5.5.4 Inflow Forecast Evaluation

5.5.4.1 Introduction

Forecasts of 72-hour inflow into NBB and ORO were previously assessed during the Yuba-Feather PVA. This analysis helped to establish a methodology to evaluate AR-related inflow forecast skill and provide quantitative skill evaluations using the CNRFC hindcasts—a dataset that mimics HEFS to a large degree—using meteorological forecast inputs relevant at the time.

This section describes the extensions to the PVA hydrologic forecast assessments that address:

- Potential changes in forecast skill due to new meteorological inputs derived since the publication of the PVA.
- The need to expand to additional aggregation times (beyond 72 hours) to support operational timelines.
- The need for skill assessments at additional locations relevant in the decision-making process in the Yuba-Feather system.
- The performance of the hindcast vs. current deterministic forecast information.

5.5.4.2 Methods and Data

This work leverages the ensemble hindcasts generated using NWS's HEFS in 2022. For a more thorough description of the HEFS system, refer to Section 6.2 of the PVA and Section5.3 5.3 of this document. The assessments in the PVA leveraged the hindcasts forced with precipitation and temperature data from GEFSv10, generated in 2015. Since then, GEFSv12 meteorological data have been generated during a new period of record (2000–2019) and the hindcasts have been updated. The newer meteorological forcings were generated using updated methodologies including new dynamical cores of the model and better spatial resolution. Inflow forecasts for NBB and ORO were compared using the two versions of the meteorological-forcings-based forecasts.

Here, skill is measured using the Brier score (for continuity with the PVA) and Brier skill score of a defined event threshold. The Brier score is a way to measure how accurate a probabilistic prediction is. A Brier score of 0 is perfectly accurate while a Brier score of 1 is perfectly inaccurate. The Brier skill score expresses skill relative to climatology where a value of 1 is best and a value of 0 means the forecasts are no better than climatology. For the inflow forecast verification, thresholds are defined by 95th and 80th percentiles of the observed 72-hour inflow volumes, respectively, to examine the skill of high flow events during AR conditions only (i.e., AR only).

In coordination with the work described in Section 3 and Section 5.3, the evaluations were also conducted for one-day and seven-day total volumes to address other operational timescales. Forecasts were also evaluated over longer lead times than they were for the PVA (now out to 13 days' lead time).

5.5.4.3 Highlights

i. Potential changes in forecast skill due to new meteorological inputs used in CNRFC hindcasts

Table 5-2 contains the Brier scores of the CNRFC ensemble inflow hindcasts at NBB and ORO, generated with GEFSv10 and GEFSv12 meteorological forcings. This analysis was performed only for the overlapping period (i.e., 2000–2010). Note that an error in the calculation of the Brier score in the PVA was corrected, so scores in Table 5-2 supersede the PVA's scores. Interestingly, the Brier scores are lower (better) for 72-hour total volume inflows using the GEFSv10 forecasts than in the GEFSv12 forecasts for all lead times out to five to seven days.

Understanding the performance differences is a complex effort involving several issues. The GEFSv12 meteorological ensemble contains 31 members at production, but only five members were archived through the entire period of record (with a small exception: one 11-member run each week was archived). GEFSv10, on the other hand, contained 10 ensemble members. The number of hindcast ensemble members is also different between versions. Changes to MEFP used to drive the ensemble forecasts also occurred (Brett Whitin, CNRFC, personal communication), including:

- Moving to a new climatology, which limited the number of members created from the MEFP distributions.
- Changing the sampling method within MEFP from stratified random sampling to fixed quantile sampling.
- Recalibrating all hydro models to use freezing level to define the rain/snow line instead of temperature.
- Different sampling techniques embedded within MEFP.

There are also considerations about the precipitation skill of the GEFS, which serves as one of the input sources for the hydrologic model calibration.

Despite the differences, both hindcast versions have Brier scores near zero, which implies high forecast skill during AR events. Recommendations for further research to address the difference in the GEFS hindcast skill include:

- Comparing reliability diagrams (v10 vs. v12) to identify any potential important differences between the two MEFP sets or advantages in capturing larger events (hits vs. false alarms).
- Comparing MEFP outputs from the different hindcasts to understand potential sampling bias.
- Comparing GEFS precipitation skill during the period in which hindcasts were calibrated to understand the impact of precipitation forcing.

Table 5-2. *Brier scores of CNRFC ensemble inflow hindcasts for 2000–2010 at NBB and ORO. The scores are computed with an 80th flow percentile threshold, for lead time aggregates of one to three, four to six, and seven to nine days and AR-only conditions. Bold scores indicate the version of GEFS with better skill.*

Lead Time Aggregate	Brier Score (AR Only)			
	NBB		ORO	
	GEFSv10	GEFSv12	GEFSv10	GEFSv12
1-3 days	**0.063**	0.076	**0.042**	0.051
4-6 days	**0.087**	0.110	**0.070**	0.081
7-9 days	**0.120**	0.140	**0.091**	0.120

ii. Brier skill score updates for additional lead times and sites using CNRFC hindcasts

Table 5-3 contains the Brier skill score (higher is better) for GEFSv12 as an update to the PVA findings of 72-hour streamflow from the CNRFC hindcasts. The table now includes scores for Englebright, as well as NBB and ORO out to 13 days' lead time. Brier skill scores above 0 indicate that the forecasts are skillful beyond climatology. Using the GEFSv12 hindcasts, the 72-hour total volume flows have Brier skill scores above 0 out to seven to nine days' lead time at all three locations. Additionally, the scores are aggregated to 24-hour total volumes and 168-hour total volumes: 24-hour total volumes have Brier skill scores above 0 out to six days at all locations and 168-hour total volumes are skillful out to seven to 14 days' lead time.

Table 5-3. *Brier skill scores of CNRFC ensemble inflow hindcasts for 2005–2019 at NBB, ORO, and Englebright only during AR conditions. The scores are computed with an 80th flow percentile threshold, for lead time aggregates of 72 hours, 24 hours, and 168 hours. Bold scores indicate lead times where skill is better than climatology.*

Lead Time Aggregate	Brier Skill Score (AR Only): GEFSv12		
	NBB	ORO	Englebright
	72-hour total volumes		
1–3 days	**0.5493**	**0.6637**	**0.5369**
4–6 days	**0.3343**	**0.4583**	**0.3234**
7–9 days	**0.0779**	**0.1722**	**0.071**
10–13 days	-0.1588	-0.0476	-0.1278
	24-hour total volumes		
1 day	**0.3706**	**0.5493**	**0.4362**
2 days	**0.4087**	**0.5223**	**0.486**
3 days	**0.3077**	**0.4186**	**0.3768**

Lead Time Aggregate	Brier Skill Score (AR Only): GEFSv12		
	NBB	**ORO**	**Englebright**
4 days	**0.1813**	**0.3671**	**0.2839**
5 days	**0.1601**	**0.254**	**0.2194**
6 days	**0.063**	**0.1254**	**0.0972**
7 days	-0.118	-0.0569	-0.0534
8 days	-0.196	-0.1637	-0.1482
9 days	-0.3377	-0.3073	-0.2574
10 days	-0.4336	-0.381	-0.3581
	168-hour total volumes		
1–7 days	**0.064**	**0.053**	**0.068**
8–14 days	**0.160**	**0.120**	**0.130**

iii. Performance of the hindcast vs. current deterministic forecast information

A comparative analysis was conducted between the operational CNRFC deterministic forecasts and the 75th percentile exceedance value of the hindcast for 72-hour total volumes at one- to three-day lead times. It is often noted that the 75th percentile exceedance value of the operational ensemble forecast aligns well with the deterministic forecast; therefore, using the 75th percentile value of the hindcast is one way to directly compare the model performance of data used to support water resources engineering research (and the assessments herein) with what is currently used operationally for water management decision support in the Folsom Dam and Lake WCM. Additionally, the FIRO ID3A alternatives for both ORO and NBB use 75 percent non-exceedance probability for daily volumes up to seven days (Section 3). In summary, the coefficient of determination (r^2) is higher in the operational forecasts at NBB and ORO and the root-mean-square error is smaller. This suggests that operational forecasts may have better skill than the hindcasts assessed for this report. This is important because the FIRO strategies developed and evaluated in Section 3 and Section 4 can be expected to perform as well or better in operational applications.

Additionally, performance of the operational deterministic 72-hour inflow volume forecasts for Englebright, ORO, and NBB at the one- to three-day lead time was evaluated. In short, the variances explained by the forecast were 76, 89, and 86 percent, respectively. This demonstrates that the forecasts are capturing a large majority of the observed forecast variability.

5.5.5 Meteorological Ensemble Forecast Evaluation

5.5.5.1 Introduction

Meteorological probabilistic forecasts play an important role in providing uncertainty estimates among single forecast predictions. Ensembles provide a range of possible outcomes that can be filtered to express likelihoods of precipitation, IVT, etc. The PVA assessed several different deterministic (or ensemble mean) forecast products to convey skillful lead times for extreme precipitation. This section describes the extension of meteorological forecast skill assessments in the PVA with additional evaluations of ensemble forecasts of precipitation and landfalling IVT.

5.5.5.2 Methods and Data

CW3E has been producing a 200-member meteorological ensemble beginning in WY2022—work summarized in fine detail in the PVA, Appendix E, Section E.3. Updates to the model system for WY2023 are already mentioned in Section 5.2.3.5 For brevity, the model configuration details are not repeated here. However, this section focuses on new analysis of the model performance of probabilistic precipitation during the December 2021–March 2022 winter season. The assessment also includes a comparison to the deep learning method applied to the 200-member ensemble also discussed in Section 5.2.3.6. Precipitation is evaluated against the PRISM model (https://prism.oregonstate.edu) 4-kilometer dataset, which serves as the observation dataset and daily climatology.

To understand the probabilistic skill of IVT at landfall, GEFS was examined using the "AR landfall tool" (Cordeira and Ralph 2021) introduced in Section 5.2.3.4. This section discusses the qualitative forecast evaluation of the tool for a series of events occurring during a period of successive AR activity during WY2023 (referred to as the deep dive period). The ensemble probabilities are calculated for a given location and aligned with observed IVT to determine how well the ensemble probabilities reflected observed AR conditions as a function of forecast lead time. The ensemble tool explicitly reflects the number of ensemble members that are predicting IVT greater than a defined threshold.

Forecast skill is assessed qualitatively by comparing the alignment of observed precipitation with probabilities of precipitation using specific thresholds. For more quantitative measures, the continuous ranked probability skill score (CRPSS) and Brier skill score are used to define skill for precipitation. CRPSS quantifies the overall difference between the forecasted probabilities and the actual distribution of events. Higher values of CRPSS are better; a value of 0 means the forecasts are no better than climatology.

5.5.5.3 Highlights

i. Performance of the 200-member ensemble

Figure 5-20 shows the probabilities of 24-hour accumulated precipitation over 1 inch (25.4 millimeters) for a representative test case (December 24, 2021) from GEFS (Figure 5-20a), the West-WRF 200-member ensemble (Figure 5-20b), and the West-WRF 200-member ensemble plus deep learning (Figure 5-20c). The application of the deep learning technique is shown to improve the skill of the raw ensemble forecast. The larger probabilities generally align well with the observed precipitation of 1 inch or greater (black contours) across all models, but the West-WRF 200-member ensemble and the ensemble with deep learning applied have greater probabilities than the GEFS over the Sierras—implying more certainty that precipitation will exceed 1 inch in these areas.

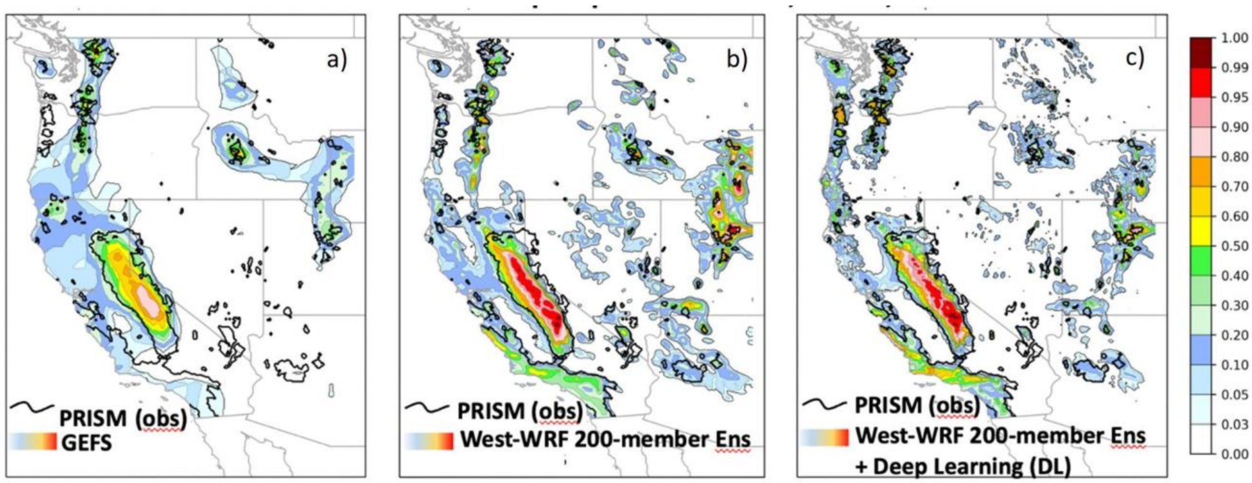


Figure 5-20. *Probability comparison among GEFS (a), West-WRF 200-member ensemble (b), and West-WRF 200-member ensemble plus deep learning (c) of 24-hr precipitation over 1 inch (25.4 mm) valid December 24, 2021. The dark black line represents the observed 1-inch (25.4 mm) precipitation contour from PRISM.*

Furthermore, for the Yuba-Feather watersheds, the deep learning post-processed West-WRF forecast (shown in purple in Figure 5-21, left) outperforms all other reference benchmark models (i.e., its CRPSS is larger), including the ECMWF (green) and the raw West-WRF (red), for the period of assessment (December 2021–March 2022), from a lead time of one to three days. The raw 200-member ensemble is competitive with the ECMWF and GEFS predictions, although it has an equivalent or larger CRPSS at all lead times compared to the GEFS. The CRPSS represents skill across the spectrum of all precipitation thresholds; the Brier skill score is calculated for specific thresholds. Figure 5-21 (right) shows that the deep-learning-applied approach has a clearer improvement over the raw ensemble counterparts, particularly for this upper threshold of 50 millimeters (1.96 inches) out through four days' lead time. This suggests that the large West-WRF ensemble plus the post-processing has desirable added value for predictions of precipitation in the West.

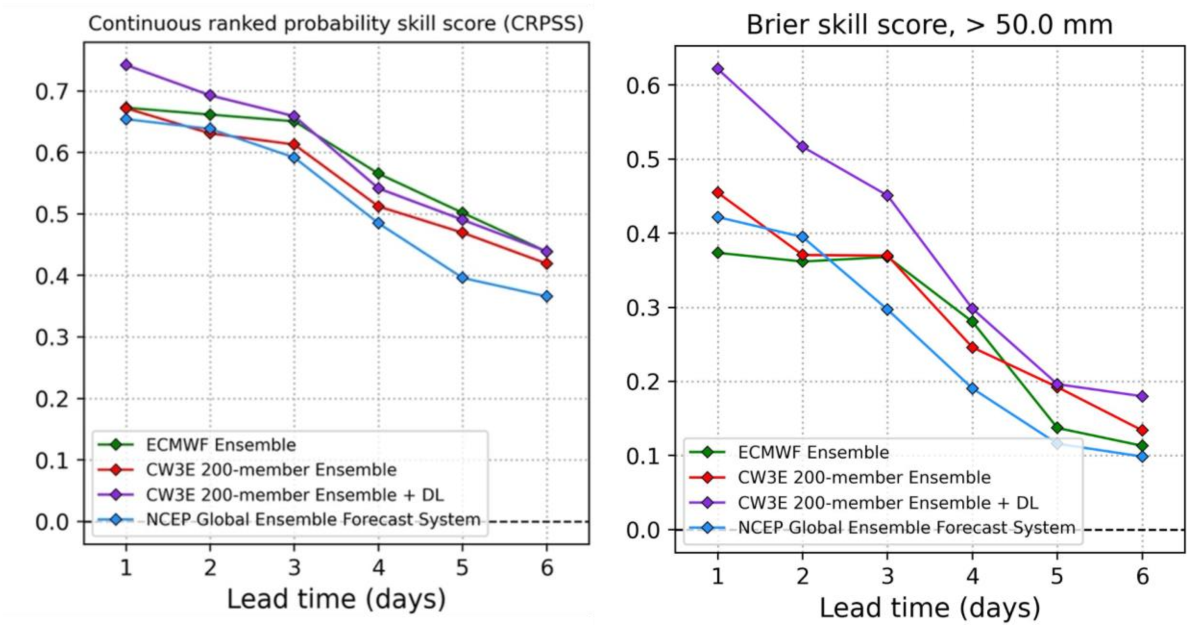


Figure 5-21. *CRPSS (left) and Brier skill score (right) among GEFS (blue), ECMWF (green), West-WRF 200-member ensemble (red), and West-WRF 200-member ensemble plus deep learning of 24-hour precipitation (purple) using combined winter season forecasts during WY2022 and WY2023. The CRPSS is calculated over the entire domain and reflects skill for all precipitation thresholds, and the Brier score is calculated for a precipitation threshold of over 50 millimeters (1.96 inches).*

ii. Performance of the GEFS ensemble probability of IVT in Northern California

Section 5.2.3.4introduces the "AR landfall tool" as a method for examining the probability of IVT exceeding defined thresholds at a certain location along the U.S. West Coast. Figure 5-22 shows the probability of IVT over 250 kg $m^{-1}s^{-1}$ at a point along the coast near Bodega Bay (37.5°N, 122.5°W) for the sequence of ARs making landfall between December 17, 2022, and January 16, 2023 (the "deep dive period") and the actual IVT magnitude as observed from the GEFS analysis. Nine ARs made landfall in this region during the deep dive period, as signified by the shaded red areas in the observed IVT time series, and the areas in purple represent where more than 90 percent of ensemble members were predicting IVT over 250 kg $m^{-1}s^{-1}$. Using a percentage threshold of 50 percent (i.e., more than 50 percent of ensemble members) as one example of forecast skill, the GEFS ensemble predicted landfalling IVT over 250 kg $m^{-1}s^{-1}$ anywhere between six and 13 days ahead of time. If that threshold is increased to 75 percent of the ensemble members, IVT over 250 kg $m^{-1}s^{-1}$ was correctly predicted from five to 12 days ahead of time. There is clear variability in the lead time predictability from storm to storm across the deep dive period. This type of analysis is helpful in that it can guide further research into meteorological patterns associated with specific storms, which may point to explanations of lead time predictability (e.g., blocking patterns). Section 5.2.3.4 also found, over a longer period of record, that GEFS was able to predict IVT 250 kg $m^{-1}s^{-1}$ in Northern California up to six days, on average, for moderate ARs on the AR scale (i.e., AR 2). More detail is provided in Appendix B, Section B.2.4.

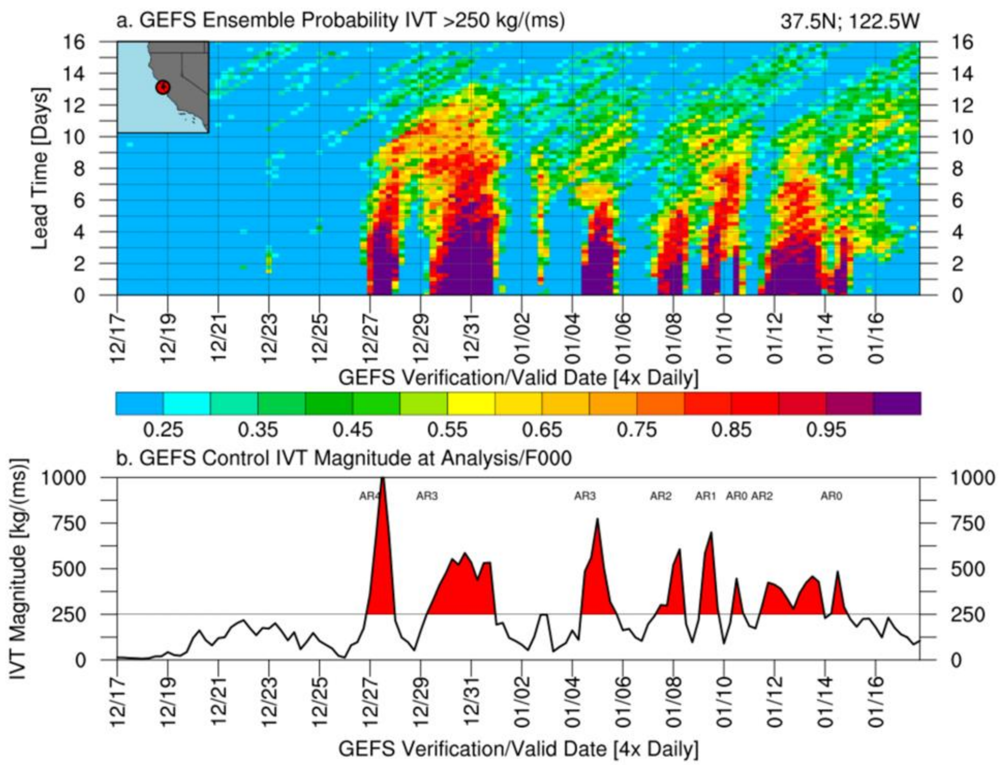


Figure 5-22. *(a) Verification time–lead time analysis of the ensemble odds of IVT magnitudes of 250 kg $m^{-1}s^{-1}$or greater (shaded) from the NCEP GEFS for forecasts verifying between December 17, 2022, and January 17, 2023. (b) Time series of IVT magnitude from the GEFS control IVT magnitude (kg $m^{-1}s^{-1}$) at the 0-hour forecast time (e.g., analysis) with periods with IVT magnitudes of 250 kg $m^{-1}s^{-1}$ or greater shaded in red.*

5.5.6 Verification Highlights

- Forecasting snowing/freezing conditions in the Yuba water remains challenging: there is a 30 percent success ratio on accurately predicting snowing/freezing conditions at targeted sites at low and high elevations of the Yuba basin using West-WRF 9-kilometer forecasts, and the probability of false alarms is about 20 percent. Success is slightly better using 1-kilometerforecasts.
- The variability (standard deviation) in the difference between freezing level and brightband heights is twice as large the mean difference, making it challenging to make a general correction to the freezing level verification.
- The evaluation of 72-hour volume inflows suggests the CNRFC GEFSv12 hindcasts are skillful out to a seven- to nine-day lead time, and 24-hour total volume flows are skillful out to six days in advance.
- The GEFSv10 hindcasts perform slightly better than GEFSv12 for NBB and ORO. It is very challenging to determine the reason, as many changes occurred between the two versions.
- Several skill scores are better in the CNRFC operational forecasts at NBB and ORO than found in the GEFSv12 hindcast using the 75th percent exceedance value.

5.5.7 Recommendations

Several recommendations were suggested throughout this section and summarized below:

- Continue to examine resolution impacts on freezing level forecast skill, particularly during transition periods between rain and snow at high elevations.
- Continue research investigating the large variability between the freezing level and brightband height with focus on sensitivity to rain rates, isothermal layers, and hydrometer concentrations.
- Further research the differences in the GEFS hindcast skill and its inputs to understand potential sampling bias and impact of initial conditions.
- Identify cases of varying lead time predictability to further investigate the meteorological patterns that may influence storm evolution.
- Continue to develop and evaluate large ensembles for extreme precipitation prediction in complex topography.

5.5.8 References

Cobb, A., Steinhoff, D., Weihs, R., Delle Monache, L., DeHaan, L., Reynolds, D., Cannon, F., Kawzenuk, B., Papadopolous, C., & Ralph, F.M. (2023). West-WRF 34-Year Reforecast: Description and Validation. *Journal of Hydrometeorology, 24*(11), 2125–2140. https://doi.org/10.1175/JHM-D-22-0235.1

Cordeira, J. M., & Ralph, F. M. (2021). A summary of GFS ensemble integrated water vapor transport forecasts and skill along the U.S. West Coast during water years 2017–20. *Weather and Forecasting*, *36*(2), 361–377. https://doi.org/10.1175/WAF-D-20-0121.1

Dodge, Y. (2008). Contingency table. In *The concise encyclopedia of statistics* (pp. 110–111). Springer New York. https://doi.org/10.1007/978-0-387-32833-1_77

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

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*, e2020WR027072. https://doi.org/10.1029/2020WR027072

5.6 Economic Benefits

NBB and ORO provide considerable social and economic benefits to the region and to the state in the form of flood risk management, municipal and industrial water supply, agricultural water supply, groundwater recharge through agricultural irrigation and in lieu of groundwater use, environmental services including benefits to endangered salmonids and migratory birds, hydropower generation, and recreation (HDR and SWRI 2007). By providing enhanced operational flexibility, FIRO is expected to increase these benefits (Ralph et al. 2022). Many disadvantaged communities in the region are disproportionately affected by flood risk and water insecurity and face higher water and energy costs relative to income levels. FIRO could alleviate these burdens by mitigating flood hazards, increasing water supply availability, and enhancing the consistency of hydropower production, thereby offering benefits to these vulnerable populations. Additionally, the flexibility provided by FIRO may increase resilience to climate change while reducing emissions from thermal energy generation through clean, carbon-free hydropower generation.

The main objective of FIRO at NBB and ORO is flood risk reduction. The social and economic benefits of municipal, industrial, and agricultural water supply; groundwater recharge; hydropower generation; environmental services; and recreation are secondary to flood risk reduction benefits but may be significant (Ralph et al. 2022). In studies at other sites, FIRO has been shown to yield economic benefits without increasing downstream flood risk (Jasperse et al. 2020; Woodside et al. 2022). An economic analysis of FIRO at Lake Mendocino in Sonoma County estimated that modified operations will generate over $9 million per year[1] 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; USBR et al. 2021). An analysis of FIRO at Prado Dam projected water supply benefits of 3,400 to 7,300 acre-feet/year of additional groundwater recharge (Woodside et al. 2022), which would reduce imported water purchases from the Colorado River by $4 to $6 million per year (OCWD 2019; OCWD, personal communication, June 2024).

5.6.1 Background

The Yuba and Feather Rivers have a history of destructive floods. The most devastating occurred in December 1955, causing 40 deaths and $572 million in damages (2023 dollars). Flooding in December 1964 caused less damage ($49 million) due to the partially completed ORO Dam, which reduced river flows. A series of storms in 1986 resulted in floods causing $263 million in damage, leading to the initiation of flood risk management studies and levee improvements. The 1997 flood of record resulted in significant damage ($567 million), prompting further risk reduction measures. The 2017 ORO spillway incident led to the evacuation of over 180,000 people and a presidential disaster declaration due to damage to the dam and levees (HDR 2022).

ORO and NBB are the second and twelfth largest reservoirs in California by capacity, respectively. The water from these reservoirs is used for agricultural, municipal, and industrial purposes and provides environmental services through wild and scenic rivers and managed wetlands. ORO is the keystone water storage facility of the State Water Project, which supplies water to 750,000 acres of farmland and to over 27 million Californians, supporting residential and industrial needs (DWR 2022).

The Yuba and Feather watersheds provide critical habitat for salmonids listed under the Endangered Species Act (Yuba Water Agency 2023, pp. E56–E91). Releases from ORO and NBB help maintain river flow rates and water temperatures, at optimal levels to support critical life stages such as spawning and smolt migration. The wetlands of the watersheds are part of the Pacific flyway, a vital habitat linkage, and provide refugia for at least 30 species of special-status wildlife (Sterling and Butner 2011). Freshwater releases from ORO and NBB also help control salinity intrusion into the Sacramento–San Joaquin Delta, which is essential for maintaining the health of the delta's ecosystems.

[1] All dollar values have been adjusted for inflation to 2023 dollars using the U.S. Bureau of Economic Affairs' 2023 price deflator.

The Federal Energy Regulatory Commission licenses hydroelectric facilities including the Edward Hyatt Power Plant at ORO and New Colgate Powerhouse at NBB. Beyond generating clean, carbon-free energy, these plants support the California electric grid with ancillary services, including load following, frequency regulation, both spinning and non-spinning reserves, voltage control, and black start capabilities, all critical for ensuring grid stability and reliability (FERC 2019).

Recreational activities at the ORO and NBB reservoirs include boating, fishing, and camping. On average, over 1.2 million people have visited ORO annually since 2002 (DWR 2023). Over 110,000 people visited NBB in 2012 (Yuba Water Agency 2017, Table 5-4). These activities provide direct benefits to residents and visitors and indirect benefits by driving tourism and supporting local businesses, sustaining employment in the hospitality and service sectors.

Roughly 63 percent of census tracts in Butte, Sutter, and Yuba Counties are listed as disadvantaged (DACs) or severely disadvantaged (SDACs) under California law (The Safe Drinking Water, Water Quality and Supply, Flood Control, River and Coastal Protection Bond Act of 2006). Flood risk, water insecurity, and energy burdens disproportionately affect frontline communities. By reducing flood risk, improving water supply availability, and providing renewable energy, ORO and NBB support vulnerable communities and populations. Without the flood protection and water supply availability provided by ORO and NBB, the continued growth of the communities of Yuba City, Marysville, Gridley, and Live Oak would be limited, and the $20 billion annual gross domestic product of Butte, Sutter, and Yuba Counties would be imperiled.

5.6.2 Methods and Analysis

This framework includes a list of required data, data sources, and methodologies that may be used in future evaluations (Table 5-4**Error! Reference source not found.**). The approach i nvolves identifying and enumerating benefits, providing background information, eliciting input from subject matter experts, and providing a qualitative discussion of potential benefits. For a quantitative analysis of FIRO's impacts, a hydrologic period of record analysis will be needed. This would identify trends, frequencies, and statistical characteristics of hydrologic events, pool elevations, and releases over time, allowing for a comparison of operations with and without FIRO alternatives. Such an analysis is anticipated to accompany the upcoming USACE WCM updates.

Table* 5*-4. *Economic benefits, data requirements, and methods.*

Benefit	Data Requirements	Methods
Flood risk reduction	Downstream stage- frequency curves over the full range of the frequency curve. Hydrologic and hydraulic analysis to develop the hydrologic loading. Inputs to USACE's HEC-FDA software from 2022 Central Valley Flood Protection Plan update.	Apply HEC-FDA to stage-frequency curves associated with FIRO alternatives to assess the economic value of flood risk reduction.
Water supply availability	Period of record conservation pool elevations. DWR (Department of Water	Use the DWR and U.S. Bureau of Reclamation CalSim water resources model to quantify potential changes in water supply associated

Benefit	Data Requirements	Methods
	Resources) Bulletin 132 Feather area water unit charge.	with FIRO alternatives. Use area water unit charges as an estimate of the value of water.
Ecological benefits	Period of record monthly streamflow and water temperature by water year type. Historical fish counts.	Empirically link fish populations to streamflow and water temperature. Estimate expected health of Endangered Species Act-listed populations with and without FIRO alternatives. Provide a qualitative estimate of economic value.
Hydropower generation	Period of record daily pool elevations by water year type. Hydropower management guidelines.	Use management decision support guidelines for hydropower facilities at ORO and NBB to estimate expected changes in hydropower generation with FIRO under different water year types.
Recreation benefits	Period of record annual pool elevations. Historical recreational usage numbers.	Estimate recreational usage as a function of summer pool elevations. Quantify the direct value of recreational activities using the Recreational Use Value Database (Rosenberger 2016).
Disadvantaged communities	U.S. Census Bureau; Centers for Disease Control and Prevention Social Vulnerability Index; U.S. Environmental Protection Agency EJ Screen; White House Climate and Economic Justice Screening Tool.	Quantify the distribution of flood risk reduction, water supply availability, energy provision, ecological benefits, and recreational benefits to disadvantaged communities and populations.
Climate resilience	Set of possible future climate scenarios. Hydrologic modeling, water resources engineering, and decision support tool analyses.	Repeat previous analyses under a set of future climate scenarios. Identify conditions under which FIRO may be most beneficial.

5.6.3 Highlights

- Over half of the structures in Butte, Sutter, and Yuba Counties are within 500-year floodplains (Figure 5-23), with combined structure, contents, and vehicle values of over $49 billion (Table 5-5). Most of these assets are protected by a levee system whose integrity depends on operations at Oroville and NBB. FIRO could increase operational flexibility, potentially producing economic benefits by reducing flood risk and providing co-benefits.
- 63% of census tracts downstream of Oroville and NBB are designated as DACs (31%) or SDACs (32%) (Figure 5-24). Benefits associated with FIRO are expected to accrue at least proportionally to DACs and SDACs. Hence, as a share of income, greater relative benefits are likely to accrue to disadvantaged communities.

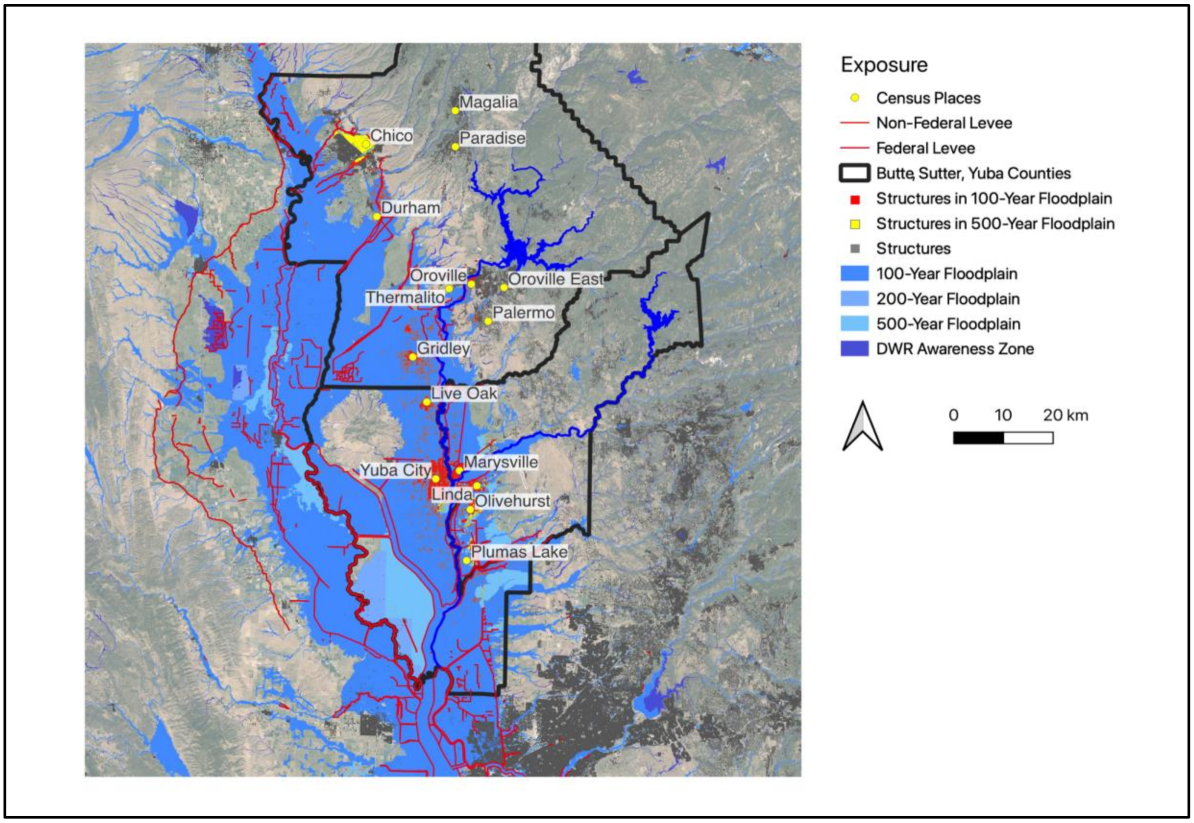


Figure 5-23. *Structures in 100-year, 200-year, and 500-year floodplains: Butte, Sutter, and Yuba Counties.*

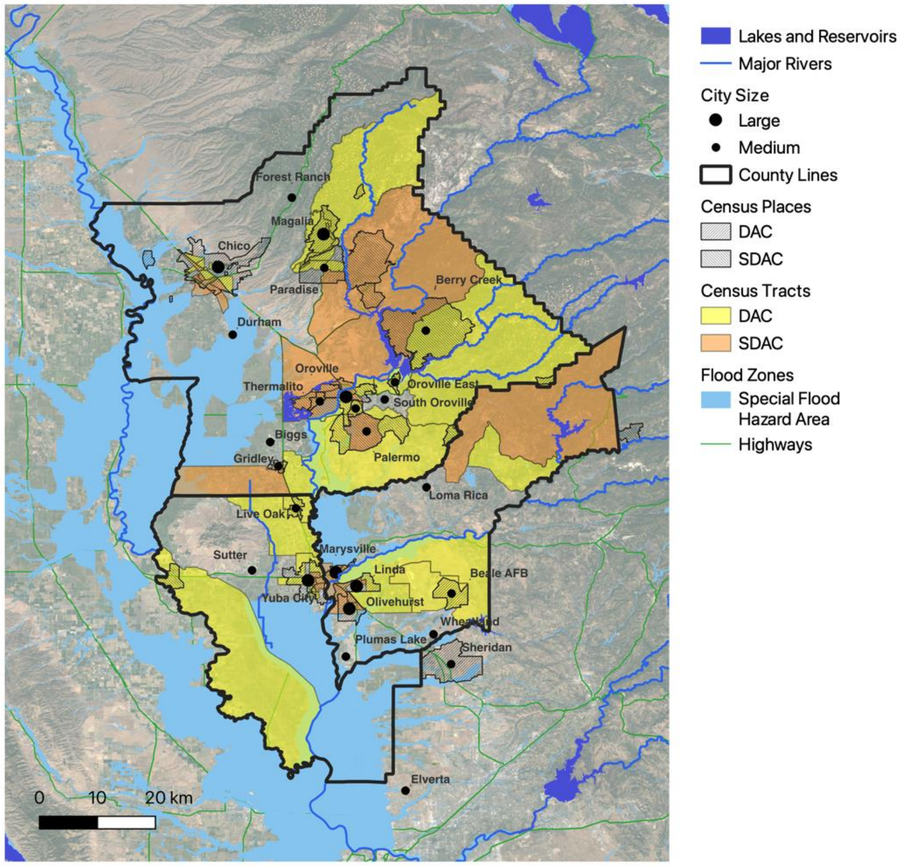


***Figure 5-24**. DACs in Butte, Sutter, and Yuba Counties.*

***Table 5-5.** Flood exposure in Butte, Sutter, and Yuba Counties.*

Exposure	100-Year Floodplain	500-Year Floodplain
Structures	$21.4 billion	$26.9 billion
Contents	$15.9 billion	$19.6 billion
Vehicles	$2.1 billion	$2.7 billion
Tota	$39.3 billion	$49.2 billion

5.6.4 Recommendations

- Conduct a HEC-FDA analysis of the economic value of flood risk reduction. This will require hydrologic and hydraulic analysis to develop the hydrologic loading, integrate a period of record simulation, and generate downstream stage-frequency curves over the full ranges of the frequency curves.
- Conduct a period of record analysis and use results to quantify the economic benefits of water supply availability, hydropower generation, recreation, and benefits to disadvantaged communities.
- Conduct a qualitative analysis of benefits to ecosystems and climate resilience.

5.6.5 References

DWR. (2022). *Central Valley flood protection plan 2022 update*.

DWR. (2023). *Fourteenth biennial recreation report: Oroville Facilities (FERC Project No. 2100)*.

FERC. (2019). *Final environmental impact statement for hydropower license: Yuba River Development Project (Project No. 2246-065—California)*. Federal Energy Regulatory Commission and U.S. Army Corps of Engineers. https://www.ferc.gov/sites/default/files/2020-06/01-02-19-FEIS.pdf

HDR. (2022). *Yuba Water flood risk management planning study*.

HDR and SWRI. (2007). *Final environmental impact report/environmental impact statement for the proposed Lower Yuba River Accord*. California Department of Water Resources, Yuba County Water Agency, and U.S. Department of the Interior Bureau of Reclamation.

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*. UC San Diego. https://escholarship.org/uc/item/3b63q04n

OCWD. (2019). *2017–2018 engineer's report on the groundwater conditions, water supply and basin utilization in the Orange County Water District*. https://www.ocwd.com/what-we-do/groundwater-management/engineer-recharge-reports/

Ralph, F. M., James, J., Leahigh, J., Anderson, M., Talbot, C., Haynes, A., Forbis, J., White, M., Lindley, S. (2022). *Yuba-Feather Forecast Informed Reservoir Operations: Preliminary Viability Assessment*. UC San Diego. https://escholarship.org/uc/item/8x57n58b

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

Sterling, J., & Buttner, P. (2011). *Wildlife known to use California ricelands* (3rd ed.). California Rice Commission. https://calrice.org/wp-content/uploads/2020/07/Species-Report.pdf

The Safe Drinking Water, Water Quality and Supply, Flood Control, River and Coastal Protection Bond Act of 2006, Cal. Pub. Res. Code § 75001 et seq. (2006). https://leginfo.legislature.ca.gov/faces/codes_displayexpandedbranch.xhtml?tocCode=PRC&division=43

USBR, Sonoma Water, & ERG. (2021). *Economic benefits of alternative reservoir operations: WaterSMART Basin Study Program—Reservoir Operations Pilot Study*.

Woodside, G. D., Hutchinson, A. S., Ralph, F. M., Talbot, C., Hartman, R., & Delaney, C. (2022). 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 Water Agency. (2017). *Amended application for new license Exh. E—environmental report.*

Yuba Water Agency. (2023). *Application for new license major project—existing dam: Volume II Exhibit E—environmental report, Narrows Hydroelectric Project (FERC Project No. 1403)*.

Section 6. Decision Support Tools

6.1 Introduction

Decision support tools (DSTs) are an essential component of reservoir operations. They are widely applied to support release decisions associated with many reservoirs. A decision support system (DSS) is an information system, built from a set of related tools, that supports decision making. A DSS for Forecast Informed Reservoir Operations (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 Water Control Plan (WCP) and the contextual information needed to confidently apply it. To facilitate that, a WCP 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 aid all those parties in making decisions related to water management 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 6-1 illustrates how a DSS could serve as a systemized WCP. It shows the different layers of information provided in a DSS and how different decision makers might interface with these layers.

This section reviews recommendations and findings from the Preliminary Viability Assessment (PVA), summarizes the existing Forecast-Coordinated Operations DSS (F-CO DSS) and its importance as a recommended DSS platform for implementing FIRO, and provides recommendations and findings for FIRO implementation as appropriate.

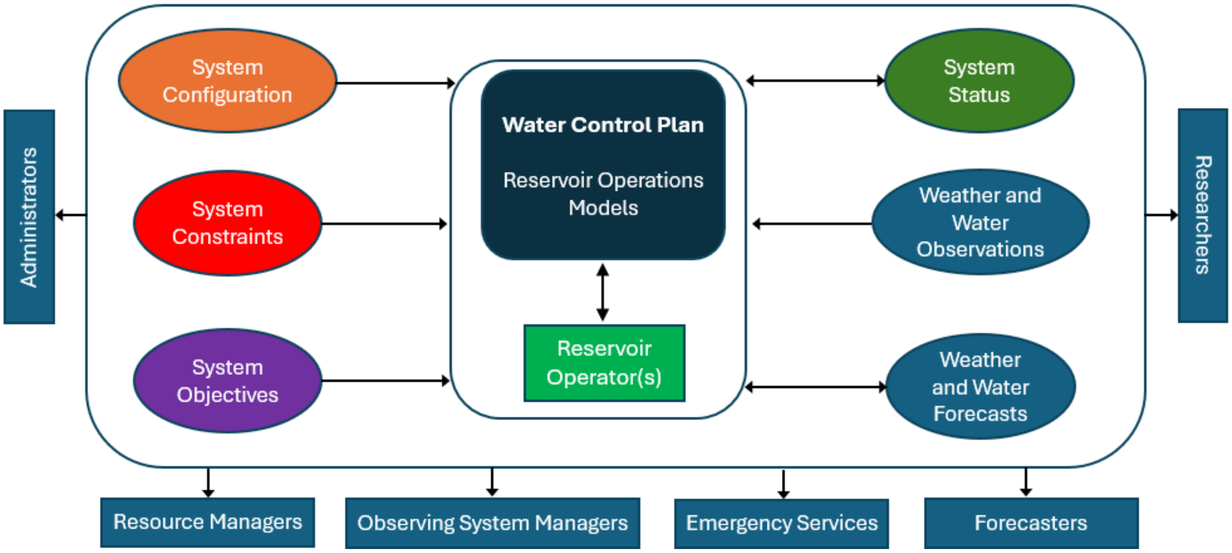


***Figure 6-1**. DSS as a systemized WCP.*

6.2 Review DSS Recommendations Identified in the PVA

For the PVA, the DST team completed an initial review of DST and DSS needs and made the following recommendations:

- Use the Yuba-Feather F-CO DSS as the framework for integrating FIRO codified in the Lake Oroville (ORO) and New Bullards Bar (NBB) Water Control Manual (WCM) updates.
- Improve overall understanding of available DSTs to provide a clearer picture and make more effective use of current and expected watershed conditions in the decision making process.
- Provide sustainable training on forecasting and observational DSTs.
- Ensure tools developed through the PVA/FVA process are fully described and made available for real-time operations through the Research and Operations Partnership.

One of the more notable findings is that reservoir operators and decision makers were most familiar and confident with the existing F-CO DSS, which meets existing operational needs. 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 coordination of reservoir releases. The F-CO DSS (including the U.S. Army Corps of Engineers' [USACE's] Hydrologic Engineering Center Reservoir System Simulation [HEC-ResSim] model) reflects procedures in the existing ORO and NBB WCPs that do not explicitly use forecast information (FIRO or another method) to formulate release options.

For the FVA, the focus has been on further developing the FIRO alternatives, improving forecast skill, and operationalizing FIRO parameters into the existing F-CO decision support system for testing and evaluation. During the FVA period, the water resources engineering (WRE) team, in coordination with the DST team and other FIRO technical teams, developed and evaluated various FIRO alternatives using HEC-ResSim and other reservoir operations simulation platforms (EFO). The DST team, assisted by the WRE team, considered DST needs for the FIRO alternatives. Also, during the FVA development period, the FIRO technical teams continued to invest in research and development of tools needed to improve forecast skill and observational data that will be important to FIRO's effectiveness in the Yuba-Feather system.

6.3 Description of the Existing DSS for the Yuba-Feather System

The Yuba-Feather FCO is a cooperative program between reservoir operators and regulatory agencies, created to facilitate systematic, coordinated decision making in an environment of incongruent operating rules. The program includes a common reservoir system operations model implemented within HEC-ResSim. That model is part of the F-CO program's 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 and accompanying F-CO DSS increases information exchange between forecasters, reservoir operators, managers, and the local communities.

The F-CO DSS helps coordinate reservoir operations that reduce the likelihood of damage at and below the confluence of the Yuba and Feather Rivers. FIRO provides a pathway and process for integrating the use of improved forecasts into operating procedures represented by the F-CO DSS and USACE's Corps Water Management System (CWMS).

6.4 Highlights and Recommendations

The F-CO DSS is currently the main DST for the coordinated operations of NBB and ORO. The DST team recommends the F-CO DSS be enhanced to provide continued support for FIRO implementation in coordination with the updates to the WCMs. The three major enhancements of the F-CO DSS that are needed to support the FIRO alternative are identified in Figure 6-2 below:

1. Update the ResSim model in the F-CO DSS with the new FIRO alternative.
2. Establish the new data streams and calculations (inflow volumes and target storage) that are needed as input to the ResSim model.
3. Modify the F-CO DSS user interface (with respect to tables and plots) to support decision making using FIRO operations.

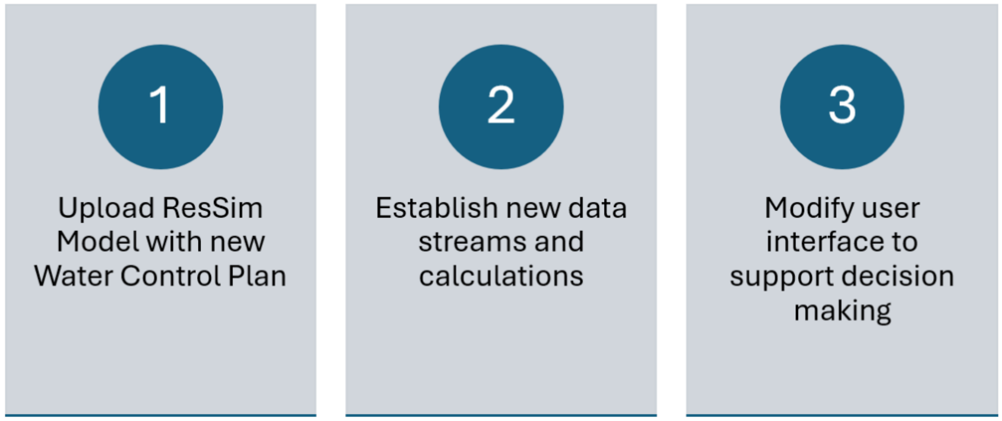


Figure 6-2. *DSS enhancements to support the FIRO alternative.*

Some of the initial enhancements to the ResSim model were completed during the development of the FVA and in support of the FIRO alternatives analysis. The initial recommended enhancements (some of which have already been implemented) include:

- **Routing updates.** The routing information has been updated from variable Lag & K to Muskingum to address identified during FVA development.
- **Englebright physical configuration updates.** Updated the Englebright Pool and notched spillway rating curves.
- **System operation updates.** The HEC-ResSim explicit system balance has been updated to span all reservoir zones.
- **NBB rule updates.** The FVA process yielded a recommendation to include the following rules in HEC-ResSim:
  - 50,000 cubic feet per second minimum release to "match inflow" at NBB.
  - 320,000 cubic feet per second maximum flow in the Feather River below the Bear River confluence (at Nicolaus).
  - A change to the Emergency Spillway Release Diagram rule to include a more sophisticated falling pool criteria that reflects the NBB WCM.

Additionally, the DST team recommends the development of a DST manual as part of the update to the WCMs. Such a manual would describe the tools and methodologies for coordinated operations of NBB and ORO; it would be an evolving document, updated to account for new data, new information, and new operations strategies as they are developed, tested, and integrated into the existing F-CO framework.

6.5 Reference

David Ford Consulting Engineers. (2008). *Oroville–New Bullards Bar Forecast-Coordinated Operations: Decision support system technical documentation.*

Section 7. FIRO WCM Roadmap

7.1 FVA and WCM Alignment Process

One of the principal goals of the Final Viability Assessment (FVA) for any Forecast Informed Reservoir Operations (FIRO) pilot project is to provide data, tools, information, results, and concepts that can be used for updated Water Control Plans (WCPs) in Water Control Manuals (WCMs). The required U.S. Army Corps of Engineers (USACE) process for updating a WCM can be complicated, so tailoring the technical work in the FVA to fit the WCM update process can realize efficiencies in resourcing and scheduling, delivering a revised WCM more quickly. To the extent practicable, both efforts use common foundational information such as hydrology and model tools. In addition, the FVA allows for an opportunity outside the formal WCM update process to explore concepts and strategies that may not be explored otherwise. The FVA technical analysis focuses on research and exploration, so it is not constrained by policy and regulatory restrictions. This allows for innovation and new ideas to be considered in the subsequent WCM update process. It must be noted that the FIRO PVA and FVA processes and results are fundamentally independent of the WCM update process (though they can be highly supportive where appropriate).

A unique development related to the Yuba-Feather FIRO project is that the USACE Sacramento District received funding to update the WCMs for Oroville Dam and New Bullards Bar Dam in March 2020, less than a year after the Yuba-Feather FIRO project started. The funding provided presented an opportunity to align the concurrent FIRO and WCM update projects.

7.2 Major Tasks, Deliverables, and Timeline

For the FIRO FVA and the WCM updates, the technical work had a significant overlap in time and resources. Also, USACE has a defined process for updating WCMs with parts that cannot be modified, so the FIRO deliverables had to work within those requirements to be supportive. For example, when updating a WCM, an environmental effects analysis adhering to the process outlined in the National Environmental Policy Act (NEPA) needs to be performed. Therefore, early efforts focused on identifying and organizing tasks under either the FIRO project or the WCM update project. The two efforts have nine main task areas in common:

- Define flood operation objectives and performance metrics.
- Define alternative development strategy.
- Define a baseline for the comparison of alternatives.
- Prepare hydrology for evaluation of the alternatives.
- Develop models and tools for alternative development and evaluation.
- Conduct basic performance evaluations.
- Develop system operations for promising alternatives.
- Conduct additional evaluation of promising alternatives.
- Identify recommended/selected alternatives.

These early efforts, including a multi-day FIRO-WCM alignment workshop, helped inform an overall FIRO-WCM alignment plan, in which subgroups were formed to synchronize with the work being done for the PVA and subsequently the FVA. The execution of the tasks and the results between the two efforts did not have to be the same. Rather, they were made equal where possible; if there were reasons for them to differ, that fact was noted and the difference was documented.

Below is the latest iteration of the FIRO-WCM update alignment schedule from USACE Sacramento District. Two of the major deliverables from the FIRO team to the WCM team were the list of potential alternatives with corresponding attributes in 2021, followed by candidate alternatives in 2023. The Yuba-Feather FVA published in early 2025 is a major milestone, and the WCM updates are scheduled to be completed, approved, and in use by the end of 2026.

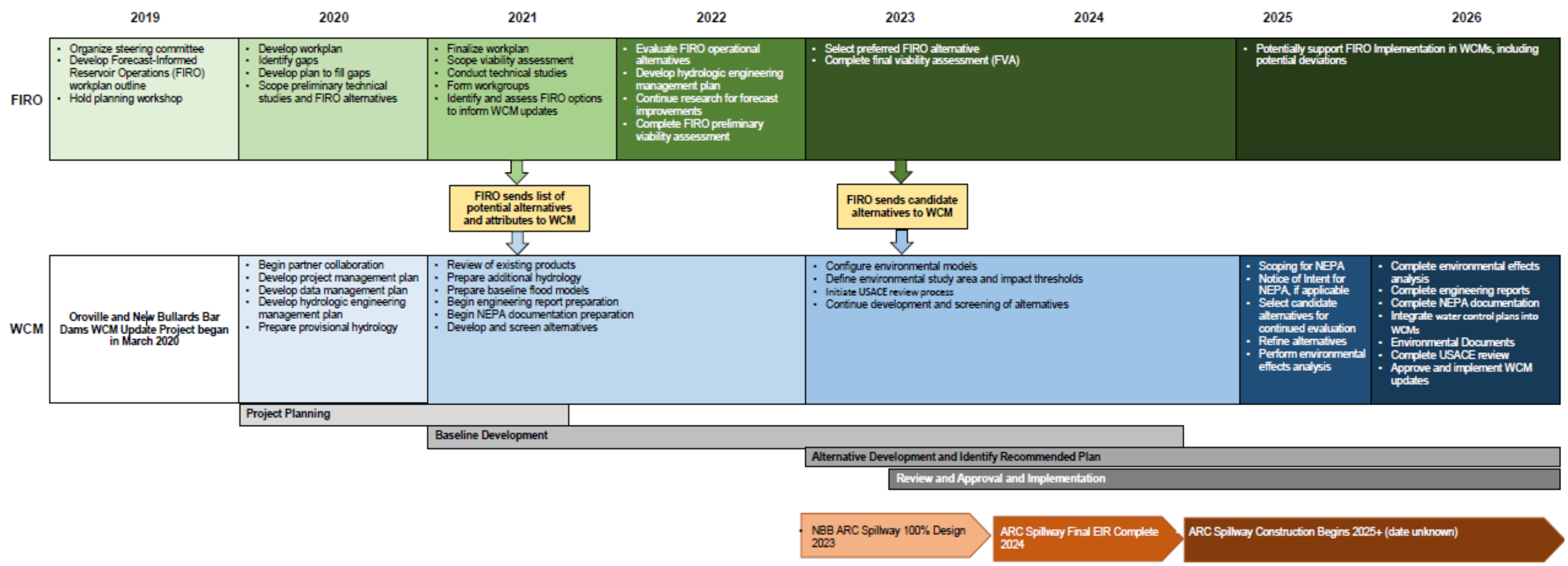


Figure 7-1. *FIRO-WCM update alignment schedule.*

7.3 Roles and Responsibilities

Resource management was a key challenge for the alignment of the FIRO and WCM update efforts, since the people working for each effort were largely the same. To help guide the alignment, a FIRO-WCM alignment committee developed the FIRO-WCM alignment plan, which established a WCM alignment leadership team with representatives from USACE, the California Department of Water Resources, the Yuba Water Agency, and the Center for Western Weather and Water Extremes (CW3E). The WCM alignment leadership team actively coordinated with the WCM update project to ensure the appropriate direction of the FIRO effort. The water resources engineering team of the FIRO FVA also coordinated closely with the WCM update project, since they were the subgroup providing the main deliverables to be leveraged in the WCM updates.

7.4 Ongoing Activities to Improve Forecast Skill

7.4.1 Observations

Since the inception of FIRO in the Yuba and Feather River watersheds, CW3E has added nine hydrometeorological stations in the watersheds to provide additional monitoring data and fill gaps in existing monitoring networks. This has included installing multiple meteorological stations that measure soil moisture, temperature, precipitation, humidity, wind speed and direction, air temperature, pressure, and solar radiation. Some of the stations have additional sensors that measure precipitation phase and freezing level using vertically pointing radar. CW3E has also installed four stream gauges in the watershed. Ongoing work in the spring/summer 2024 has included the installation of four stand-alone disdrometer stations and one surface meteorology station with a disdrometer to fill in gaps in precipitation phase data, rehabilitation of the Feather River Hydrologic Observatory to maintain soil moisture measurements, and the addition of a surface metrology and soil moisture station to fill spatial gaps in the Feather River watershed. Table 7-1 lists existing and planned stations.

Table 7-1. *CW3E stations, existing and planned, with the observations included for each station type.*

Station Type	Observations Included	Number Deployed/ Additional Stations Planned
Streamflow	• Stream stage measurement with pressure transducers	4/0
Surface meteorology and soil moisture	• Standard suite of meteorological sensors to measure temperature and relative humidity, precipitation amount, wind speed and direction, air pressure, and incoming solar radiation • Soil moisture and soil temperature	6/4
Rad Met	• Standard suite of meteorological sensors • Vertically pointing Micro Rain Radar to derive snow level in the atmosphere • Disdrometer to derive precipitation type • GPS to derive integrated water vapor • Sometimes soil moisture and soil temperature (one station)	2/0

Station Type	Observations Included	Number Deployed/ Additional Stations Planned
Disdro Met	• Standard suite of meteorological sensors • Disdrometer to derive precipitation type • Soil moisture and soil temperature • Snow depth • Sometimes snow water equivalent (1 station)	1/1
Stand-alone disdrometer	• Disdrometer to derive precipitation type	0/4

See Section 5.4.2.2 for brief explanations of Rad Met, Disdro Met, and Micro Rain Radar.

As these stations continue to operate and collect data, their period of record grows and they become increasingly more useful in forecast studies. At present all of them are publicly available on multiple platforms in near real time, including the California Data Exchange Center, MesoWest, and the National Oceanic and Atmospheric Administration's (NOAA's) Physical Sciences Laboratory (PSL). Precipitation data from CW3E's monitoring network are often used in the California Nevada River Forecast Center quantitative precipitation estimate products. CW3E additionally launches radiosondes, which measure a vertical profile of temperature, humidity, air pressure, wind speed, and direction as they ascend through the atmosphere attached to a weather balloon. The radiosondes are launched every three hours during atmospheric river (AR) conditions from Marysville, California, and travel across the Yuba River and Feather River watersheds. These observations are incorporated into the Global Telecommunications System and used to update the global circulation models in near real time.

7.4.2 AR Recon

Created by CW3E, with key support from the California Department of Water Resources and USACE, the AR Reconnaissance (AR Recon) Research and Operations Partnership is an annual program that leverages the Air Force Reserve Command's 53rd Weather Reconnaissance Squadron and the NOAA Aircraft Operations Center to fill critical data gaps needed to improve forecasts of landfalling ARs affecting the U.S. West Coast (Ralph et al. 2020). To accomplish this, AR Recon has built a robust international, interagency network of experts to actively monitor and investigate ARs in the North Pacific. The foundational data collection happens with dropsondes, which provide vertical profiles of temperature, humidity, winds, and pressure; these profiles are then sent directly to a global data storage tank and are assimilated by multiple operational global numerical weather prediction (NWP) models, including the Global Forecast System (GFS), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Navy Global Environmental Model (NAVGEM). These campaigns have led directly to documented improvements in forecasting skill (Stone et al. 2020; Lord et al. 2023a, b; DeHaan et al. 2023; Zheng et al. 2021, among many others), and advanced our underlying understanding of ARs (e.g., Cannon et al. 2020; Cobb et al. 2021). The improved forecasts support the "F" in FIRO by arming reservoir operators with better tools to more precisely determine when and how much water to release ahead of storms. AR Recon is a critical input to FIRO-enabled adaptation to more frequent and severe weather events while building drought resilience. AR Recon is conducted from November 1 to March 31 each year. Each year, significant effort is put into assessing data impact, assessing novel observing strategies, and making targeting strategy improvements for subsequent years (e.g., Lavers et al. 2024; Wilson et al. 2022).

7.4.3 Decision Support Tools

The Yuba-Feather Forecast-Coordinated Operation (F-CO) program is a cooperative program between reservoir operators and regulatory agencies, created to facilitate systematic, coordinated decision making in an environment of incongruent operating rules. The program includes a common reservoir system operations model implemented within the USACE Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim). 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 and accompanying F-CO DSS increases information exchange between forecasters, reservoir operators, managers, and the local communities.

F-CO is currently operational and is the main decision support tool (DST) for the coordinated operations of NBB and Oroville. It can support the preferred FIRO alternative with minor enhancements, including minor modifications to HEC-ResSim to incorporate the new rules developed through the engineering analysis described in Section 3 and Section 4. A DST manual could be developed as part of the updated WCMs that will describe the tools and methodologies for coordinated operations of New Bullards Bar and Oroville. It would be an evolving document, updated to account for new data, new information, and new operations strategies as they are developed, tested, and integrated into the existing F-CO framework.

7.5 Ongoing Coordination and Communication

As the FIRO effort pivots from the FVA to FIRO implementation via the WCM updates underway by USACE Sacramento District, the Steering Committee will be reconstituted. A smaller group and less frequent meetings are anticipated. Work will continue on several fronts as articulated in other sections of this roadmap, including continued work on forecast skill improvement and associated needs (e.g., improved observations); support to USACE in its work to finalize the WCM updates for both reservoirs, including the NEPA process; extracting lessons learned from the Lake Mendocino WCM update, the first to incorporate FIRO; and outreach as needed to communicate important milestones such as WCM deviations (if initiated), ARC spillway construction progress, and benefits associated with FIRO operations. The communications work team will spearhead public outreach and engagement. Their tasks may include producing press releases, fact sheets, videos, FAQs and other outreach materials as requested by the Steering Committee. The team will also document lessons learned from the Yuba-Feather FIRO process for the benefit of future FIRO projects.

7.6 References

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 over Southern California on 2 February 2019. *Weather and Forecasting*, *35*(5), 2083–2097. https://doi.org/10.1175/WAF-D-20-0012.1

Cobb, A., Michaelis, A., Iacobellis, S., Ralph, F. M., & Delle Monache, L. (2021). Atmospheric river sectors: Definition and characteristics observed using dropsondes from 2014–20 CalWater and AR Recon. *Monthly Weather Review*, *149*(3), 623–644. https://doi.org/10.1175/MWR-D-20-0177.1

David Ford Consulting Engineers. (2008). *Oroville–New Bullards Bar Forecast-Coordinated Operations: Decision support system technical documentation.*

DeHaan, L. L., Wilson, A. M., Kawzenuk, B., Zheng, M., Monache, L. D., Wu, X., Lavers, D. A., Ingleby, B., Tallapragada, V., Pappenberger, F., & Ralph, F. M. (2023). Impacts of dropsonde observations on forecasts of atmospheric rivers and associated precipitation in the NCEP GFS and ECMWF IFS models. *Weather and Forecasting*, *38*(12), 2397–2413. https://doi.org/10.1175/WAF-D-23-0025.1

Lavers, D. A., Wilson, A. M., Ralph, F. M., Tallapragada, V., Pappenberger, F., Reynolds, C., Doyle, J. D., Delle Monache, L., Davis, C., Subramanian, A., Torn, R. D., Cordeira, J. M., Centurioni, L., & Haase, J. S. (2024). Advancing atmospheric river science and inspiring future development of the Atmospheric River Reconnaissance Program. *Bulletin of the American Meteorological Society*, *105*(1), E75–E83. https://doi.org/10.1175/BAMS-D-23-0278.1

Lord, S. J., Wu, X., Tallapragada, V., & Ralph, F. M. (2023). The impact of dropsonde data on the performance of the NCEP Global Forecast System during the 2020 Atmospheric Rivers Observing Campaign. Part I: Precipitation. *Weather and Forecasting*, *38*(1), 17–45. https://doi.org/10.1175/WAF-D-22-0036.1

Lord, S. J., Wu, X., Tallapragada, V., & Ralph, F. M. (2023). The impact of dropsonde data on the performance of the NCEP Global Forecast System during the 2020 Atmospheric Rivers Observing Campaign. Part II: Dynamic variables and humidity. *Weather and Forecasting*, *38*(5), 721–752. https://doi.org/10.1175/WAF-D-22-0072.1

Ralph, F. M., Cannon, F., Tallapragada, V., Davis, C. A., Doyle, J. D., Pappenberger, F., Subramanian, A., Wilson, A. M., Lavers, D. A., Reynolds, C. A., Haase, J. S., Centurioni, L., Ingleby, B., Rutz, J. J., Cordeira, J. M., Zheng, M., Hecht, C., Kawzenuk, B., & Delle Monache, L. (2020). West Coast forecast challenges and development of atmospheric river reconnaissance. *Bulletin of the American Meteorological Society*, *101*(8), E1357–E1377. https://doi.org/10.1175/BAMS-D-19-0183.1

Stone, R. E., Reynolds, C. A., Doyle, J. D., Langland, R. H., Baker, N. L., Lavers, D. A., & Ralph, F. M. (2020). Atmospheric river reconnaissance observation impact in the Navy Global Forecast System. *Monthly Weather Review*, *148*(2), 763–782. https://doi.org/10.1175/MWR-D-19-0101.1

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*(3), E810–E816. https://doi.org/10.1175/BAMS-D-21-0259.1

Zheng, M., Delle Monache, L., Cornuelle, B. D., Ralph, F. M., Tallapragada, V. S., Subramanian, A., Haase, J. S., Zhang, Z., Wu, X., Murphy, M. J., Higgins, T. B., & DeHaan, L. (2021). Improved forecast skill through the assimilation of dropsonde observations from the Atmospheric River Reconnaissance Program. *Journal of Geophysical Research: Atmospheres*, *126*(21), e2021JD034967. https://doi.org/10.1029/2021JD034967