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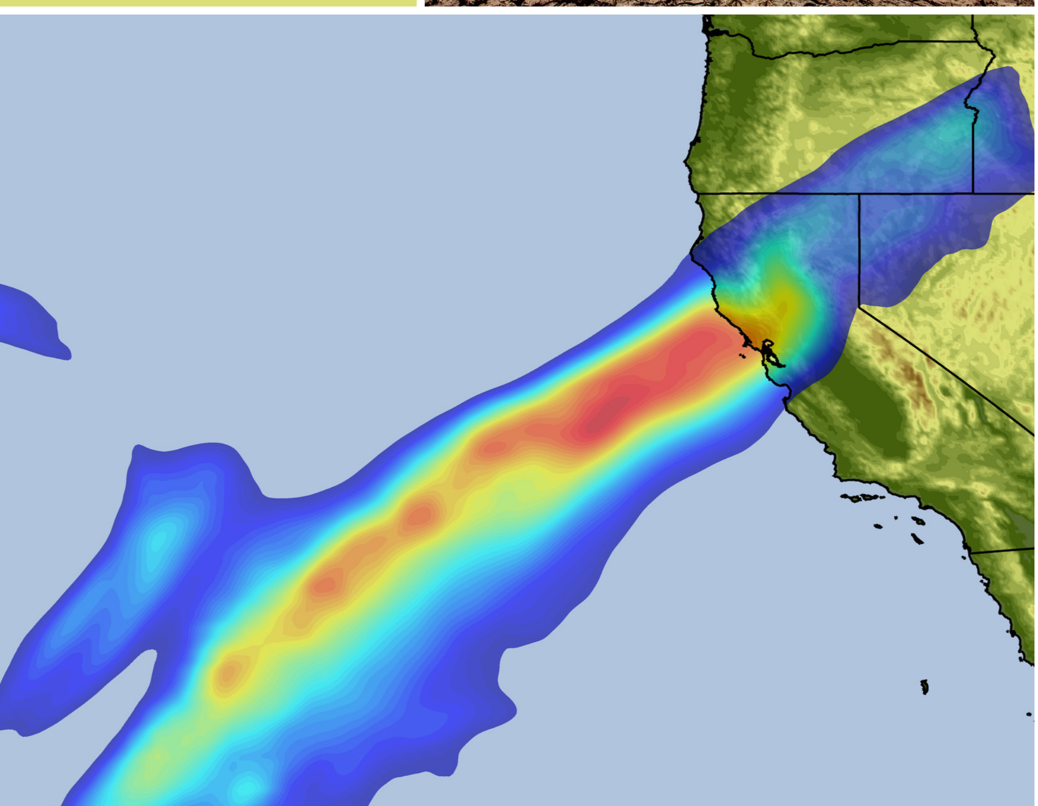
DEPARTMENT OF WATER RESOURCES · STATE OF CALIFORNIA

Sonoma Water

Lake Mendocino
FORECAST INFORMED RESERVOIR OPERATIONS

Final Viability Assessment

December 2020



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The final viability assessment (FVA) for Lake Mendocino was produced by the Lake Mendocino FIRO Steering Committee. The FVA does not address all USACE regulations and requirements for a potential update of the Water Control Manual at Coyote Valley Dam-Lake Mendocino. Because each watershed and location is unique, the analysis, results, and conclusions of the FVA are only applicable to Lake Mendocino.

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Dedication

We wish to dedicate this document to Mike Dillabough of the U.S. Army Corps of Engineers and David Ford of HDR-David Ford Consulting Engineers. Mike and David were critical to the success of FIRO at Lake Mendocino and beyond. Their contributions will be long-lasting and they will be sorely missed by all who had the pleasure of knowing and working with them.

Mike Dillabough

Mike committed himself diligently to this effort from the very beginning, in 2014, until he was unable to continue serving on the Steering Committee due to health reasons. Mike's dedication to the Corps' mission was well known and his service to the community day in and day out was a constant. He had a curious nature and was willing to explore new and innovative solutions to challenges. He also embraced teamwork, partnerships, and collaboration. Mike admirably represented USACE and was always deliberate, practical, and measured in his approach. He was a strong influence in setting a positive direction for FIRO, and his contributions will endure. We deeply miss his humor, thoughtfulness, and respectful engagement.

David Ford

David played important roles in the development of FIRO at Lake Mendocino, and thereby for FIRO overall. He brought credibility to the developing project—credibility earned through a long career making a difference in water resources engineering. His risk assessment work in 2004 examining the 1997 California floods highlighted the risk to a major urban center. The estimated impacts approached $50 billion, which was hard for people to accept. Sadly, that scope of risk was demonstrated just a year later, in New Orleans, with more than 1,000 fatalities and $100 billion in damage. David brought a unique perspective, deep experience, and guidance that were baked into the FIRO process, and thus are infused throughout this Final Viability Assessment. He was a dear friend to many of us and he stayed engaged in FIRO, commenting on various documents, throughout his illness.

Mike and David will be fondly remembered and deeply missed.

Contributors

The Lake Mendocino forecast informed reservoir operations (FIRO) draft final viability assessment (FVA) is the result of a collaborative and cooperative effort by a team of federal, state, and county agency representatives, academicians, and consultants. In addition to the Steering Committee members and staff listed above, we would like to thank the following individuals who provided thoughtful input, hours of their time on working groups, and insights and perspectives that were invaluable throughout this process. In particular, we wish to thank Grant Davis, General Manager of Sonoma Water, and Sean Smith, Principal Hydrologic and Hydraulic Engineer at the U.S. Army Corps of Engineers (USACE), for their ongoing leadership, enthusiasm, and support.

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External Expert Panel Reviewers

We also wish to thank our expert reviewers, who provided valuable comments and suggestions on the draft Final Viability Assessment. Their review led to significant improvements in the document, for which the Steering Committee is most appreciative.

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Jerry Cotter, *USACE, Fort Worth District*

Abbreviations

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

Abbreviation	Definition
ac-ft	acre-feet
AEP	annual exceedance probability
AMS	American Meteorological Society
AR	atmospheric river
CDEC	California Data Exchange Center
CEQA	California Environmental Quality Act
cfs	cubic feet per second
CNRFC	California-Nevada River Forecast Center
CW3E	Center for Western Weather and Water Extremes
DSS	decision support system
DWR	California Department of Water Resources
EAD	expected annual damage
ECMWF	European Centre for Medium-Range Weather Forecasts
EFO	Ensemble Forecast Operations
ER	Engineering Regulation
FERC	Federal Energy Regulatory Commission
ft	feet
FIRO	Forecast Informed Reservoir Operations
FVA	Final Viability Assessment
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HAS	Hydrometeorological Analysis and Support
HEC	Hydrologic Engineering Center
HEC-FIA	HEC Flood Impact Analysis
HEC-RAS	HEC River Analysis System
HEC-ResSim	HEC Reservoir System Simulation
HEC-WAT	HEC Watershed Analysis Tool
HEMP	hydrologic engineering management plan
hr	hour
HRRR	High-Resolution Rapid Refresh
in	inches
IVT	integrated water vapor transport
IWV	integrated water vapor
MPAS	Model for Prediction Across Scales
NCEP	National Centers for Environmental Prediction
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NWM	National Weather Model
NWP	numerical weather prediction
NWS	National Weather Service
PG&E	Pacific Gas and Electric Company
PVA	Preliminary Viability Assessment
PVID	Potter Valley Irrigation District
PVP	Potter Valley Project

Abbreviation	Definition
QPF	quantitative precipitation forecast
R^2	coefficient of determination
RMSE	root mean square error
S2S	subseasonal-to-seasonal
SIO	Scripps Institution of Oceanography
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WCM	Water Control Manual
WCP	Water Control Plan
WPC	Weather Prediction Center
WRF	Weather Research and Forecasting Model
WY	water year

Executive Summary

This Final Viability Assessment (FVA) is the culmination of a six-year effort led by the Lake Mendocino Forecast Informed Reservoir Operations (FIRO) multi-agency Steering Committee. The purpose of the FVA is to demonstrate the viability of FIRO and to ultimately support the U.S. Army Corps of Engineers' (USACE) approval and adoption of FIRO-based operations in the Lake Mendocino Water Control Manual (WCM). This FVA establishes the basis and pathway for updating the WCM to explicitly incorporate forecasts in order to improve water supply reliability and environmental conditions in the Upper Russian River watershed.

Project Overview

What is FIRO?

FIRO is a flexible water management approach that uses data from watershed monitoring and improved weather and hydrologic forecasting to help water managers selectively retain or release water from reservoirs in a manner that can adapt to weather extremes and that leverages advancements in the science of meteorological and hydrologic forecasting. FIRO represents an innovative use of emerging science and technology to optimize limited resources and adapt to changing climate conditions without costly reservoir infrastructure improvements. In 2020, the American Meteorological Society formalized a definition of FIRO (see text box below), which was initiated by the Steering Committee.

> FIRO is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts (American Meteorological Society, 2020).

The Case for FIRO at Lake Mendocino

FIRO offers the potential to inform reservoir management decisions at Lake Mendocino with improved awareness and forecasting of atmospheric rivers (ARs) and their extremes and absences, which lead to floods and droughts, respectively. The goal of FIRO at Lake Mendocino is to increase water supply reliability without reducing—and while possibly enhancing—the existing flood protection capacity of Lake Mendocino and downstream flows for fisheries habitat.

Lake Mendocino offers an ideal setting for FIRO for several reasons. The Russian River basin experiences some of the most variable climate in the U.S., and ARs are responsible for these extremes. In addition, Lake Mendocino has experienced significantly reduced water supply reliability since diversions from the Eel River were decreased in 2006. This is an opportune time to update the 1950s-era WCM (with minor revisions in 1986) to benefit from modern weather and streamflow forecasting improvements to increase resilience and water supply reliability.

Project Approach

The FVA was developed by a Steering Committee consisting of a Research and Operations Partnership (RAOP; Ralph et al. 2020) co-chaired by the Center for Western Weather and Water Extremes (CW3E) and Sonoma Water. The Committee followed a systematic approach for assessing FIRO viability, as described in the Lake Mendocino FIRO Work Plan (2016). A Preliminary Viability Assessment (PVA) in 2017 contained research, technical studies, and a path forward for the FVA. The FVA was informed by collecting observational data, conducting research, modeling FIRO alternatives, and testing FIRO operations via USACE-approved major deviations from the Lake Mendocino WCM.

"This is exactly how we want the federal government to operate."

Jaime Shimek

Minority Clerk, House Committee on Appropriations,

Energy and Water Development and Related Agencies Subcommittee

April 12, 2018

Key Finding: FIRO is Currently Viable at Lake Mendocino and Will Deliver Significant Benefits

Viability with Current Forecast Skill

Flooding and water supply in the Russian River basin are driven almost entirely by ARs, so the success of FIRO at Lake Mendocino will depend on forecasting ARs well. This has allowed the FIRO team to focus efficiently on understanding the role of ARs to improve reservoir operations. The focus on ARs is particularly advantageous because ARs can develop across half the width of the Pacific Ocean (Figure E.1), which provides a long lead time for forecasting.

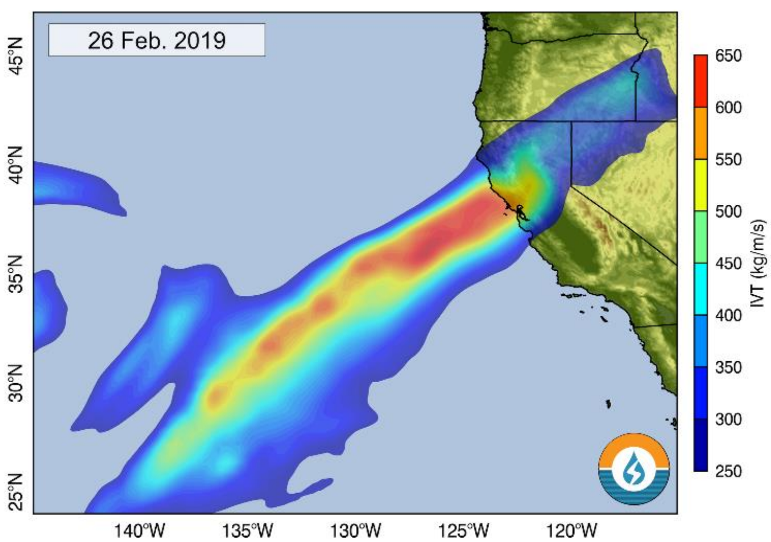

Figure E.1. *An AR making landfall in the Russian River area on February 26, 2019. Shading represents integrated water vapor transport (IVT), which indicates the strength of the AR.*

A large body of observation, science, modeling, and tools have enabled prediction of ARs and associated precipitation and runoff to be of sufficient skill to support FIRO at Lake Mendocino. This body of work includes important contributions by CW3E, including an AR scale to distinguish between beneficial and hazardous ARs, a landfall tool to predict AR location, and the AR Reconnaissance program, which fills major gaps in observations over the ocean, especially within ARs. These additional observations feed into global weather forecast models and improve their accuracy.

Results from Operational Testing at Lake Mendocino

Planned major deviations provided USACE with the flexibility to apply the Hybrid Ensemble Forecast Operations (EFO) model in real-world operations during water years (WYs) 2019 and 2020. The Hybrid EFO adds a variable buffer pool to the guide curve and uses a 15-day streamflow ensemble forecast to recommend flood releases. WY 2019 was a relatively wet year, while WY 2020 was the third driest year over a 127-year record. In both years, FIRO increased water supply benefits and managed flood risks. Figure E.2 shows the outcome for WY 2020, where FIRO enabled a 19 percent increase in water storage by the end of winter.

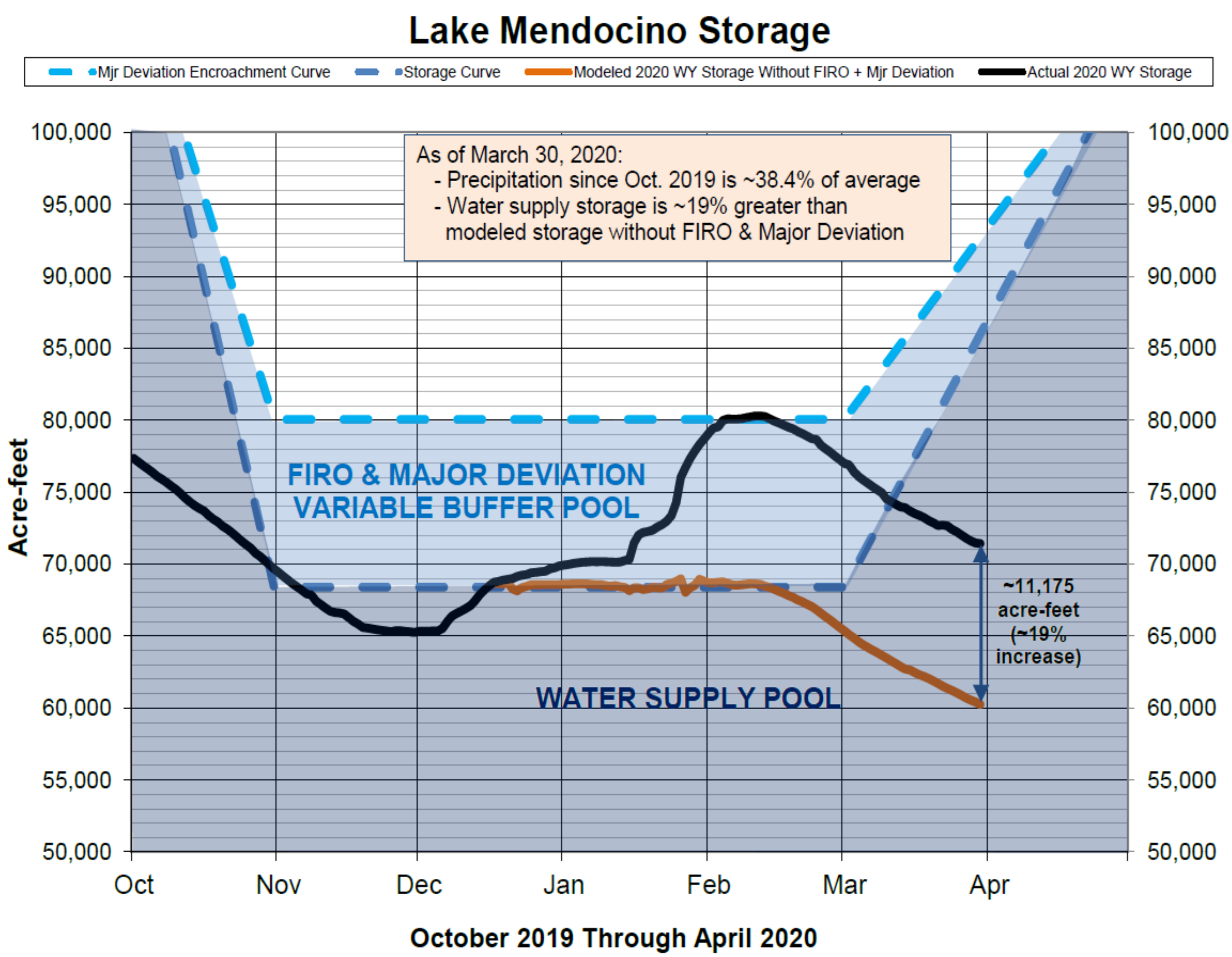

Figure E.2. *Lake Mendocino storage increased by 19 percent (more than 11,000 acre-feet) during major deviation operations in WY 2020.*

Alternatives Analysis and Modeled Benefits

Four FIRO management options were evaluated, in addition to the current operations, using 16 objective metrics (Table E.1). All four alternatives have various forms of flexibility in operations to allow more water storage to be carried into the dry season safely to avoid water supply shortages, and to allow reservoir levels to be lowered below the guide curve to enable additional flood protection when major storms are predicted.

Table E.1. *Evaluated WCP alternatives and increases in median May 10th Lake Mendocino reservoir storage over baseline WCM operations. Modified Hybrid EFO is the Steering Committee's preferred option.*

Alternative	Description	Percent Increase in Median May 10th Storage
Existing Operation (Baseline)	Includes the seasonal guide curve and release selection rules from the 1986 USACE WCM and 2003 update to the flood control diagram.	0%
EFO	Operates without a traditional guide curve and uses the 15-day ensemble streamflow forecasts to identify required flood releases.	27%
Hybrid EFO	A combination of the baseline approach and the EFO. This option was used for major deviation operations in WYs 2019 and 2020.	15%
Modified Hybrid EFO	Identical to Hybrid EFO, but with a "corner-cutting" strategy that allows for greater storage to begin February 15 to aid with spring refill. **Preferred option for near-term implementation.**	20%
Five-Day Deterministic Forecast	Defines alternative guide curves with 11,000 acre-feet encroachment space and 10,000 acre-feet draft space above and below the baseline guide curve. Uses five-day deterministic streamflow forecasts to choose the guide curve and make release decisions.	18%

Analysis shows that all four FIRO alternatives would improve water supply reliability while retaining, or even enhancing, flood risk management and environmental objectives relative to baseline operations. **After considering all evaluation criteria, the Modified Hybrid EFO is the preferred option for near-term implementation.** This option ranks favorably across all metrics, can be implemented feasibly with USACE standard decision tools, explicitly uses the uncertainty in streamflow forecasts, and offers a pathway for growth with improving forecast skill and model refinements. The Steering Committee also identified EFO as a "reach" option to consider pursuing in the future.

The Steering Committee conducted an economic assessment to quantify the benefits of FIRO for dam operations, water supply, fisheries, recreation, and hydropower. FIRO will lead to positive benefits in all these areas except hydropower. The Modified Hybrid EFO results in total estimated annual benefits of $9.4 million. The "reach" alternative, EFO, has estimated total annual benefits of $9.9 million.

The Steering Committee also conducted a fisheries temperature study, which concluded that EFO and Modified Hybrid EFO would offer the greatest benefits to summer rearing juvenile steelhead, while an analysis of high-flow frequency concluded that FIRO is unlikely to negatively affect Chinook salmon spawning and migration. A flood risk study found no significant difference between the baseline and the FIRO alternatives when measuring damages to structures and contents. However, when considering populations at risk in addition to damages, all FIRO alternatives would significantly reduce risk upstream from Hacienda Bridge (near Guerneville).

Key Finding: Further Investment in Research Will Increase Future Benefits at Lake Mendocino and Transferability to Other Locations

Opportunity for Continued Improvement in FIRO at Lake Mendocino

Current forecasts are already adequate to support FIRO. Given the significant improvements in forecast skill that have been possible in just the past decade, and given many promising leads in ongoing AR research, there is ample reason to believe that even greater benefits may be possible with enhanced FIRO in the future. This future phase—dubbed "FIRO 2.0"—will be important to further improving water supply reliability and adapting to a changing climate.

FIRO 2.0 will require support for enhanced observations and forecasting, modeling, and decision support tools. Figure E.3 shows, conceptually, how investing in research to improve precipitation and streamflow forecasts will eventually make FIRO 2.0 possible. This evolution recognizes that even greater operational improvements can be realized via scientific advances that continued research will bring.

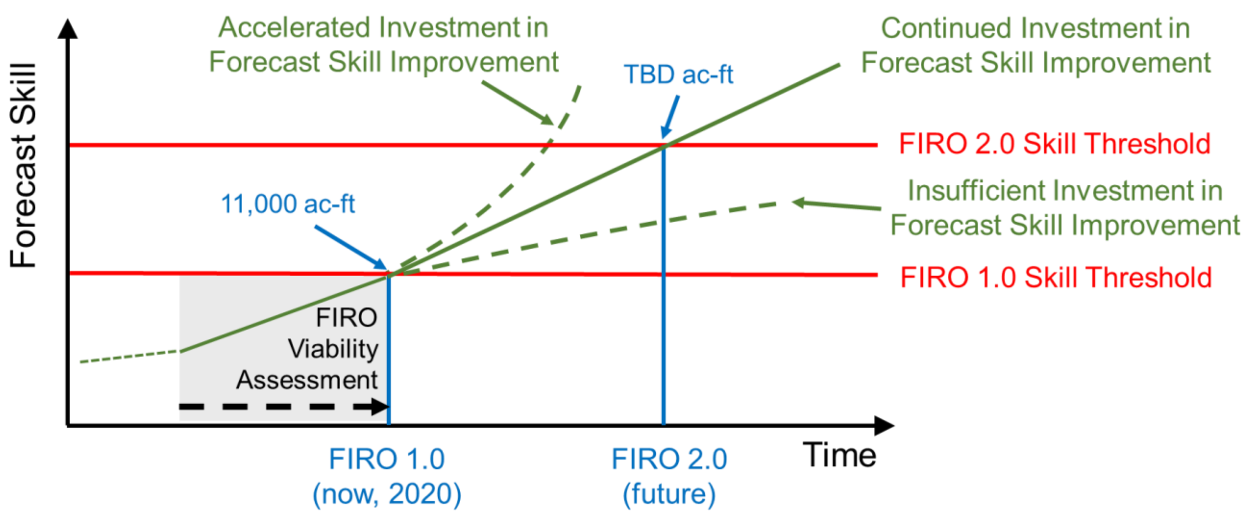

Figure E.3. *Conceptual diagram of the evolution of FIRO 2.0 for Lake Mendocino.*

Transferability of FIRO to Other Locations

USACE and CW3E are also actively assessing FIRO opportunities in other settings, starting with AR-dominated systems. Efforts are underway to apply FIRO to Prado Reservoir, New Bullards Bar Reservoir, and Lake Oroville in California, as well as the Howard Hanson Dam in Washington. These projects will yield valuable insights on the characteristics of FIRO viability for very different sites. This knowledge is being incorporated into a screening tool that will help prioritize further FIRO viability assessments at other sites across the United States.

Key Finding: This Research and Operations Partnership Offers a Model for Successful Collaboration

By building a partnership between research and operations right from the start, the Steering Committee achieved several outcomes that make this a model for future FIRO assessments:

- The composition and structure of the Steering Committee created an atmosphere of trust, cooperation, and engagement. The Committee setting provided a safe space for exploration and a forum to seek common ground among flood risk management, water supply reliability, and ecological interests, ultimately resulting in a "win-win" for formerly competing interests.

- FIRO represents a major policy change for USACE, so support from multiple levels of USACE was of great value to the project.
- Positioning this effort within the realm of research and development enabled exploration of how science and engineering can support operational improvements.

Recommendations

The Steering Committee recommends updating the WCM to include the concept of "FIRO Space" consistent with the Modified Hybrid EFO model. When forecast skill improves, it may be appropriate to implement FIRO 2.0 as the next phase of operations (Figure E.4). This phased movement would be triggered by improvements in a specific set of forecast skill metrics—defined in the WCM—that correspond to the required level of improvements in reservoir operator confidence.

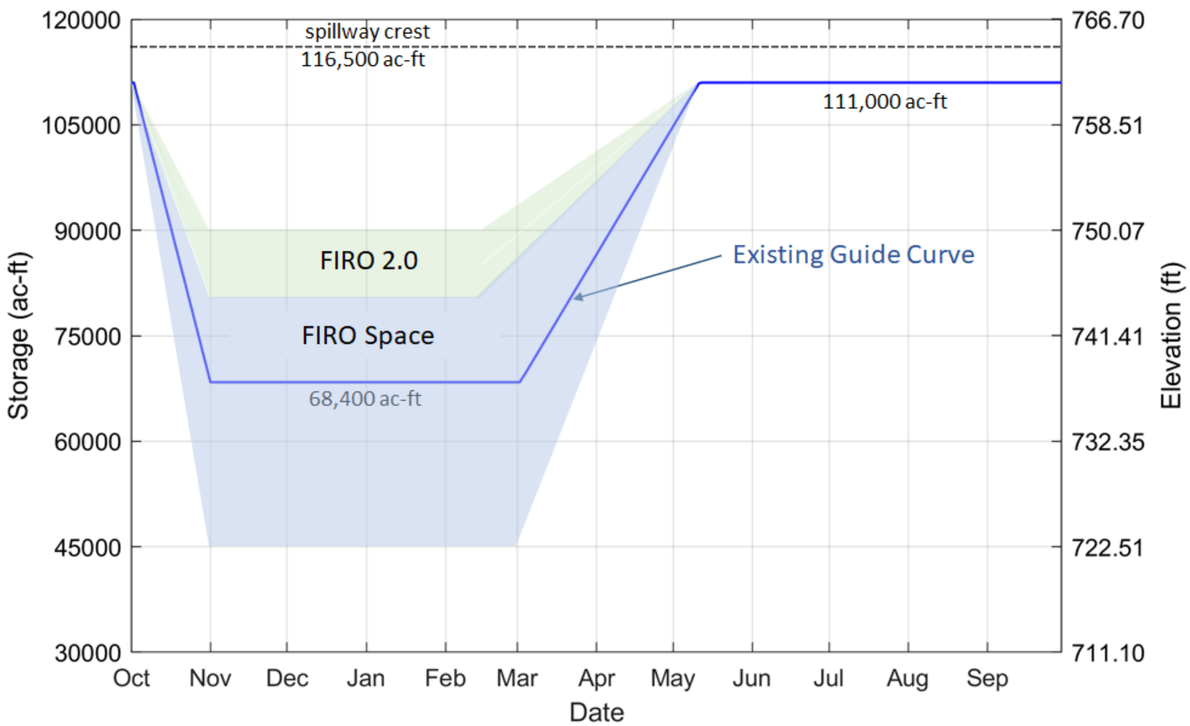

Figure E.4. *Conceptual FIRO Space for Lake Mendocino.*

This FVA also recommends three steps to continue the evolution of FIRO:

- Support and continue developing even better FIRO decision support tools, models, and observations.
- Continue investments to improve forecast skill and to develop reservoir operations models that even more effectively leverage forecast skill.
- The Steering Committee should continue its activities to support updates of the Lake Mendocino WCM.

Section 1. Introduction

1.1 Overview

This Final Viability Assessment (FVA) represents the culmination of a six-year effort, led by the Lake Mendocino Forecast Informed Reservoir Operations (FIRO) Steering Committee, to demonstrate the viability of FIRO and ultimately support adoption of FIRO-based operations by the U.S. Army Corps of Engineers (USACE) in the Lake Mendocino Water Control Manual (WCM). Since 2014, the Steering Committee has collaborated to produce a significant body of technical and scientific work covering watershed and atmospheric observations, forecast analyses, interim operations, parallel modeling applications, a hydrologic engineering management plan (HEMP) to evaluate management alternatives, and decision support system (DSS).

This collaborative effort has demonstrated that weather and water forecasts can be used to improve the operation of Lake Mendocino for increased water supply reliability without compromising—and while potentially improving—flood risk management. In addition, significant environmental benefits may be achieved by improving downstream habitat conditions (e.g., temperature and low flow compliance) for three species of endangered salmonids. These conclusions were reached through studies conducted by the USACE's Hydrologic Engineering Center (HEC), Scripps Institution of Oceanography's Center for Western Weather and Water Extremes (CW3E), and Sonoma Water. The body of this assessment describes these studies in detail.

This FVA has been developed in cooperation with USACE San Francisco District, Sacramento District, Engineer Research and Development Center, and the South Pacific Division. The FVA builds on the Lake Mendocino FIRO Work Plan (FIRO Steering Committee 2015) and the Preliminary Viability Assessment (FIRO Steering Committee 2017). The Preliminary Viability Assessment (PVA) outlined a significant body of research, technical studies, and a process for moving to the FVA provided here.

The Steering Committee followed a systematic method for assessing FIRO viability. The process and schedule for conducting the FVA and goals for its implementation are shown in Figure 1.1.

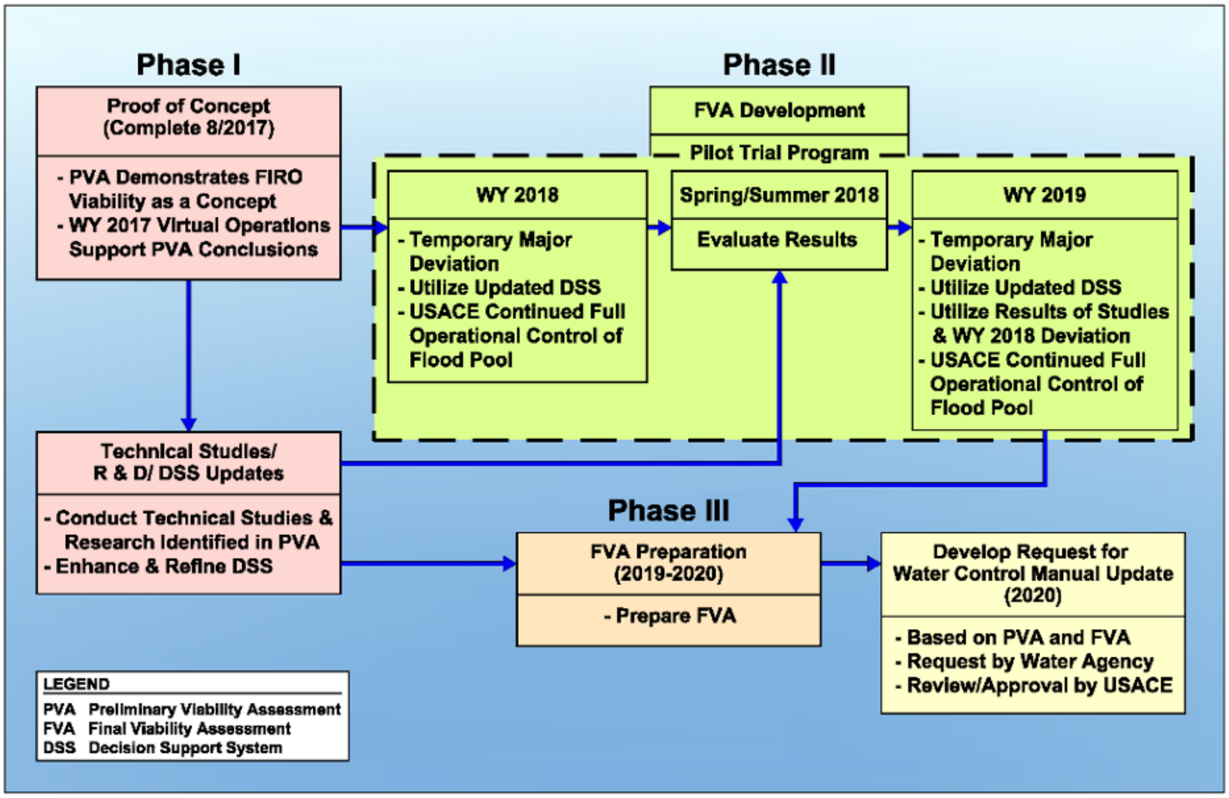

Figure 1.1. *The initial process diagram and timeline for the FIRO program at Lake Mendocino, consisting of three phases for moving from the PVA to the request for a change to the WCM. Note that Phase II was delayed one year from the initial plan. This FVA document is represented by the beige box under Phase III. It will be followed by a request for an update to the WCM.*

1.2 The Russian River Watershed, Lake Mendocino, and Lake Sonoma

1.2.1 Russian River Watershed

The 1,485-square mile Russian River watershed is a narrow valley between two adjacent northern coastal mountain ranges. The watershed is about 100 miles long and varies from 12 to 32 miles in width (Figure 1.2). The climate is Mediterranean with 93 percent of annual precipitation in October through May. A large percentage of the rainfall typically occurs during three or four major winter storms. These major storms often come in the form of an atmospheric river (AR). Climatic conditions vary across different portions of the watershed. Average annual precipitation is as high as 80 inches in the mountainous coastal region of the watershed and 20 to 30 inches in the valleys. Precipitation can also vary significantly from season to season, which can result in a large amount of variability in flows in the Russian River.

Water released from Lake Mendocino flows southward, where the East and West Forks meet. Flow continues south to Hopland, Cloverdale, and Healdsburg. Below Healdsburg, Dry Creek (Lake Sonoma) joins the Russian River. Sonoma Water operates recharge and streamside pumping and filtration facilities below the Dry Creek confluence. This consists of six collector wells along the river, an inflatable temporary dam, and recharge basins. Groundwater is extracted by each collector well from the alluvial aquifer adjacent to and beneath the Russian

River. The Russian River continues through the town of Guerneville and to the Pacific Ocean at Jenner. The Guerneville region has been the victim of multiple major flooding episodes (1955, 1964, 1986, 1995, 1997, 2006, 2019). Table 1.1 provides travel times between key Russian River locations as a function of flow level.

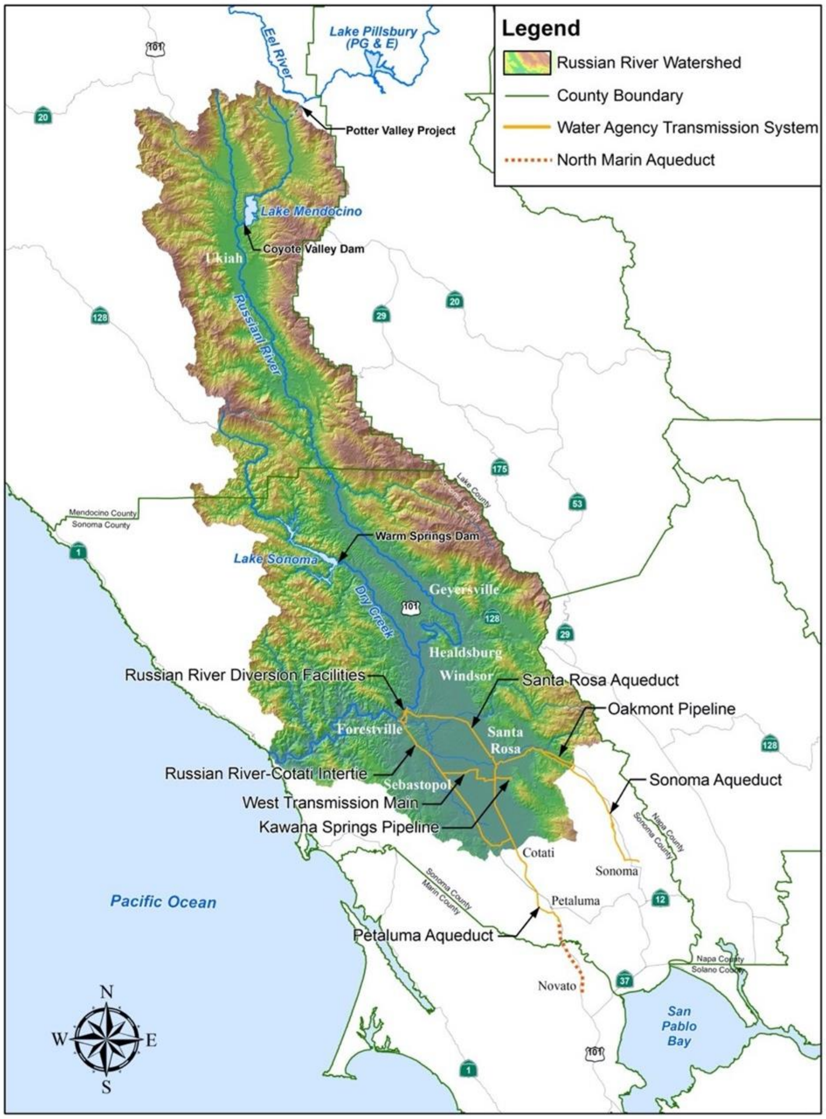

Figure 1.2. Schematic of the Russian River watershed and water transmission system (FIRO Steering Committee 2015).

Floods in the Russian River watershed are normally of short duration, lasting three to four days, developing within 24 to 48 hours after the beginning of a storm but rapidly receding within two or three days. Floods occur during the rainy season from November through April and larger storms can inundate the portions of the alluvial valleys (e.g., Ukiah, Hopland, and Alexander) adjacent to the river. However, storms have occurred in October and May, which have caused minor or moderate flooding.

Table 1.1. *Russian River travel times (hours) between key locations as a function of discharge (from 1986 Lake Mendocino WCM).*

Reach	Length (miles)	Discharge								
		400 cfs	1,000 cfs	2,000 cfs	4,000 cfs	6,000 cfs	8,000 cfs	10,000 cfs	20,000 cfs	40,000 cfs
Forks of RR to Hopland	14	11	9	7.5	6.5	6	6	5.5	5	4.5
Hopland to Cloverdale	16	12.5	9	7	5.5	5	4.5	4	3	2.5
Cloverdale to Healdsburg	28	18.5	13	10.5	9.5	8.5	8	7.5	6.5	6
Healdsburg to Guerneville	16	43	31	26	21	19	18	16.5	14	13

The City of Hopland and surrounding areas are some of the most flood prone regions along the Upper Russian River. Flood stage at the United States Geological Survey (USGS) gage (11462500) near Hopland is 15 ft (8,000 cfs). Since Coyote Valley Dam was completed, the maximum flow rate recorded at the Hopland was 41,500 cfs (December 1964), and water levels have exceeded 15 ft in 70 of the last 80 years. Flooding at Hopland can cause closure of the Highway 175 bridge. The City of Healdsburg is prone to flooding during only exceptionally extreme events. Flood stage at Healdsburg (USGS 11464000) is 23 ft, or 53,000 cfs. Since Coyote Valley Dam was completed, the maximum flow rate of recorded flow at Healdsburg was 69,300 cfs in January 1995, and water levels have reached flood stage only four times (7 percent of the years). The City of Guerneville is prone to flooding from heavy rainfall events. Flood stage at the Johnson Beach gage (USGS 11467002) is 32 ft. The Johnson Beach gage is no longer rated; however, 32 ft is approximately 35,000 cfs. Levels at this location have reached flood stage in slightly more than 50 percent of years since 1943. February 1986 was the flood-of-record for this location, with a peak stage of 49.5 ft. Guerneville has experienced significant flooding as recently as February 2019.

1.2.2 Lake Mendocino

Created by Coyote Valley Dam in 1958 for flood control, Lake Mendocino also provides water supply, recreation, and environmental streamflow. The USACE owns and operates the project and makes flood control releases in accordance with the WCM. Sonoma Water controls releases when water levels are in the water supply pool. Lake Mendocino has a watershed drainage area of 105 square miles and storage capacity of 116,500 acre-feet (ac-ft). It is located on the East Fork of the Russian River watershed (see Figure 1.2). Table 1.2 provides an overview of Lake Mendocino and Lake Sonoma attributes.

Table 1.2. *Lake Mendocino and Lake Sonoma attributes*

Attribute	Lake Mendocino	Lake Sonoma
Location	East Fork Russian River Mendocino County, CA	Dry Creek Sonoma County, CA
Impoundment	Coyote Valley Dam Earth embankment, 160 ft high, crest length of 3,500 ft	Warm Springs Dam Earth embankment, 319 ft high, Crest length of 3,000 ft

Attribute	Lake Mendocino	Lake Sonoma
Construction Completed	1959	1982
Owner	USACE	USACE
Cooperating Agency	Sonoma Water owns/operates the water conservation space	Sonoma Water owns/operates the water conservation space
Drainage Area	105 mi2	217 mi2
Storage Capacities	153,700 ac-ft at top of dam 116,500 ac-ft at spillway crest 68,400 ac-ft winter conservation 111,000 ac-ft summer conservation	448,600 ac-ft at top of dam 342,000 ac-ft at spillway crest 245,000 ac-ft conservation (not seasonally adjusted)
Water Control Manual	Original 1959 Updated 1986 Minor revisions 2003	Original 1984
Control Points and objective flows	Russian River near Hopland (<8,000 cfs)	Dry Creek near Geyserville (<7,000 cfs) Russian River near Guerneville (<35,000 cfs)
Standard Project Flood	December 1955 Peak inflow 25,800 cfs Volume 98,400 ac-ft	December 1955 Peak inflow 34,000 cfs Volume 170,000 ac-ft
Authorized Purposes	Flood control, water conservation, and related purposes	Flood control, water conservation, and related purposes
Hydropower	City of Ukiah, CA	None
Fish Hatchery	Bill Townsend (below dam)	Don Clausen (below dam)

Water from the Eel River is stored in Lake Pillsbury. Releases from Lake Pillsbury are required to meet Federal Energy Regulatory Commission (FERC)-required minimum in-stream flows in the Eel River and to provide water for diversions at Cape Horn Dam and through a trans-basin tunnel to the Potter Valley Project (PVP) powerhouse. The trans-basin tunnel to the PVP powerhouse has been in operation since 1908 and Lake Pillsbury construction was completed in 1922. Eel River flows diverted through the PVP powerhouse are released into the East Fork of the Russian River to maintain FERC-required minimum flows below the powerhouse. A portion of the water released from the PVP is diverted by the Potter Valley Irrigation District (PVID) into two canals located just below the powerhouse. PVID can divert up to 50 cfs here in addition to water rights to divert from the East Fork of the Russian River downstream. Water not diverted by PVID or other water rights holders flows into the East Fork of the Russian River and into Lake Mendocino. Other inflows to Lake Mendocino are from the natural runoff from the 105-square mile drainage area.

Lake Mendocino has a seasonally adjusted guide curve as shown in Figure 1.3. Release decisions are made based on required environmental flows, constrained rates of change in flow to protect fish species, pool level, non-regulated flows, flood stages downstream, and current releases. Releases will be restricted to the extent possible so that the flow at Hopland does not exceed 8,000 cfs.

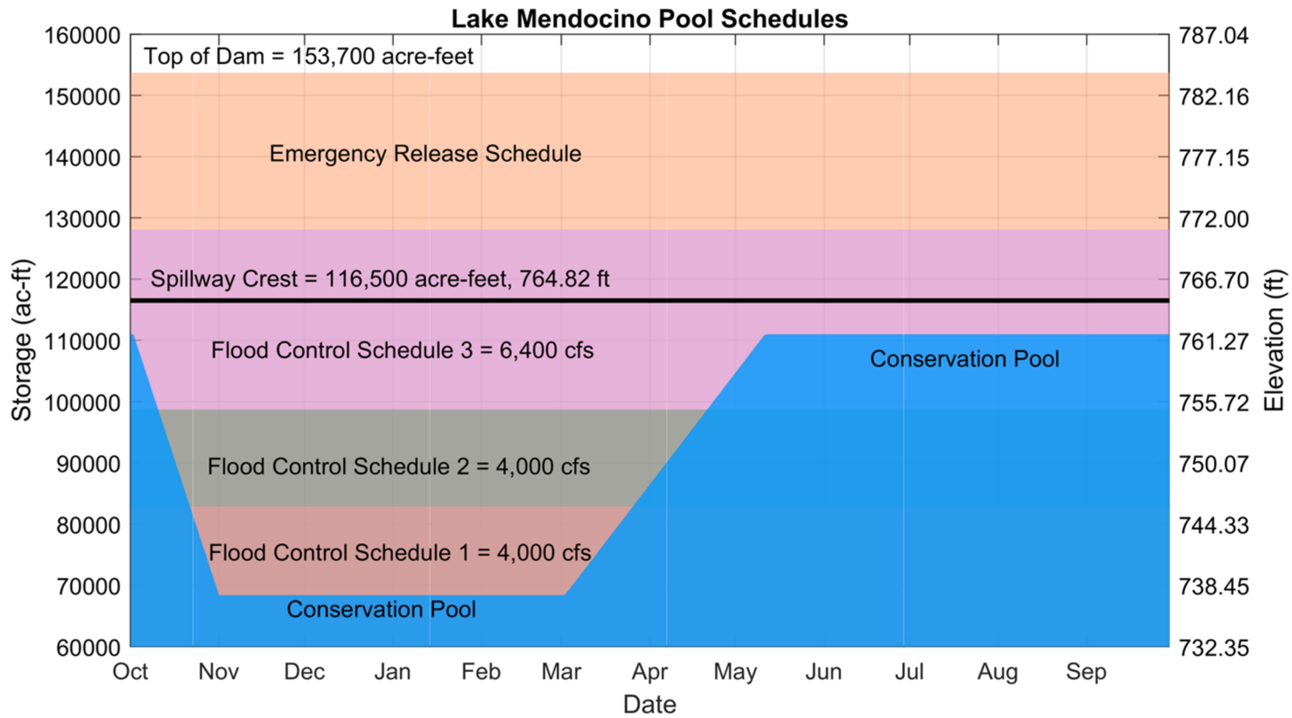

Figure 1.3. *Lake Mendocino operations guide curve.*

1.2.3 Lake Sonoma

While this effort is focused on Lake Mendocino, there is a second, larger reservoir in the Russian River watershed. Lake Sonoma and Warm Springs Dam are shown near the center of Figure 1.2 and key attributes are provided in Table 1.1. Lake Sonoma was created by the construction of Warm Springs Dam by the USACE in 1982. Lake Sonoma provides flood management, water supply, environmental, and recreation benefits. In fact, Lake Sonoma is the primary source of water delivered by Sonoma Water. Lake Sonoma has a total capacity of 381,000 ac-ft with a water supply pool of 245,000 ac-ft. Just downstream of Lake Sonoma, the Warm Springs Hatchery—also known as the Don Clausen Fish Hatchery—produces coho salmon and steelhead trout for the waters of the Russian River drainage. The Dry Creek channel between Lake Sonoma and the Russian River confluence has been the focus of a major habitat restoration project that began in 2012.

Lake Sonoma is operated, to the extent possible, to keep flows in Dry Creek near Geyserville below 7,000 cfs and flows in the Russian River near Guerneville below 35,000 cfs. The Lake Sonoma operations guide curve is shown in Figure 1.4. Note that it does not vary with season.

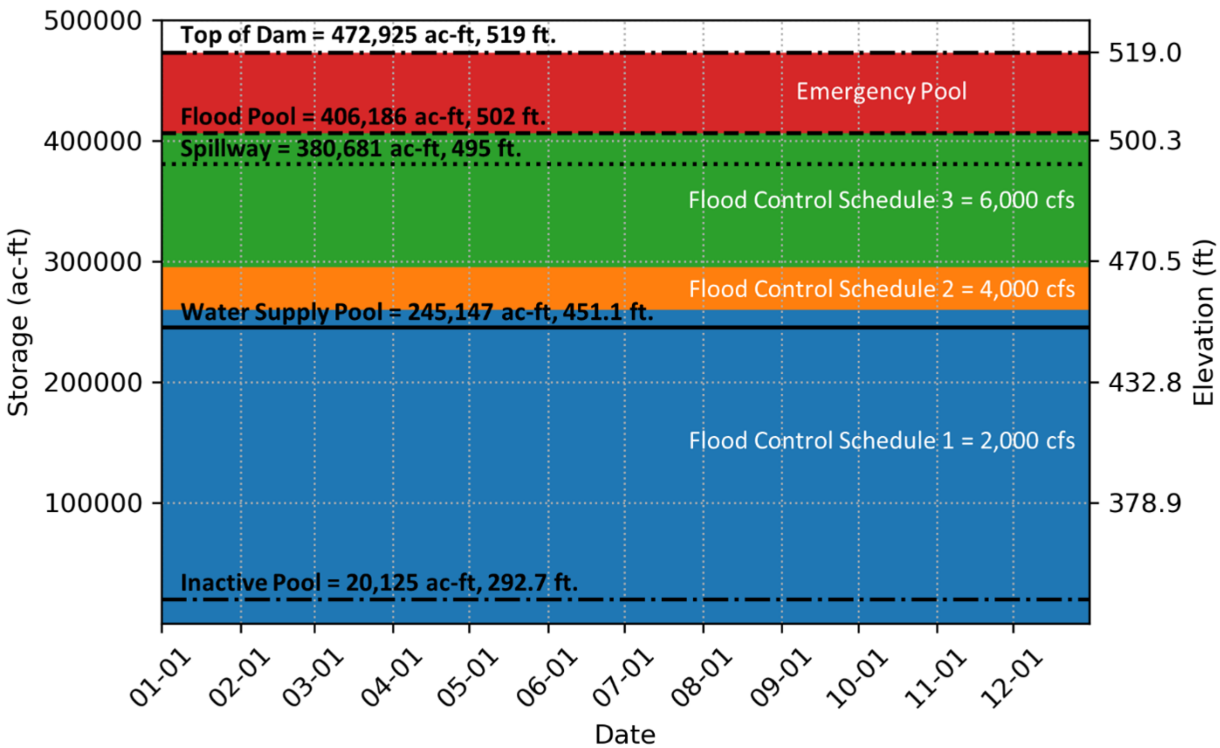

Figure 1.4. *Lake Sonoma operations guide curve.*

1.2.4 Russian River System Operation

Hydrologic studies have shown that Warm Springs Dam flood control operation would normally be independent from that of Coyote Valley Dam. This is because of the length of time it takes releases from Coyote Valley Dam to reach the mouth of Dry Creek. The Lake Mendocino WCM does not have specific criteria or objectives for reducing flood impacts downstream of Hopland. However, the WCM does indicate that Coyote Valley Dam operators should avoid releases that would contribute to flows greater than 35,000 cfs at Guerneville. It is also important to note that the combined drainage area of Lake Mendocino and Lake Sonoma only represents 15 percent of the drainage area of the Russian River above Guerneville.

1.3 The Case for Change at Lake Mendocino

The key drivers for investigating FIRO at Lake Mendocino include:

- A clearer awareness of natural weather variability due to the number and intensity of ARs
- Anticipated climate change that is expected to increase climate variability and extreme events
- Significant decreases in trans-basin diversions from the Eel River into the East Fork of the Russian River

This region experiences some of the most variable climate in California, with frequent droughts and floods. The information in Figure 1.5 shows the role and importance of ARs to annual precipitation in the upper Russian River. Large storms, which are in the 95th percentile of daily precipitation and are nearly exclusively ARs, account for 84 percent of the variance in total annual precipitation. Droughts occur when there are few ARs bringing precipitation to the Russian River. The bottom line is that ARs drive both floods and droughts.

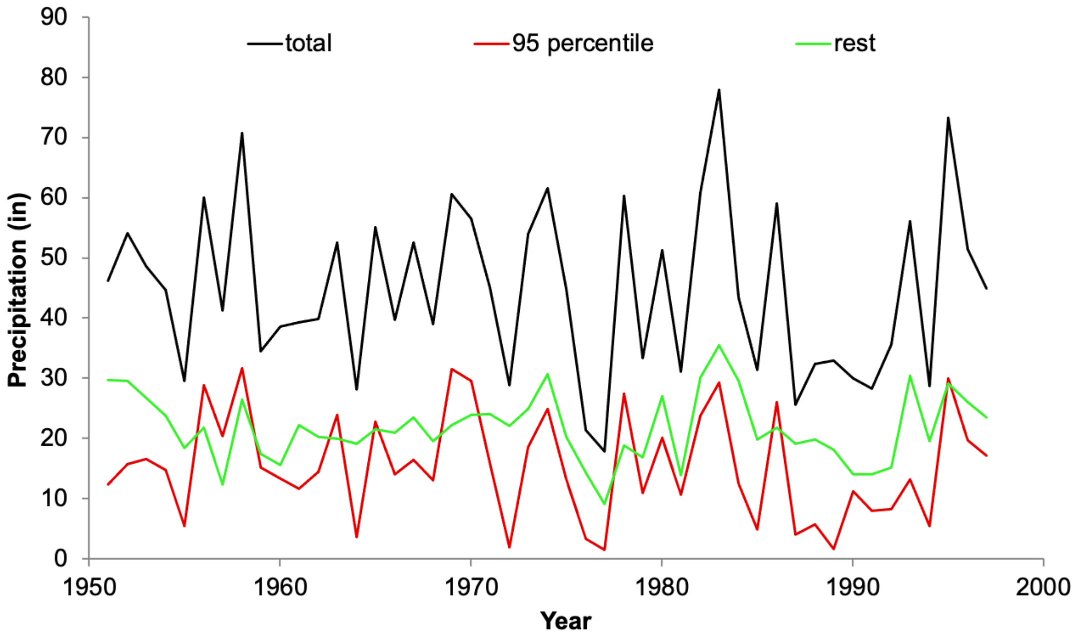

Figure 1.5. *Annual precipitation variability and contribution of ARs for the Russian River above Hopland. From M. Dettinger, USGS.*

California's Fourth Climate Change Assessment includes the following statements for the *North Coast Region Report* (Grantham 2018):

- Annual precipitation is not expected to change significantly, but will likely be delivered in more intense storms and within a shorter wet season. As a result, the region is expected to experience prolonged dry seasons and reduced soil moisture conditions, even if annual precipitation stays the same or moderately increases.
- There is a higher likelihood of extreme wet years and extreme dry years (i.e., drought). An "average" rainfall year will become less common.

Lake Mendocino has experienced significantly reduced water supply reliability since flows were decreased from the Eel River. Figure 1.6 shows the magnitude of the decrease in transfers since 2006. Transfers have been most reduced during the late winter and spring when Lake Mendocino normally refills toward summer conservation storage levels.

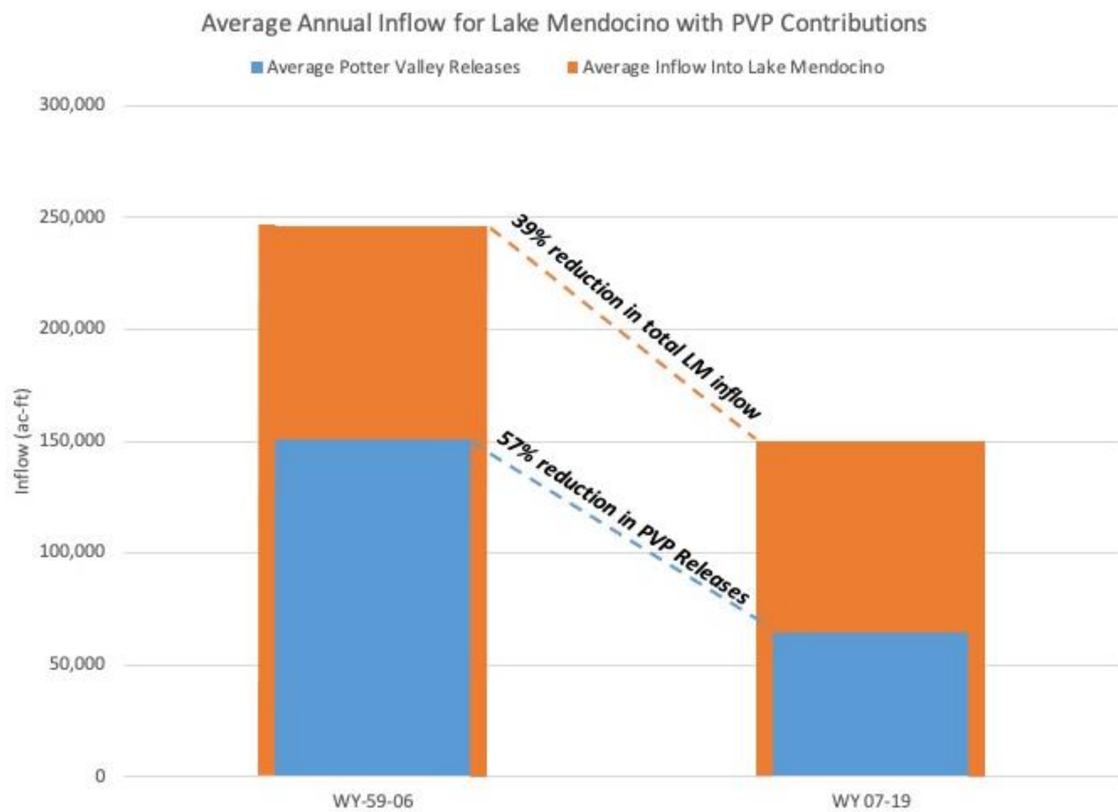

Figure 1.6. *Pre- and post-2006 average annual transfers from the Eel River into the East Fork of the Russian River through the PVP (shown as blue bars) and Lake Mendocino inflows (shown as orange bars).*

The WCM, issued in 1959 and with minor revisions in 1986, was developed without the benefit of modern weather and streamflow forecasting information. The WCM specifies reservoir operation according to a guide curve, which dictates water storage during a flood event and safe water releases soon thereafter to create storage space for the next potential flood. The guide curve is predicated on historical weather patterns—wet during the winter, dry otherwise—therefore, the required flood control space is larger in the winter while smaller in the remainder of the year (Figure 1.3).

As noted above, this region experiences some of the most variable climate in California, with frequent droughts and floods. The guide curve does not account for increased variation in weather patterns nor a 56 percent reduction of diversions into Lake Mendocino from the Eel River due to changes in hydroelectric operations of the PVP (see Figure 1.4). As a result, the water supply reliability of Lake Mendocino is impaired, with significant consequences to downstream municipal and agricultural water users as well as threatened and endangered salmonids.

The case for FIRO is demonstrated in Figure 1.7, which shows storage levels and cumulative precipitation for water years (WYs) 2013 and 2014. This figure shows that both years experienced very similar total rainfall, but timing of the rainfall relative to the reservoir guide curve resulted in very different storage outcomes. This experience prompted the question of whether some of the inflow and storage that occurred in December 2012 could have been saved to mitigate the subsequent precipitous decline in reservoir storage that followed over the next two years due to lack of any significant rainfall.

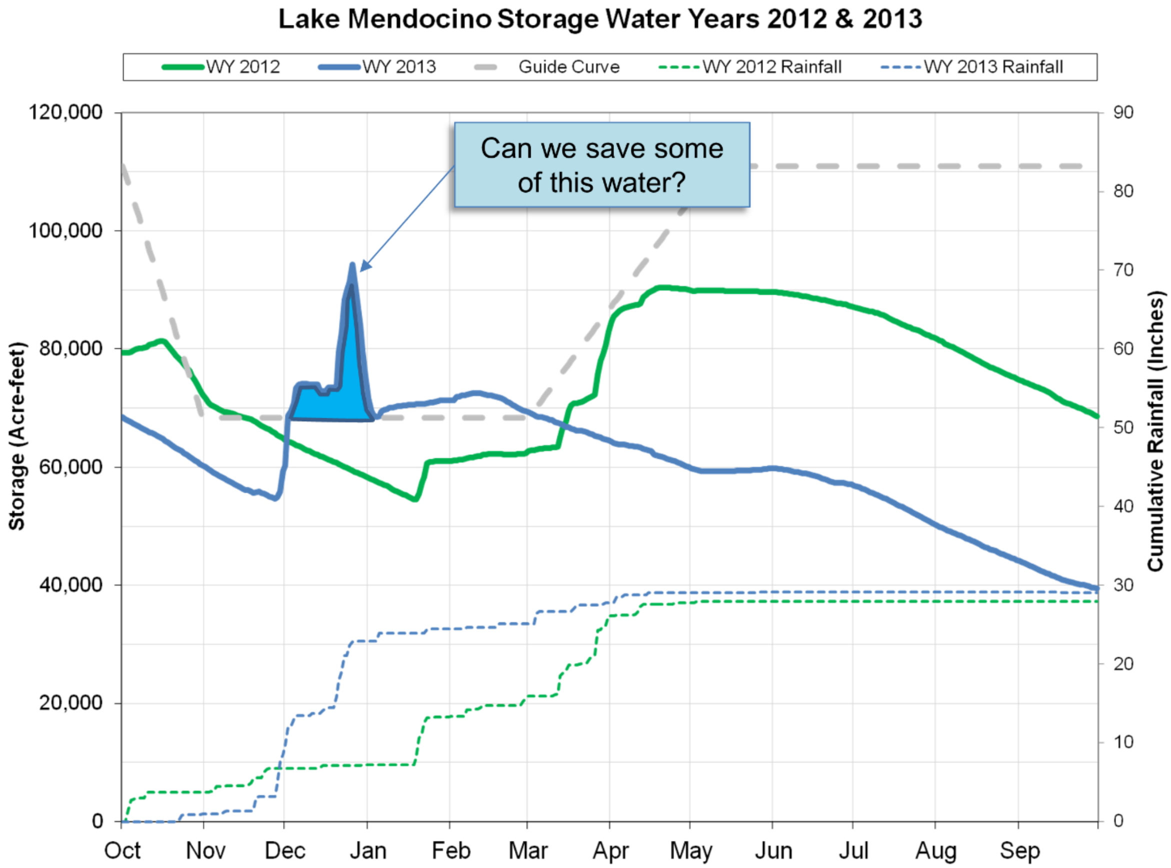

Figure 1.7. *Storage (solid lines) and cumulative precipitation (dashed lines) for WYs 2012 (green) and 2013 (blue).*

1.4 FIRO and FIRO at Lake Mendocino

FIRO is a flexible water management approach that uses data from watershed monitoring and improved weather and hydrologic forecasting to help water managers selectively retain or release water from reservoirs in a manner that can adapt to weather extremes and that leverages advancements in the science of meteorological and hydrologic forecasting. FIRO represents an innovative use of emerging science and technology to optimize limited resources and adapt to changing climate conditions without costly reservoir infrastructure improvements. The goal of FIRO at Lake Mendocino is to increase water supply reliability without reducing—and while possibly enhancing—the existing flood protection capacity of Lake Mendocino and downstream flows for fisheries habitat.

In January 2020, in response to the emergence of FIRO permutations, the SC decided to develop an official definition of FIRO, for adoption by the American Meteorological Society (AMS). The following draft definition is currently being refined based on input at the 2020 AMS meeting and subsequent experience with other FIRO projects. A refined definition will likely be adopted at the 2021 AMS Annual Meeting:

"FIRO is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts."

1.5 Importance of Atmospheric River Research

AR forecasts are a key element of FIRO. California's water supplies rely on adequate precipitation, which largely depends on ARs. ARs originate in the Pacific Ocean and can make landfall along the California coastline. The absence of AR storms often leads to drought in California, whereas strong ARs can cause flooding. Figure 1.8 shows an AR that impacted the Russian River basin in February 2019. California Governor Gavin Newsom declared a state of emergency in five counties due to the impacts from this event. This AR was observed by aircraft offshore, by weather balloons onshore, and by other instrumentation installed in the Russian River watershed, including radars, soil moisture sensors, rain gauges, and other sensors.

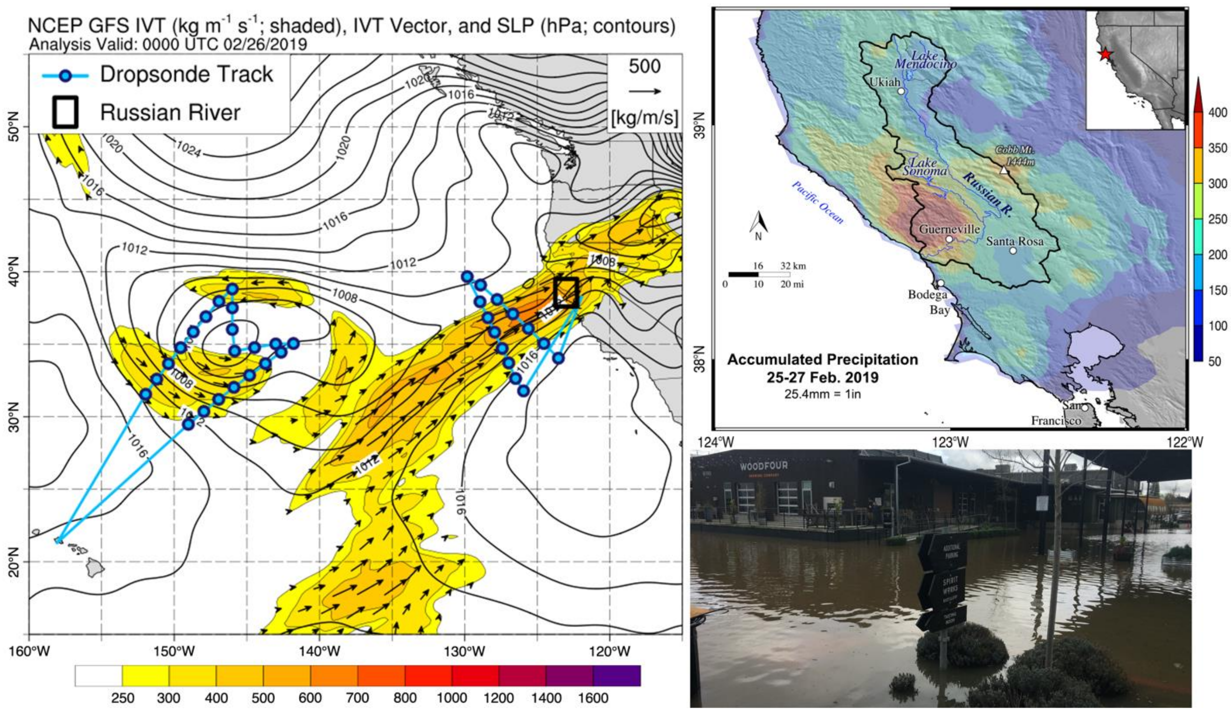

__Figure 1.8.__ AR impacting the Russian River basin in February 2019. The left panel shows integrated water vapor transport (IVT), a measure of the AR's strength, along with the aircraft flight tracks. The top-right panel shows the 48-hr rainfall totals observed between Sunday, February 25, at 4 a.m. and Tuesday, February 27, at 4 a.m., reported by the California-Nevada River Forecast Center (CNRFC). The bottom-right panel is a photograph of flooding in the town of Sebastopol on February 27 (courtesy Nina Oakley).

Currently, most reservoirs are operated without the benefit of AR forecasts. Predicting the timing and intensity of these critical precipitation events 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. FIRO requires both sufficient forecast skill at lead times necessary for water management decisions at Lake Mendocino, and the provision of usable, relevant forecast information that enables decision makers to take effective action. CW3E is pursuing important advances to improve existing skill in forecasting ARs and has developed a variety of tools that are being used by Lake Mendocino reservoir operators to better anticipate impacts of ARs as they approach the watershed, such as the AR Landfall Tool (Figure 1.9). These decision support tools allow operators to implement FIRO through the flexibility provided in two consecutive major deviations to the Lake Mendocino WCM.

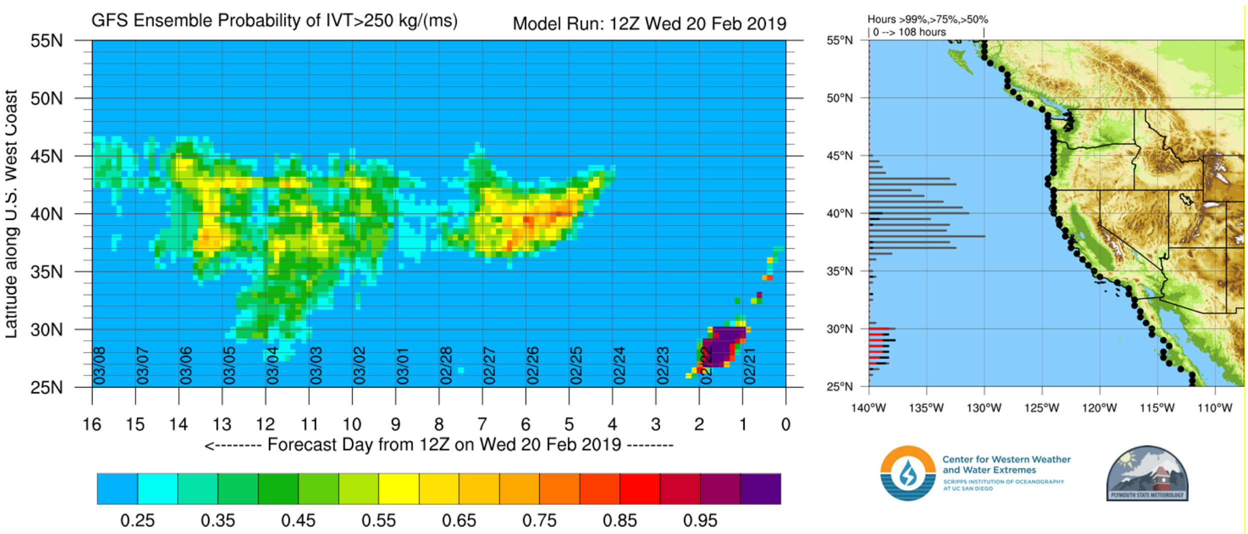

Figure 1.9. *The AR Landfall Tool depicts the likelihood of an AR (shaded in colors) by latitude (y-axis) and forecast time (right to left on the x-axis) from February 20, 2019, providing forecast guidance 5 to 7 days in advance of the AR on February 25–27, 2019. The probability of AR conditions at a coastal point through time is displayed as the percentage of ensemble members with IVT > 250 (colorfill) (left). The duration of landfalling conditions according to ensemble probability thresholds of 99%, 75%, and 50% is plotted at half-degree latitude increments (right).*

Significant progress on understanding the current forecast skill of ARs, making and quantifying improvements to this skill, and communicating relevant information to decision makers in an accessible format are essential components of measuring FIRO viability and maximizing FIRO benefits. In support of the FVA, CW3E, in partnership with Sonoma Water and other agencies, has instituted comprehensive monitoring networks that operate offshore and onshore, in the atmosphere as well as the landscape; identified key physical processes that must be represented properly in models to produce accurate forecasts at all relevant timescales; developed and operationally run a regional weather model covering the watershed that focuses specifically on AR prediction; developed meaningful partnerships with academic institutions and operational agencies to support ongoing forecasting, monitoring, and decision support tool evaluation and improvements; and integrated novel, promising techniques such as machine learning into all of their efforts. This work leverages and builds on the National Oceanic and Atmospheric Administration (NOAA) Hydrometeorological Testbed instrumentation and research. See Section 2 for more details on these advances.

1.6 Research and Operations

Early on in the FIRO viability assessment process, the Steering Committee recognized that the development and execution of plans to assess FIRO viability would require using an organizing principle now recognized as a "Research and Operations Partnership" (RAOP; Ralph et al. 2020) between the various entities of the Steering Committee. Such a partnership would bring both operational practitioners and their mission requirements together with scientists and their innovations and discoveries to advance the knowledge, methods and tools upon which FIRO is built. The Steering Committee then devised the flow diagram shown in Figure 1.10 as a process for evaluating the viability of various FIRO strategies. This diagram, first published in the Lake Mendocino FIRO Work Plan (FIRO Steering Committee 2015), depicts the original FIRO process and is described in detail in the Work Plan. RAOP principles formed the basis of this original process as FIRO scenarios were tested in the PVA and then progressed in a clockwise (not yet viable) or counterclockwise (viable) flow path, with research and operations working together to define requirements for needed scientific improvements to support decision tools or how a tested strategy that was proven viable could be safely incorporated into practice. As the PVA was conducted and various FIRO scenarios evaluated, a more comprehensive FIRO evaluation process began to take shape.

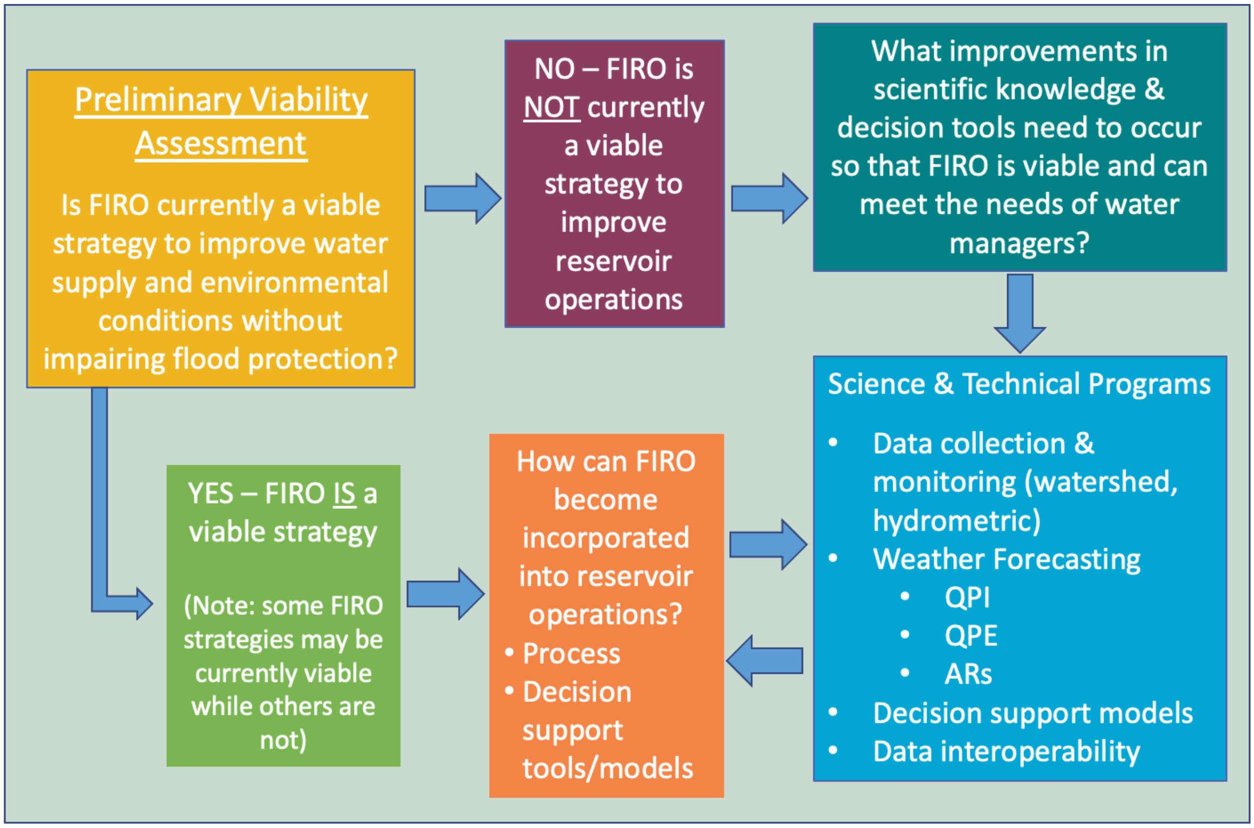

Figure 1.10. *Flow diagram showing the FIRO viability assessment process (after FIRO Steering Committee 2015).*

The FIRO Work Plan included a strategy for testing and evaluation involving meteorology, hydrology, ecology, and water resources management. This strategy is represented schematically in Fig. 1.11 as a set of scientific and technological (S&T) tasks that form the foundation for the full assessment of FIRO viability at Lake Mendocino, represented as a pyramid in Fig. 1.11. The second row in the pyramid represents demonstration (Demo) processes including a preliminary viability assessment consisting of a paper study (the PVA), followed by a real-world demonstration through submission and implementation of a series of progressively more flexible planned major deviations in operating the reservoir.

The primary intermediate deliverable from the overall viability assessment was the PVA, two years into the planned five-year FIRO assessment. The results were a breakthrough. They showed very encouraging initial evaluations that ARs are the main storm type to be concerned about, and that there is promising skill in predicting them, including both their absence and their chance of occurrence. Also, the development of the ensemble forecast operations decision support tool provided an objective way to consider ensemble forecasts and manage risk associated with the inevitable uncertainty in forecasting. This led to the decision to request a planned major deviation from normal operating procedures for the reservoir, built upon the FIRO tools that had been created. The Steering Committee prepared and submitted the request formally in 2017, and after a thorough review under normal USACE processes, it was approved in fall 2018. During the following two winters—including one with significant flooding in WY 2019, and one that was a drought in WY 2020—operations at Lake Mendocino successfully demonstrated the viability of FIRO and did so in the context of two years representing opposite extremes in the weather. In particular, by the end of WY 2020—the third driest year on record in the Russian River basin—there was more than 11,000 ac-ft of additional water in the reservoir due to FIRO.

By 2019, it became apparent that the FIRO findings would warrant a potential update to the WCM to incorporate a flexible "FIRO Space" (see Figure E.4 and Section 6.3) and efforts in that direction began. Because the WCM update process could take some time, a 5-year-long major deviation was requested to use the FIRO method while the WCM update is being considered and developed, thus allowing the benefits of FIRO to accrue after the FIRO FVA is completed and before the WCM is possibly updated, which would involve additional studies specific to WCM updating. Finally, the FVA recognized that there is potential for additional flexibility (i.e., the FIRO Space could have greater volume) if forecast skill improves beyond a threshold that safely allows for such flexibility. This concept is expanded upon below and in Fig. 1.12. It is referred to as "FIRO 2.0."

In short, the process envisioned in 2015 in the FIRO Work Plan (Fig. 1.10) evolved through experience into what is shown in Fig. 1.11. This evolution included the set of scientific and technical tasks across several disciplines, which formed the foundation for demonstrations through the PVA (i.e., a paper study) and through real-world testing in operations through planned major deviations. Lessons from the scientific and technical studies, plus the demonstrations (i.e., PVA and major deviations) fed into the FVA, which formally recommends the adoption of FIRO at Lake Mendocino. These steps represent the culmination of the full 5-year study. However, it is important to note that they feed into the vital steps required to codify and implement the FIRO recommendations through a Water Control Manual update. This, and the 5-year FIRO major deviation to be used in the meantime, are activities beyond the formal FVA laid out in the original goals and FIRO Work Plan in 2015. The core elements and foundation of the FIRO FVA phase are distinguished from those in the post-FVA phase by a dashed box in Fig. 1.11. Although the FIRO 2.0 concept is envisioned as involving FIRO methods to consider, and potentially trigger, adopting a larger FIRO Space in the future as forecast skill advances, this evaluation would be conducted after concluding the FVA phase.

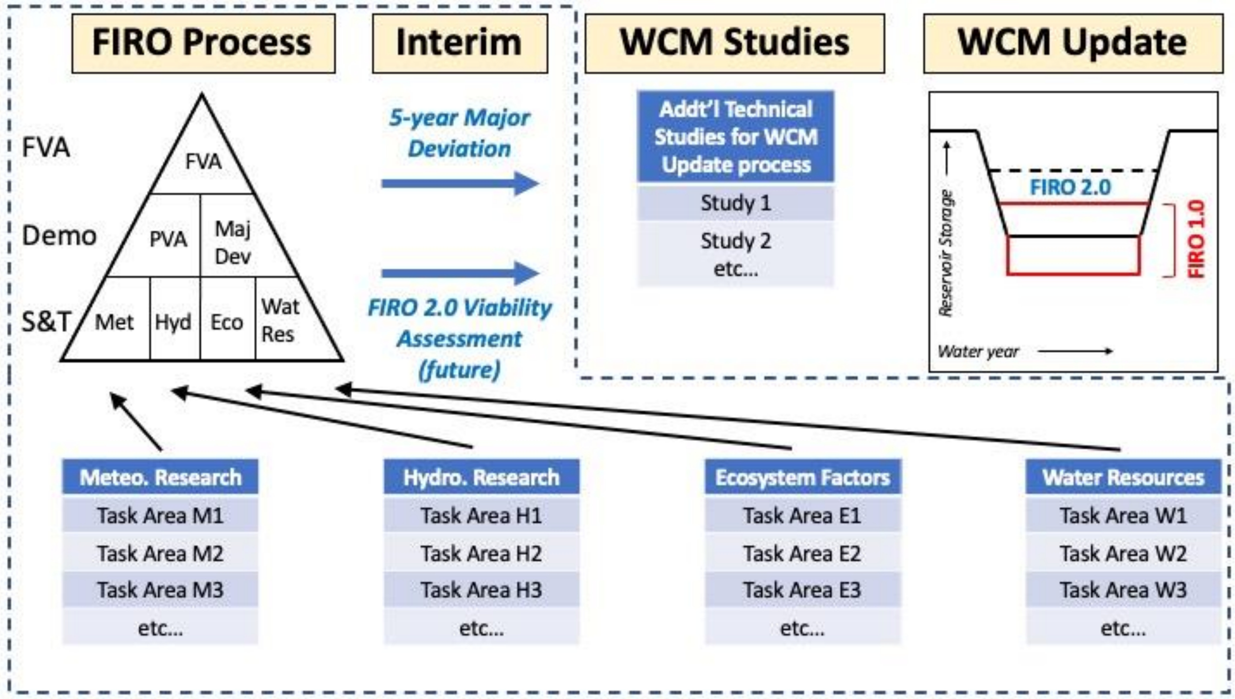

Figure 1.11. *Schematic summary of the key elements used in assessing the viability of FIRO at Lake Mendocino, anticipated steps after completion of the FVA, and how these support the potential update of the WCM for Coyote Valley Dam that creates Lake Mendocino. The figure also notes the role of the PVA and of major deviations in allowing FIRO methods to be demonstrated and carried out as part of the work feeding into the FVA, and as a link between the FVA and the WCM update. These planned major deviations represent "interim" operations strategies. The FVA builds upon the Work Plan (FIRO Steering Committee 2015), which included a detailed set of S&T research, as well as engineering studies in meteorology (Met; tasks M1, M2, M3, etc.), hydrology (Hyd; tasks H1, H2, H3, etc.), ecology (Eco; tasks E1, E2, E3, etc.), and water resources (Wat Res; tasks W1, W2, W3, etc.). The WCM update will require specialized studies (Study 1, Study 2, etc.).*

The concept of FIRO 2.0 in its idealized form is that the updated WCM includes a threshold of higher forecast skill, which, when achieved, would trigger the ability to operate with a larger FIRO Space. The ability to reach this higher skill threshold is dependent on increasing skill in prediction of ARs, as well as their associated extreme precipitation and runoff. This concept is envisioned to include a highly streamlined process to trigger the increase. Ideally, the WCM update would incorporate the guidelines by which this evaluation and ultimate decision are to be considered. In principle, the shift to the larger FIRO Space could be triggered by having established a set of forecast skill metrics during the WCM update, and objective ways to calculate these metrics, such that it becomes possible to operate with the larger FIRO Space without another WCM update.

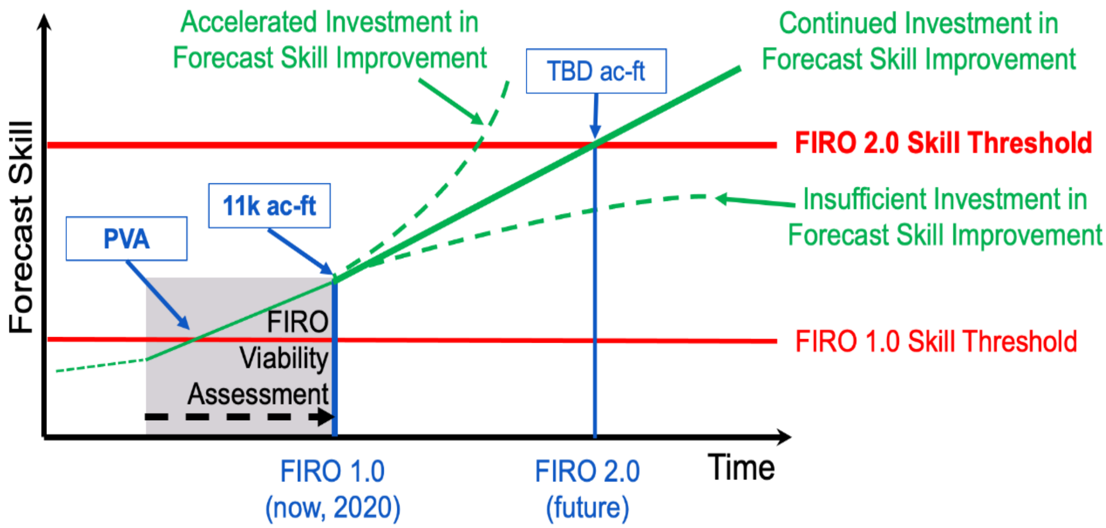

Figure 1.12. *The FVA concludes that current forecast skill is sufficient to support using forecasts in Lake Mendocino operations, yielding up to roughly 11,000 ac-ft of additional water supply reliability or flood mitigation capacity. This figure illustrates how future improvements in forecast skill could enable even greater flexibility in operating the reservoir, and how achieving this is supported by research to improve predictions of ARs and their associated precipitation and runoff.*

1.7 Lake Mendocino Steering Committee

FIRO was first initiated in 2014 by the creation of the Lake Mendocino Steering Committee, which convened to develop and test FIRO at Lake Mendocino (Figure 1.10). The Steering Committee was formed voluntarily and without any mandate. It brought together a multi-disciplinary group of individuals representing key agencies and organizations that were all stakeholders and were all interested in and able to significantly contribute to exploring the potential of FIRO to produce multiple benefits. The Steering Committee was formed with all members signing a Terms of Reference, which spelled out the mission, goals, and roles and responsibilities of the members. The Steering Committee is chaired by Jay Jasperse of Sonoma Water and Dr. Marty Ralph of CW3E. It has met in person quarterly since its inception, with technical work groups formed as needed throughout the process. Stakeholder outreach is an important function of the Steering Committee. It regularly engages with stakeholders in the Lake Mendocino and Upper Russian River watersheds and hosts an annual FIRO workshop that brings together a broad range of stakeholders, practitioners, and researchers for robust technical transfer and information exchange. The Steering Committee also produces one-page updates on its progress at least annually for wide distribution. CW3E hosts a FIRO website where information about the Steering Committee and Lake Mendocino FIRO is regularly updated, along with tools and other information related to AR research.

Figure 1.13. *Photo of the Lake Mendocino Steering Committee at Lake Mendocino (2018). From left: Mike Anderson (California Department of Water Resources), Jay Jasperse (Sonoma Water), Nicholas Malasavage (USACE San Francisco District), Marty Ralph (CW3E), Patrick Rutten (NOAA National Marine Fisheries Service), Robin Webb (NOAA Office of Oceanic and Atmospheric Research), Joseph Forbis (USACE Sacramento District), Cary Talbot (USACE Engineer Research and Development Center). Missing from photo: Levi Brekke (U.S. Bureau of Reclamation), Mike Dettinger (CW3E), Alan Haynes (NOAA National Weather Service, CNRFC). Photo by Cary Talbot.*

Current Steering Committee members are listed below:

- Jay Jasperse, *Sonoma Water* (Co-chair)
- F. Martin Ralph, *U.C. San Diego, Scripps Institution of Oceanography, CW3E* (Co-chair)
- Michael Anderson, *California Department of Water Resources*
- Levi Brekke, *U.S. Bureau of Reclamation*
- Nicholas Malasavage, *USACE, San Francisco District*
- Michael Dettinger, *CW3E (formerly U.S. Geological Survey)*
- Joseph Forbis, *USACE, Sacramento District*
- Alan Haynes, *NOAA, National Weather Service, California-Nevada River Forecast Center*
- Joshua Fuller, *NOAA, National Marine Fisheries Service*
- Cary Talbot, *USACE, Engineer Research and Development Center*
- Robert Webb, *NOAA, Office of Oceanic and Atmospheric Research, Earth System Research Laboratory*

Section 2. Evaluation of Existing Weather and Water Forecast Skill

2.1 Existing Forecasting Methods

The weather and water forecasts used in evaluating Forecast Informed Reservoir Operations (FIRO) water control plans (WCPs) (Section 3) were provided by the California-Nevada River Forecast Center (CNRFC). These forecasts were chosen because they are provided through National Weather Service (NWS) real time operations. Both archived forecasts and hindcasts were made available for developing and evaluating FIRO WCP schemes.

2.1.1 Weather Forecasting

Weather forecasts are used for both situational awareness and explicit inputs into the hydrologic models used to generate the streamflow forecasts. Weather forecasts are fundamentally anchored in global numerical weather prediction (NWP) models such as the National Oceanic and Atmospheric Administration (NOAA) Global Forecast System (GFS) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS). These models provide direct information, as well as the boundary conditions for higher resolution mesoscale NWPs. Information from these models is used to generate a plethora of analyses and graphics that provide insight on how the future weather may unfold in the coming days and weeks. Human value-added forecasts rely heavily on the forecaster choosing the right model for the right situation. There are dozens of models and guidance products to choose from that are becoming much more sophisticated in this age of digital forecasts, such as the National Blend of Models (Craven et al. 2020). Because atmospheric rivers (ARs) are key to extreme rainfall events in the West, the Scripps Institution of Oceanography's Center for Western Weather and Water Extremes (CW3E) website provides an AR web portal with additional guidance on AR forecasts (see Sections 4 and 5) (https://cw3e.ucsd.edu/iwv-and-ivt-forecasts).

Once the CNRFC Hydrometeorological Analysis and Support (HAS) forecaster has chosen the model of the day and made adjustments using local knowledge, the precipitation, temperature, and freezing level information is passed to the Community Hydrologic Prediction System where the hydrologist may make further adjustments before producing the final streamflow forecasts. It should be noted that the HAS forecaster focuses most on the precipitation forecast, with temperature and freezing levels mainly model driven. Figure 2.1 shows the process used by the CNRFC HAS unit to provide the weather forecasts used in CNRFC deterministic streamflow forecasts.

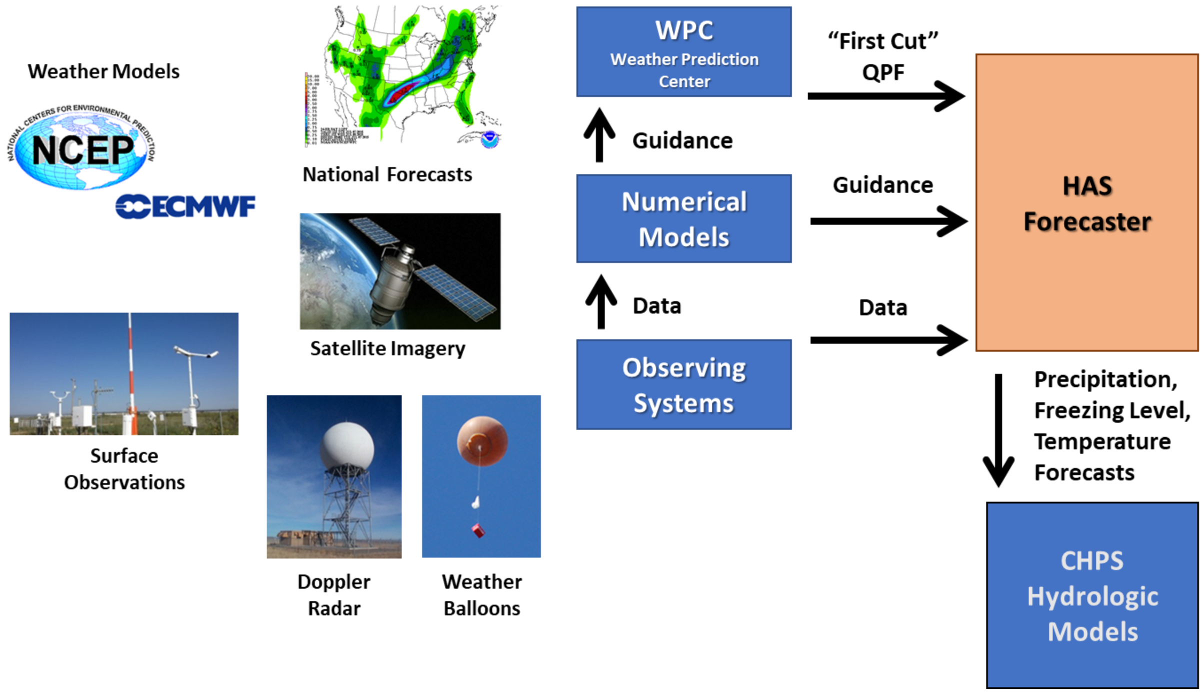

Figure 2.1. *Generalized process used by the CNRFC HAS unit to generate weather forecast information used in the streamflow forecast process.*

In addition to these direct hydrologic model inputs, weather forecasts provide context and situational awareness for reservoir operators, the emergency services community, and the public. Today, weather forecasts are readily available on mobile devices and on a variety of public and private sector websites.

2.1.2 Water Forecasting

CNRFC provided the operational streamflow forecasts leveraged in the Lake Mendocino FIRO effort. Figure 2.2 shows the generalized forecast process used by CNRFC to generate both five-day deterministic and 15-day (hourly timestep) and 365-day (daily timestep) streamflow forecasts.

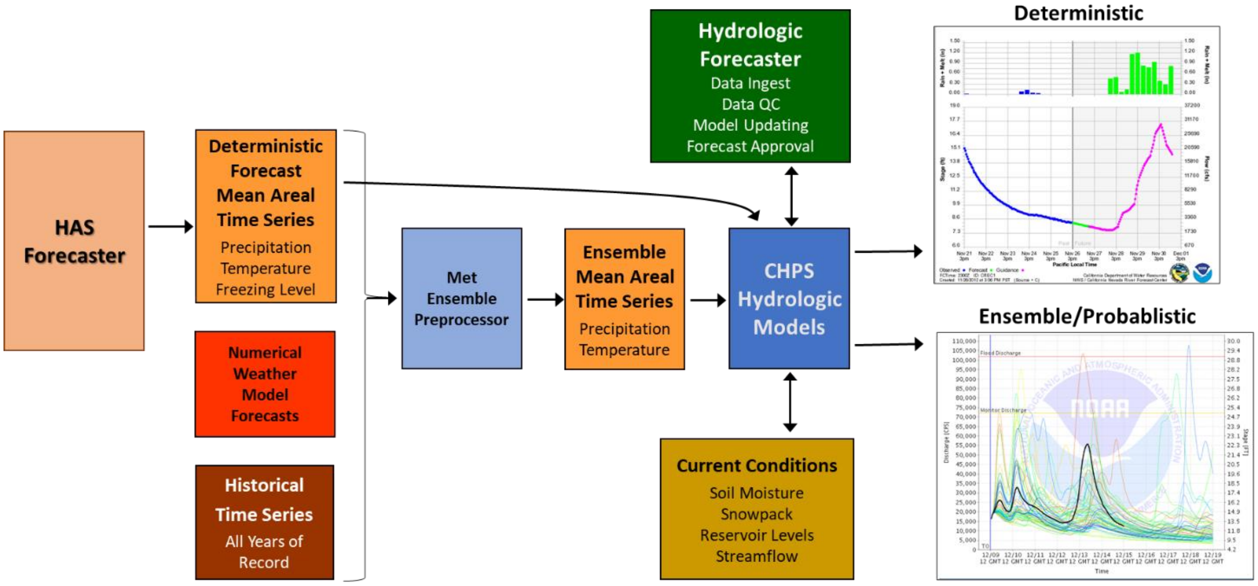

Figure 2.2. *Generalized process used by CNRFC to generate deterministic and ensemble streamflow forecasts.*

The deterministic and ensemble streamflow forecasts utilize the same modeling system with the same initial conditions at the start of the forecast simulation run. The only difference is the weather forecast. The deterministic forecast uses the five-day deterministic weather forecast (i.e., precipitation, temperature, and freezing level) from the HAS unit. These five-day forecasts are the basis of the National Weather Service (NWS) flood warning program and are heavily used by emergency services agencies and reservoir managers. Archiving of five-day streamflow forecasts for flood forecast locations began in 2003, followed by reservoir inflow in 2005.

The ensemble forecast uses an ensemble of weather forecasts (precipitation and temperature) created by the Meteorological Ensemble Forecast Preprocessor (MEFP). For the ensemble forecasts, the freezing level forecast—needed to type precipitation as either rain or snow—is computed from the lapsed air temperature forecast. Since the elevation of the Russian River watershed is normally well below the snowline, especially during warm AR events, temperature forecasts are not a significant source of streamflow forecast error or uncertainty.

The MEFP is calibrated for each watershed using historical observations and forecasts. The calibration was done for (1) archived deterministic HAS forecasts and (2) the ensemble-mean of the Global Ensemble Forecast System (GEFS) version 10 hindcasts generated by NOAA (Hamill et al. 2013). The MEFP produces a set of ensemble weather forecasts that are unbiased and whose spread is proportional to the skill of the forecast used (e.g., HAS or GEFSv10). The MEFP uses the historical climatology of the observations as a ranking framework to create ensembles reflective of the current forecast conditions. As the skill diminishes with longer lead times, the MEFP generated ensembles become more like the historical observations to the point where when skill is zero, they are the same. The MEFP process is described by Demargne et al. (2014).

In real time operations, MEFP is forced with three days of HAS forecasts followed by 12 days of the GEFSv10. This is done to take advantage of the more skillful short-term HAS forecasts. This method of ensemble streamflow forecast generation has been operational at the CNRFC since 2012.

The archive of real time deterministic and ensemble forecasts is far too short for a robust evaluation of FIRO WCP alternatives. To provide a longer period of record, daily hindcasts (e.g., hourly time step, 15-day duration) were generated by the CNRFC for 1985–2017. The hindcasts used the same hydrologic modeling system and historical observations, and MEFP was forced with the GEFSv10 hindcasts (1985–2010) and archived GEFSv10 forecasts (2011–2017).

2.2 Forecast Verification

As described in Section 2.1, both deterministic and ensemble-based probabilistic streamflow forecasts are operationally available for developing FIRO approaches and decision support. Reservoir operators have used deterministic forecasts, where proven reliable, to hedge release decisions for some time. More recently, ensemble-based probabilistic forecasts provide the additional dimension of uncertainty and longer forecast lead times. Additionally, the hindcasting capacity of the ensemble forecasts provides for more robust development, testing, and evaluation of alternative FIRO WCPs. Both types of forecasts are verified here for context and in support of the WCPs evaluated in Section 3.

The verification information summarized here was taken directly from Weihs et al. (2020), Delaney et al. (2020), and Reynolds et al. (2016). Each of these reports can be found in Appendices E and H.

2.2.1 Deterministic Precipitation and Streamflow Forecasts

Using median travel times of the water releases (i.e., flood wave) and release limits from the reservoir, the Lake Mendocino PVA established that forecasts at one- to five-day lead times are the most critical to support FIRO decision making. Based on this, CNRFC cool-season forecasts at these lead times of precipitation from 2000–2017 and inflows from 2005–2017 were evaluated over several accumulation periods to address flood timing-related errors. In addition, the skill in predicting larger events (those with a frequency of a two-year return period or greater) were evaluated to provide insights into predictability and impacts of larger precipitation on watershed scales.

This assessment found that the deterministic CNRFC Quantitative Precipitation Forecast (QPF) captures 50 percent or more of the variance (i.e., $R^2 > 0.5$) in the forecast for all lead times (one to five days) and accumulated precipitation metrics (24 hrs to 120 hrs), except the 24-hr accumulated precipitation at five-day lead (Table 2.1). The 24-hr total inflow forecast skill gradually decreases with lead time, with R^2 from 0.9 for one-day forecasts to still greater than 0.5 at five-day lead time. Even though this analysis is restricted to the cool season, where nearly all precipitation falls, the analysis is still dominated by many days with no rain and stable inflows.

Table 2.1. *CNRFC deterministic cool season QPF error statistics for the Lake Mendocino watershed. Data from January 2000 through May 2017. Root mean square error (RMSE) and bias in inches.*

		Lead Time				
Period	**Metric**	**1 day**	**2 days**	**3 days**	**4 days**	**5 days**
24-hr	R^2	0.83	0.76	0.65	0.54	0.39
	RMSE	0.18	0.2	0.23	0.24	0.26
	Bias	0.02	0.02	0.01	-0.01	-0.02
72-hr	R^2			0.83	0.77	0.68
	RMSE			0.39	0.41	0.46
	Bias			0.05	0.02	-0.02
120-hr	R^2					0.79
	RMSE					0.58
	Bias					0.03

Table 2.2. *CNRFC deterministic cool season Lake Mendocino inflow forecast error statistics. Data from January 2005 through March 2017. RMSE and bias in acre-feet (ac-ft).*

		Lead Time				
Period	**Metric**	**1 day**	**2 days**	**3 days**	**4 days**	**5 days**
24-hr	R^2	0.84	0.8	0.73	0.66	0.53
	RMSE	433	446	470	474	540
	Bias	20	13	-10	-36	-37
72-hr	R^2			0.85	0.81	0.75
	RMSE			1008	1042	1126
	Bias			22	-35	-85
120-hr	R^2					0.83
	RMSE					1565
	Bias					-54

Forecast errors were then further subdivided by the magnitude to focus on the events with a climatological return period frequency greater than two years. Forecast errors for inflow and precipitation were loosely associated with the corresponding observed (verification) magnitudes (R^2 = 0.38 for 120-hr precipitation, R^2 = 0.44 for 120-hr total inflows). On average, 72-hr and 120-hr forecasts that were forecasted to be smaller than the two-year event were generally biased high, while forecasts that were observed to be larger than the two-year event were biased low. Figure 2.3 shows the best-fit linear relation between 120-hr forecast inflow and precipitation errors for events greater than two years. Using this relationship for the largest such forecast error (occurring on January 25, 2008), the estimated inflow error was -9700 ac-ft. More details on this regression and other statistics of these larger events can be found in Weihs et al. (2020).

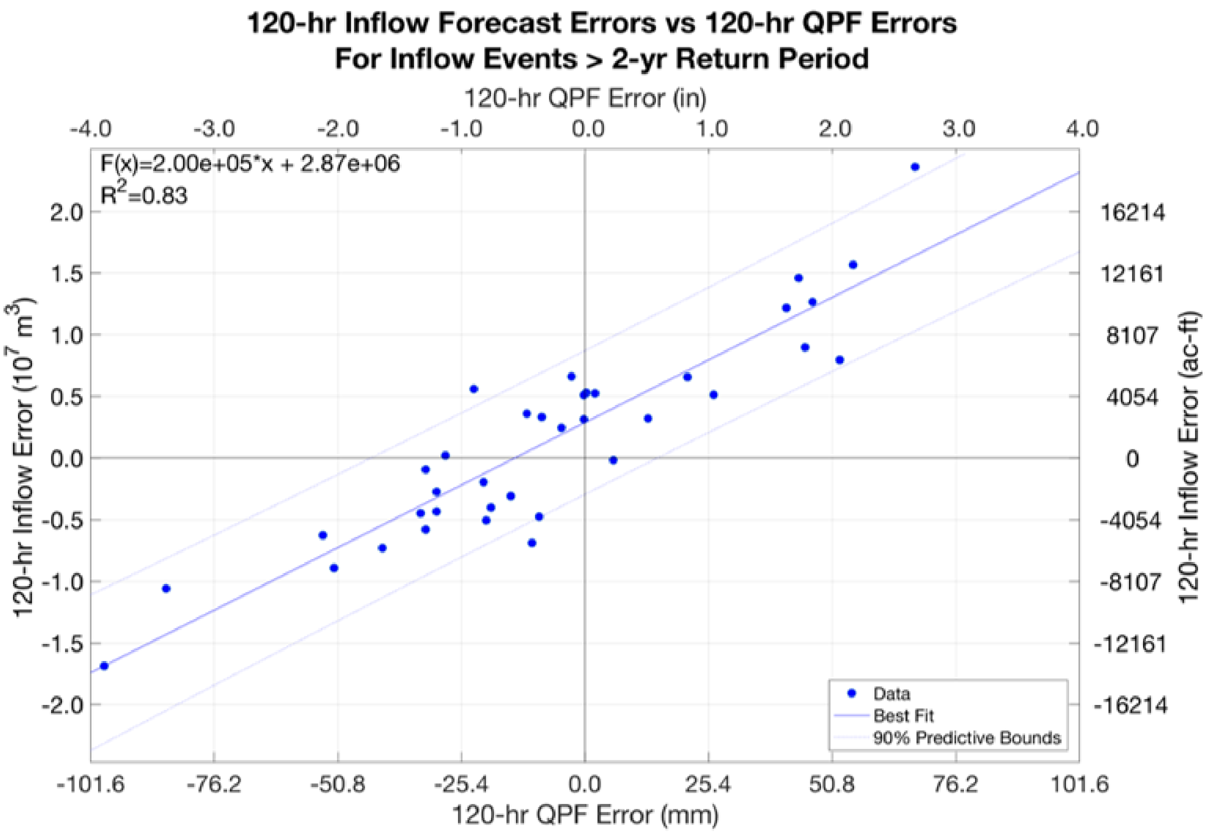

Figure 2.3. *Relation of 120-hr forecasted inflow errors to their respective QPF errors for inflows with a return period greater than two years.*

Overall, this analysis suggests that there is significant skill in current cool-season single and multi-day forecasts of total rainfall and inflow for Lake Mendocino that can be used in FIRO implementation. The 24-hr precipitation forecasts agree well with observations (R^2 exceeding 0.5) out to four-day lead times, while inflow forecasts agree with observations to five-day lead times. Forecasted dry periods will also be important for reservoir operations because they may provide the basis for keeping encroached water in the reservoir for future supply. Forecasts of no significant rainfall (i.e., less than one inch per day) were found to be quite skillful (hit rate of 0.97). Inflow forecast errors that exceed 10,000 ac-ft over a five-day period were rare during the 1985–2010 period (Figure 2.3).

2.2.2 Ensemble Forecasts

2.2.2.a GEFSv10 Ensemble Mean Precipitation

As described in Section 2.1, the ensemble streamflow forecasts leverage the deterministic QPF generated by the CNRFC HAS unit as well as the ensemble mean precipitation from the GEFSv10. Since the period of record for the CNRFC HAS QPF is relatively short as of 2000, GEFSv10 hindcasts (1985–2010) and archived forecasts (2011–2017) were used to seed the MEFP to generate the full 15-day duration of the ensemble streamflow hindcasts used to develop and test FIRO WCP alternatives in Section 3. In Hydrologic Ensemble Forecasting System (HEFS) operations since 2011, the CNRFC uses the HAS QPF for the first three days followed by the GEFSv10 for days four through 15.

Figure 2.4 shows the 1985–2010 GEFSv10 ensemble mean six-hour precipitation R^2 and RMSE in inches for the Lake Mendocino watershed. CNRFC six-hour calibration quantitative precipitation estimates (QPEs) were used as observations. The R^2 falls off quickly as expected for six-hour duration forecasts. Longer durations (i.e., 24 hours or longer) retain higher correlation with increasing lead time because the effects of timing errors are reduced.

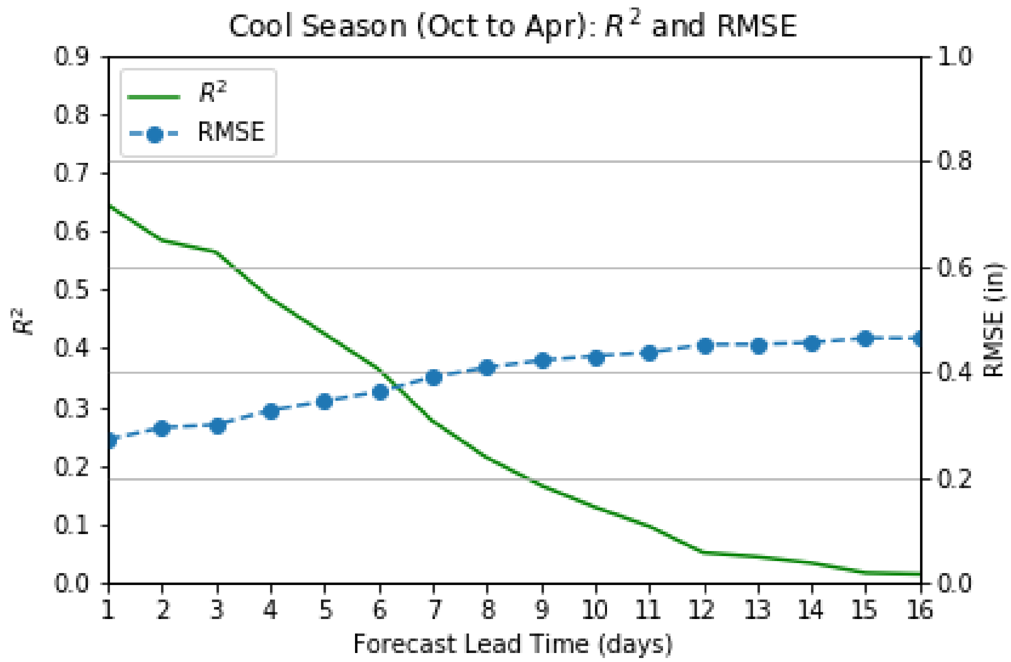

Figure 2.4. *1985–2010 GEFSv10 six-hour ensemble mean precipitation R^2 and RMSE in inches for the Lake Mendocino watershed.*

Figure 2.5 compares the CNRFC HAS 24-hr QPF with that of the GEFSv10. Note that because the effects of timing errors are reduced, the 24-hr R^2 is higher than shown in Figure 2.4. This reduction also shows that the R^2 for the CNRFC HAS QPF is substantially higher than the GEFSv10's for the first 4 days. The RMSE is also significantly higher, but may be affected by an expected low bias in the GEFSv10 precipitation forecasts.

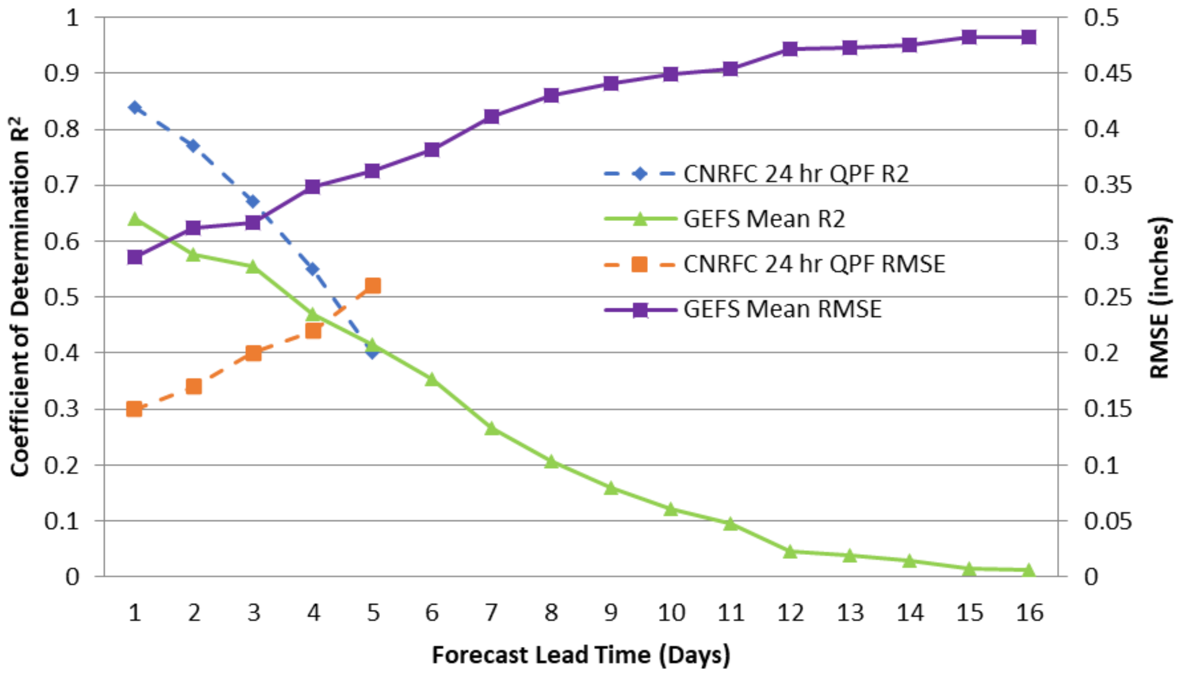

Figure 2.5. *The 24-hr (daily total) QPF forecast skill metrics comparing CNRFC HAS with GEFSv10 ensemble mean.*

The comparison in Figure 2.5 is important because the WCP evaluations presented in Section 3 were exclusively generated with GEFSv10 hindcasts and forecasts due to the CNRFC HAS QPF only being available back to 2000. Since operational HEFS ensemble forecasts leverage the CNRFC HAS QPF for the first three days, the hindcasts used in the FIRO WCP evaluations in Section 3 are likely less skillful than those operationally available. As such, the results of the evaluations in Section 3 are most likely a conservative estimate of potential benefits over baseline Water Control Manual operations.

2.2.2.b Lake Mendocino Ensemble Inflow Forecasts

Reliability is important when assessing ensemble forecasts because it describes how well the ensemble forecast distribution captures the observation. Rank histograms are a commonly used tool to evaluate the statistical reliability (i.e., Type I conditional bias) of ensemble forecast systems and are useful for determining the reliability of ensemble forecasts, as well as diagnosing errors in its mean and spread. As an additional assessment of hindcast reliability, cumulative rank frequency plots (provided in Figure 2.6), which are similar to rank histograms, were developed using the ensemble hindcast and observed Lake Mendocino three-day inflow volumes from 1985–2010 for the months of December through March.

To calculate the rank frequency, each daily observed inflow volume is ranked by the order in which it falls within the range of the ensemble spread. Since there are 61 ensemble members in the hindcast, there are 62 possible ranks with ranks 1 and 62 accounting for observations that fall either less than (rank 1) or greater than (rank 62) the ensemble range. The calculated frequency of each rank is displayed in the plots shown as the monotonic accumulation ordered by increasing rank. The frequency plots were generated for subsets of the hindcast for five different forecast lead times (1 to 3, 4 to 6, 7 to 9, 10 to 12, and 13 to 15 days) shown as rows in Figure 2.6. Stratification was applied to sample different quantile ranges (shown as columns in the figure), which are conditioned by the ensemble forecast median. The first column of frequency plots shows the entire range of hindcasts (0 to 100 percent), while columns two through four stratify the hindcasts into ranges of quantiles (50 to 75, 75 to 90, and 90 to 100 percent). The upper and lower forecast volumes used to condition each stratified subset are provided in the title of each subplot.

An ideal forecast would produce ensemble members that are equally probable, presented in the frequency plots as red dashed lines, which show a straight line with a slope equal to the expected equal probability (i.e., one divided by the 62 possible ranks). These results show a strong tendency for the observation to fall in the upper tail of the ensemble distribution (higher ranks) of the hindcast for one through six days of lead time, as evidenced by the hindcast cumulative frequency falling well below the idealized cumulative frequency for most of the distribution and then increasing significantly for the top ranks, especially for the 0 to 100, 50 to 75, and 75 to 90 percent stratified subsets. Forecast reliability improves for the seven- to 15-day lead times with decreasing bias; however, there is still an asymmetric pattern, which implies that the central tendency of the forecasts is systematically too low (i.e., an under-forecasting issue). Forecast reliability improves for all lead times for the 90 to 100 percent subset. The one- to three-day lead time of this subset shows possible issues of under-dispersion, with higher frequencies occurring in the upper and lower tails of the ensemble distribution. The four- to six-day lead time of the 90 to 100 percent subset shows the best reliability with the cumulative frequency of the hindcast closely matching the idealized cumulative frequency. Improved reliability in the higher flow ranges is the most important for FIRO as these events drive the most important release decisions.

The evaluation demonstrated a systematic bias of the hindcast to under forecast conditions for the months December through March. Bias decreases with increasing days of lead time and for the higher range of forecasts when conditioned on the ensemble median. Based on results of a chi-square test (X^2 results and associated p-values are included as insets in each of the cumulative rank frequency plots), the hindcast shows the greatest reliability for the 90 to 100 percent stratified subset for lead times of four to 15 days, where p-values exceed a significance level of 0.05. It is important to note that the stratification volume ranges for the 90 to 100 percent subsets includes the range of hindcasts (i.e., >10,000 ac-ft in three days) that inform many of the flood control pre-release decisions of candidate WCPs evaluated in Section 3.

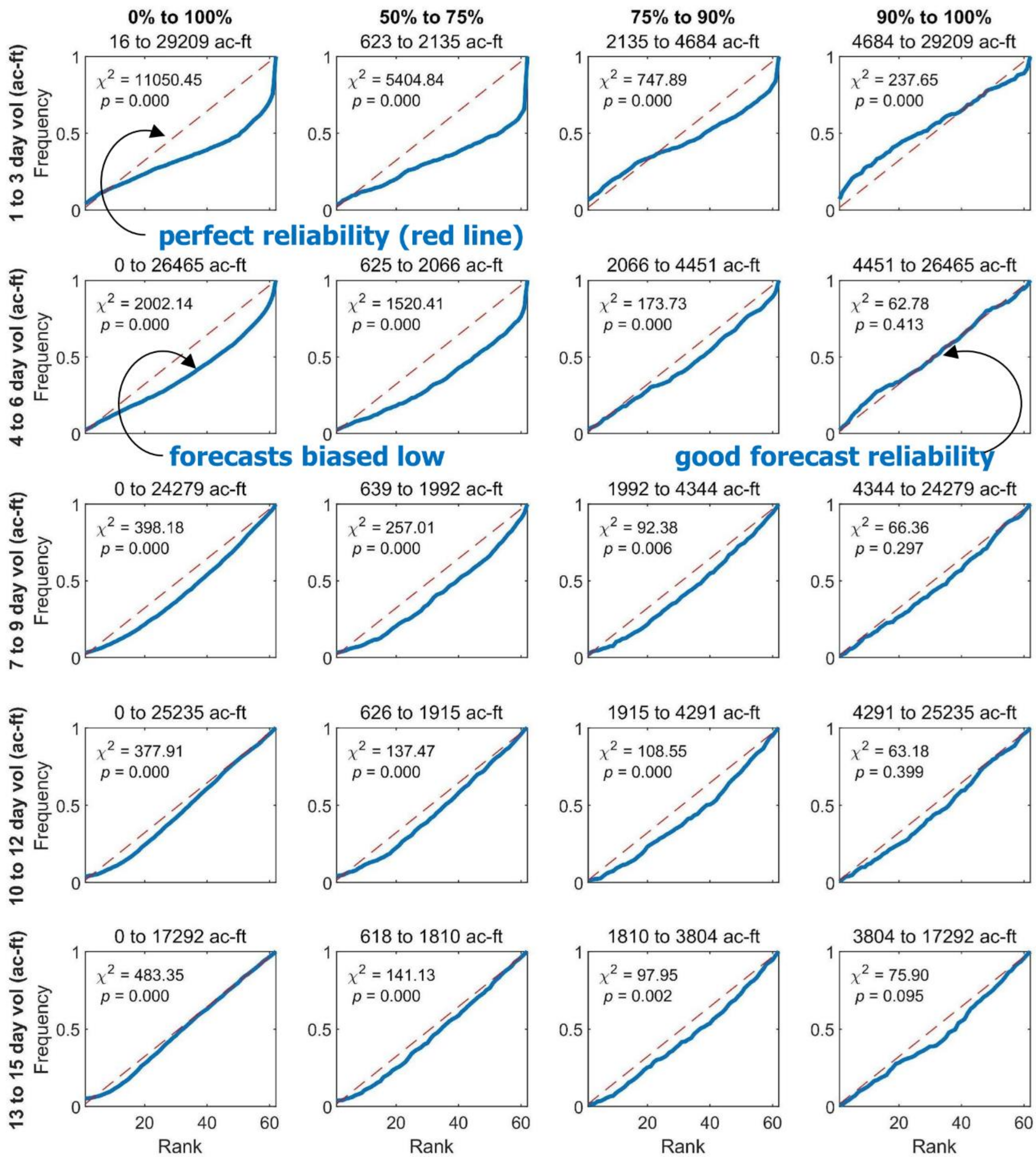

Figure 2.6. *Cumulative rank histograms for three-day inflow forecasts to Lake Mendocino for five lead times and four stratified volume ranges.*

2.3 Regional Variation in Forecast Skill

Weather and water forecast skill are not consistent across the United States. Sukovich et al. (2014 provided key insights on how skill varies across the country using National Centers for Environmental Prediction (NCEP) and WCP QPF and QPE. Figure 2.7 shows the top 1 percent and 0.1 percent thresholds for the heaviest daily precipitation by NWS River Forecast Center. The color scheme in Figure 2.7 is used in Figure 2.8 where the NCEP/WPC 32 km QPF verification for 2007–2011 is shown for each River Forecast Center area. During the cool season, the QPF skill along the West Coast tends to be highest, likely because the dominant rainfall mechanisms are frontal as opposed to convective in nature. This variation in QPF forecast skill has direct implications for the potential application and transferability of FIRO.

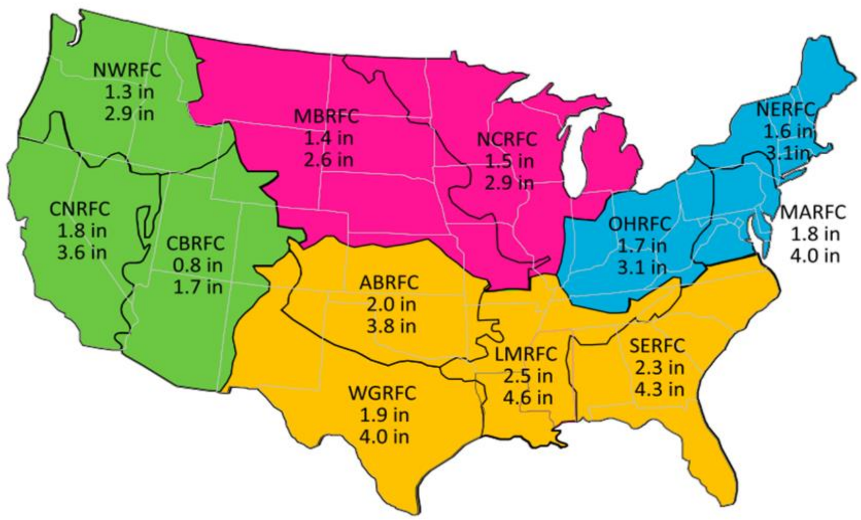

Figure 2.7. *Map of NWS River Forecast Centers and regional thresholds for top 1 percent and 0.1 percent heaviest daily precipitation (from Sukovich et al. 2014).*

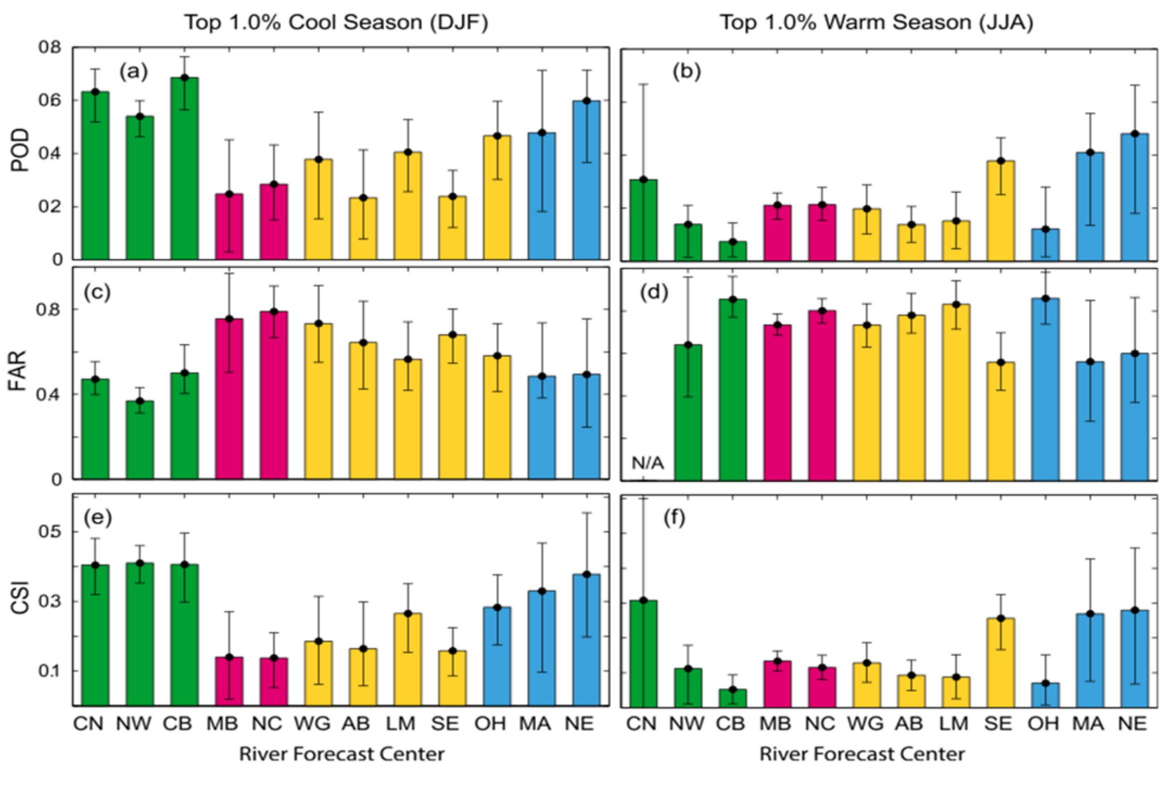

Figure 2.8. *Variation of NCEP/WPC QPF verification metrics from 2007–2011 by River Forecast Center (from Sukovich et al. 2014).*

2.4 Sustainability of Existing and Future Forecast Services

Historically, WCPs that include flood risk management objectives have been engineered to be "observation driven." As a result, resources are dedicated to ensuring that the required observations (e.g., precipitation, temperature, streamflow, reservoir elevation) are reliable, accurate, and available when needed. As FIRO WCPs are considered, the same resource dedication must be applied to forecasts.

Work conducted for this FVA relied heavily on the ensemble streamflow forecasts provided by the CNRFC. This includes the hindcasts used to develop and evaluate alternative FIRO WCPs as well as real time forecasts used in major deviation operations and virtual operations testing (Section 4). While it seems reasonable to assume these forecasts will be provided at equal or higher skill levels in the future, it is important to establish the requirement for their sustained operational provision and support. This includes a robust hindcast process and a framework for reliably integrating updated NWP models into reservoir decision support tools. This does not preclude the development of other forecasting services and technologies, so long as they can provide for a robust evaluation of FIRO WCPs and be reliably delivered for real time operational decision support.

Section 3. Evaluation of FIRO WCP Alternatives Using Existing Streamflow Forecasts

3.1 Background

In 2014, the Lake Mendocino Forecast Informed Reservoir Operations (FIRO) Steering Committee undertook a study to evaluate whether Lake Mendocino could be managed more efficiently for authorized project purposes by integrating reservoir inflow forecasts explicitly in release schedule decision making. That study—referred to as the preliminary viability assessment (PVA)—confirmed that water supply benefit could be increased without adversely affecting the flood risk reduction capability if FIRO procedures were used. The U.S. Army Corps of Engineers (USACE), which is responsible for flood control releases from Lake Mendocino, agreed with the finding and subsequently approved the Steering Committee's request for a major deviation from the Lake Mendocino water control plan (WCP). A WCP is a well-defined set of rules and tools that guide daily decisions about releasing or retaining water in the flood control pool of a reservoir. This temporary deviation permitted greater flexibility in managing Lake Mendocino flood control storage, pending additional investigation that would support incorporating FIRO procedures in a formal revision of the Water Control Manual (WCM).

The PVA evaluated candidate FIRO strategies in a reconnaissance-level technical study, confirming viability of FIRO in concept. However, the PVA did not recommend a single specific strategy for integrating FIRO into a future WCP. That task was to be completed in a subsequent planning study—this study, the Final Viability Assessment (FVA).

The objective of the FVA is to identify, through appropriate detailed technical analyses and other considerations, the best FIRO strategy for Lake Mendocino, along with the manner in which the strategy can be implemented in real-time operation by Sonoma Water and USACE, and enable the WCP changes necessary to permit that change permanently. The FVA also evaluates potential adaptive strategies that allow operators to utilize new technology and improved forecast skill as it becomes available in the future (see Section 6).

As with the PVA, the FVA was managed by the Lake Mendocino FIRO Steering Committee, which identified technical studies consistent with USACE guidance needed for FIRO strategy analysis. The Steering Committee prepared a hydrologic engineering management plan (HEMP) that is "a technical outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem" (FIRO Steering Committee 2019). The objective of the HEMP was to identify and evaluate Lake Mendocino FIRO alternatives in a systematic, defendable, repeatable manner, providing information to the Steering Committee so it may identify the best FIRO strategy. The full text of the HEMP is provided in Appendix B.

3.2 WCP Alternatives

Through Task 2 of the HEMP, the Steering Committee defined and refined the five WCP alternatives listed in Table 3.1 to be evaluated for the FVA. A basic description of each is provided below and complete information on each is provided in Appendix B.

Table 3.1. *Candidate FIRO alternatives evaluated.*

ID	WCP alternative	Description
1	Existing WCP operation (baseline)	Includes the seasonal guide curve and release selection rules from the 1986 USACE WCM and 2003 update to the flood control diagram.
2	Ensemble Forecast Operations (EFO)	Operates without a traditional guide curve and uses the 15-day ensemble streamflow forecasts to identify required flood releases.
3	Hybrid	A combination of the baseline WCP and the EFO. This option was used for major deviation operations in WYs 2019 and 2020.
4	Modified Hybrid	Identical to Hybrid but with a "corner cutting" strategy that allows for greater storage to begin February 15 to aid with spring refill.
5	Five-Day Deterministic Forecast	Defines alternative guide curves with 11,000 acre-feet encroachment space and 10,000 acre-feet draft space above and below the baseline guide curve. Uses five-day deterministic streamflow forecasts to choose the guide curve and make release decisions.

In addition to the baseline, four FIRO WCPs were evaluated through this study. Three of the alternatives were Ensemble Forecast Operations (EFO) type plans and the fourth was developed by USACE Hydrologic Engineering Center (HEC) and USACE San Francisco District to leverage the five-day deterministic forecasts issued by the California-Nevada River Forecast Center (CNRFC) and employ a simpler operation approach. To ensure direct comparison, each WCP had to meet hard (inviolable) operational constraints (Table 3.2), as well as a set of operational considerations (Table 3.3) that could be measured. The details associated with the hard constraints and operational considerations are available in the PVA as well as in the Sonoma Water PVA report (*FiroViability_ScwaReport_Final180222*) located in Appendix B.

Table 3.2. *Hard (inviolable) operational constraints that must be satisfied by all WCP alternatives.*

ID	Limiting Condition
1	Must satisfy limits on release rate of change
2	Must minimize exceeding target maximum flow at Hopland relative to the baseline of current operations
3	Must accommodate maximum release schedule
4	Must not require forecast updates at a frequency other than what is currently available
5	Must meet instream minimum flow requirements
6	Must properly represent current Potter Valley Project diversion
7	Must account for contributions to flood mitigation downstream of Hopland

Table 3.3. *Operational considerations that should be evaluated.*

ID	Operational Consideration
1	Should simulate operation of Ukiah Power and limits on that operation
2	Should avoid spillway flow to maximum extent possible
3	Should consider Lake Mendocino bank protection desires
4	Should consider and address Lake Mendocino Campgrounds operation objective
5	Should consider adverse impact to Lake Sonoma flood operations relative to baseline/current operations
6	Should not require excessive frequency of gate changes

3.2.1 Baseline WCP

The baseline WCP is drawn directly from the 1986 WCM and 2003 update to the Flood Control Diagram. The maximum release schedule, as a function of reservoir elevation, is applied to all other WCPs. The baseline WCP has a winter Top of Conservation (TOC) at 68,400 acre-feet (ac-ft) and a summer TOC of 111,000 ac-ft. Drawdown to the winter TOC begins October 1 and is to be completed by November 1. Spring refill can begin March 1 and can be completed on May 10. The guide curve for the baseline WCP is shown as the black line in Figure 3.1. No forecasts are utilized. Storage above the guide curve is always evacuated as quickly as feasible. The performance of the baseline WCP provides the conditions against which all WCP alternatives are measured.

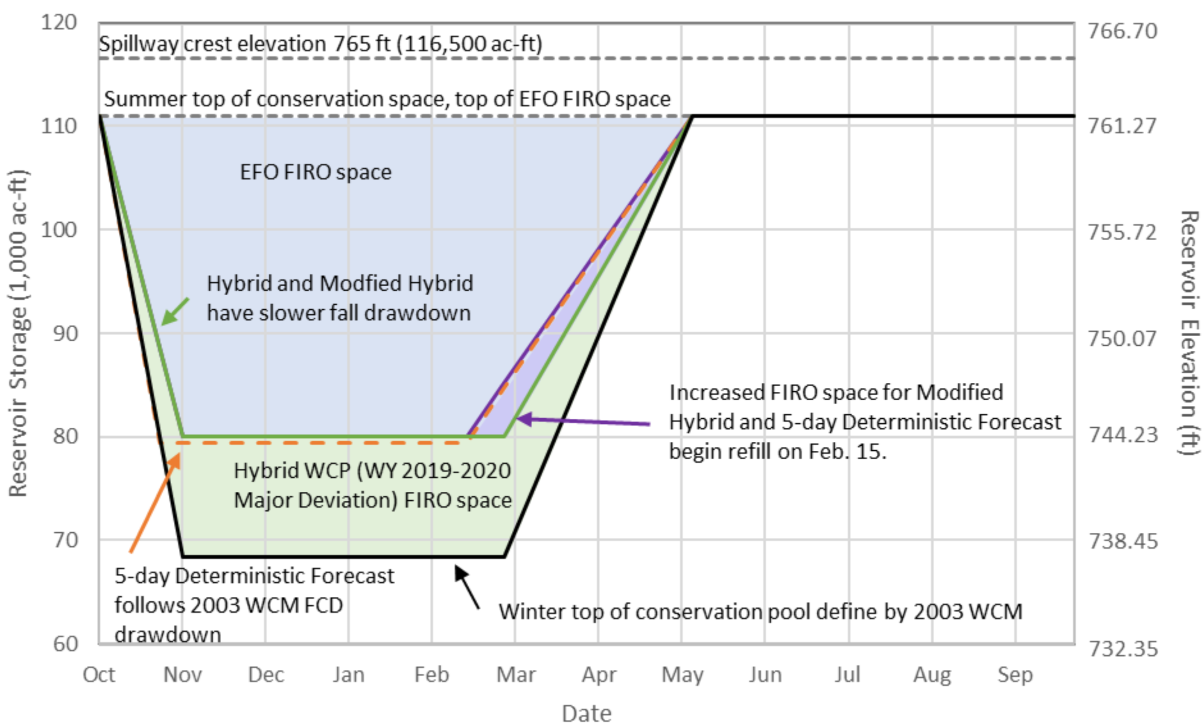

Figure 3.1. *Lake Mendocino guide curves showing the baseline WCP (black line) and conditional storage spaces for the EFO (all shaded areas above black line), Hybrid (light green shaded area), and Modified Hybrid (light green plus light purple shaded areas) WCPs. The drawdown for the Five-Day Deterministic Forecast WCP is the same as the baseline WCP and roughly the same as the Modified Hybrid on the refill portion (dashed orange line).*

3.2.2 EFO

As a part of the Lake Mendocino PVA, Sonoma Water developed the EFO. This WCP, described in Section 4 as well as Section 5.4, leverages the skill in the 15-day ensemble streamflow forecasts operationally provided by the CNRFC to manage the probability of the reservoir rising above the summer TOC (111,000 ac-ft). The forecasts utilized are described in Section 2. To accomplish this, each inflow forecast ensemble member is processed into the reservoir assuming zero release. The resulting ensemble members of reservoir storage for the next 15 days are then measured against a “risk curve” that defines the allowable risk of exceeding the summer TOC over the forecast time domain of 15 days. Risk is defined by the fraction of ensemble members exceeding the summer TOC. A sample risk curve is provided in Figure 3.2.

Whenever an issued forecast results in risk above the allowable level, the model identifies the release needed to mitigate the risk to the acceptable level (i.e., reduce the number of ensemble members exceeding). The release is also subject to the set of physical and system constraints common to all WCP alternatives. Forecast ensemble storage and risk of exceeding the storage threshold is shown in Figure 3.3 before release is modified. Figure 3.4 shows the same after the recommended release has been identified and processed into the forecast storage ensembles.

Figure 3.1 also shows the domain where the EFO model permits conditional retention of storage in the reservoir given the current streamflow forecast (all shaded areas above baseline guide curve). The EFO model permits unbounded drafting of the storage below the winter TOC as needed when an extreme flood event is forecast.

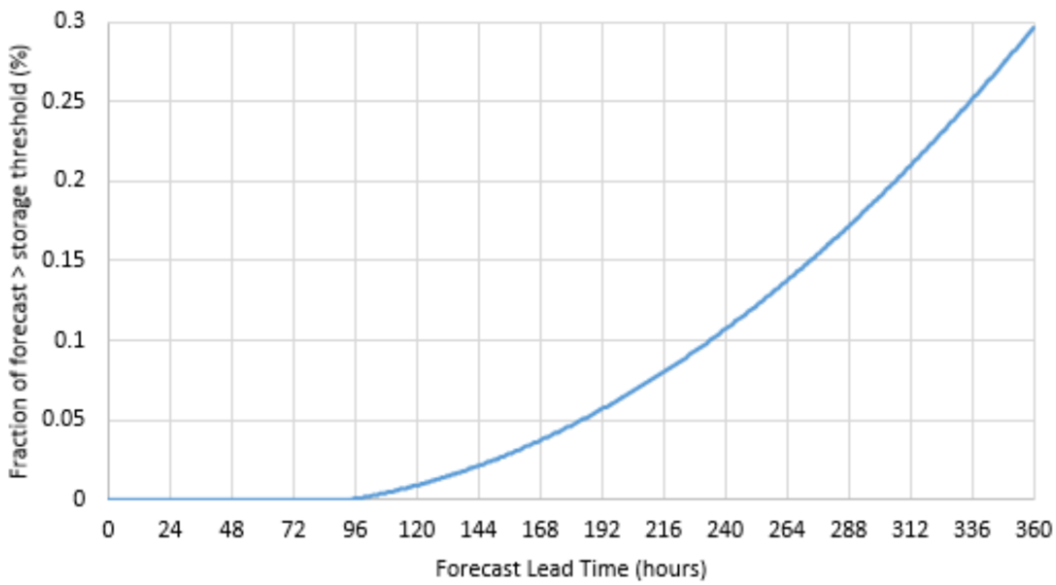

Figure 3.2. *Sample risk curve for EFO-type WCPs. The blue line describes the maximum percentage of ensemble storage members that can exceed the 111,000 ac-ft threshold with time in hours.*

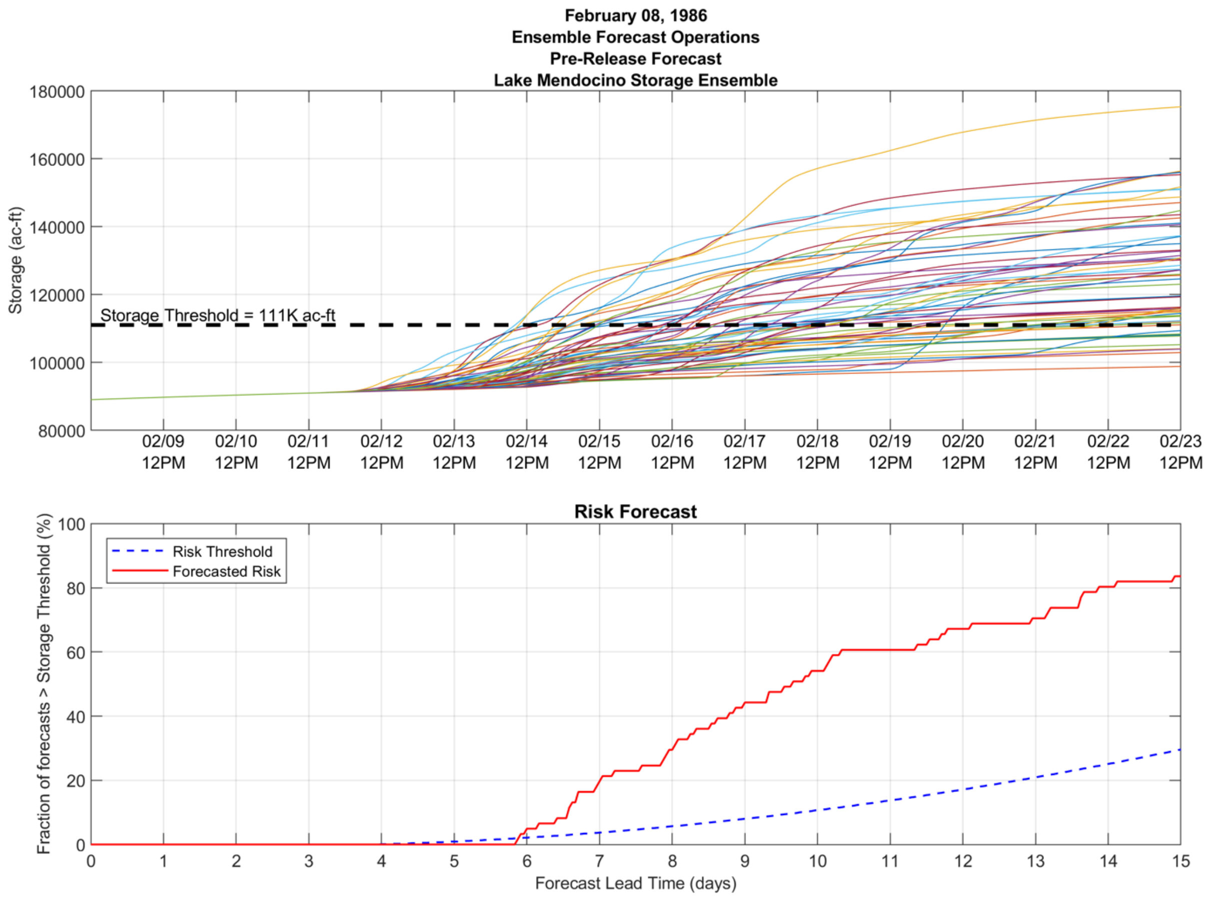

Figure 3.3. *Forecast ensemble storage (top plot), risk curve (blue dashed line, bottom plot) and frequency of storage threshold exceedance (red line, bottom plot) with time before recommended release is identified and processed into storage ensemble members.*

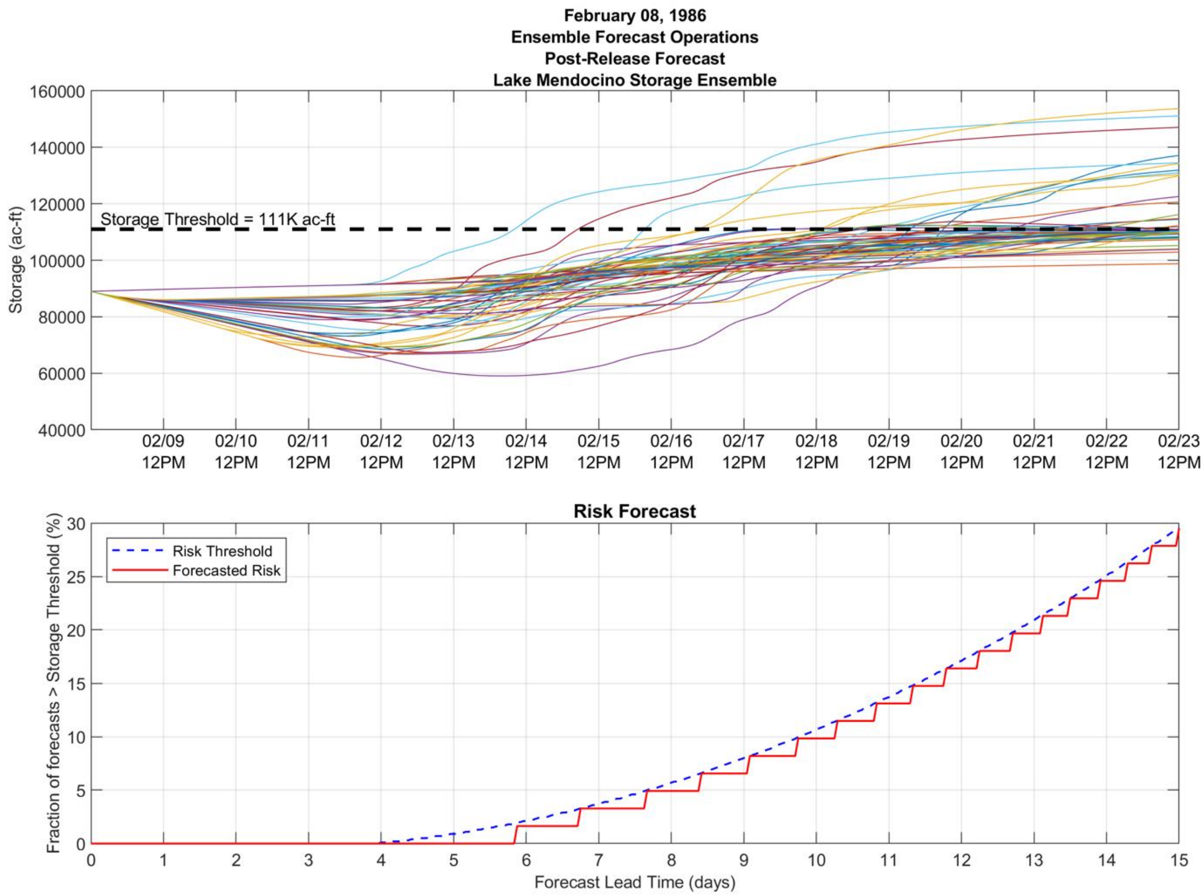

Figure 3.4. *Forecast ensemble storage (top plot), risk curve (blue dashed line, bottom plot), and frequency of storage threshold exceedance (red line, bottom plot) with time after recommended release is identified and processed into storage ensemble members.*

3.2.3 Hybrid EFO

The Hybrid version of the EFO model is identical to the EFO model except that the conditional retention of storage is only allowed up to 80,050 ac-ft at mid-winter. This creates a "FIRO Space" where storage can be conditionally retained. Above this storage level, excess water is released as quickly as feasible. The Hybrid model also permits unbounded drafting of the storage below the winter TOC as needed when an extreme flood event is forecast. This WCP was the basis of the major deviation operations during water year (WY) 2019 and 2020. Figure 3.1 shows the FIRO Space associated with the Hybrid WCP (light green shaded area).

3.2.4 Modified Hybrid EFO

The Modified Hybrid EFO WCP is identical to the Hybrid EFO except that the FIRO Space allows the spring refill to begin on February 15. As with the EFO and Hybrid EFO, this WCP also permits unbounded drafting of the storage below the winter TOC as needed when an extreme flood event is forecast. Figure 3.1 shows the FIRO Space associated with the Modified Hybrid EFO (light green plus light purple shaded areas).

3.2.5 Five-Day Deterministic Forecast

This WCP was developed by HEC and the San Francisco District of the USACE. This WCP employs a simpler FIRO that chooses among three alternative guide curves based on the five-day deterministic streamflow forecasts issued by the CNRFC. Because five-day deterministic forecasts were not archived for the full 1985–2017 evaluation period, HEC developed a process to approximate the deterministic forecast volumes from the ensemble reforecasts available for that full period as described in Section 2. The Lake Mendocino deterministic five-day inflow volume forecast was taken as the ensemble mean volume or the ensemble 75th percentile volume. The Hopland deterministic forecast was taken as the ensemble 75th percentile flow for each day. This procedure is documented and provided in Appendix B.

In this alternative, the operation decisions are primarily achieved by simple changes in the guide curve based on the deterministic inflow forecast. In the absence of a large inflow forecast, the flood control pool is "encroached" by 11,000 ac-ft (State 1). When the five-day volume forecast exceeds Trigger 1 (15,000 ac-ft), the guide curve is returned to the standard (State 0). When the five-day volume forecast exceeds Trigger 2 (20,000 ac-ft), the guide curve is dropped to the "draft" guide curve 10,000 ac-ft below the standard (State -1). As forecasts decrease, the guide curve is returned to higher levels only as forecasted volume falls below the trigger, minus a buffer volume of 3,000 ac-ft (an "untrigger"), to prevent oscillation when the forecast is close to the trigger. Spring refill for the encroachment space begins on February 16th. This WCP's allowance for a 10,000 ac-ft draft into the conservation pool to accommodate a major flood event is limited to the November 1 through March 1 period. Figure 3.1 shows the encroached guide curve for this WCP along with other WCPs, and Figure 3.5 shows the encroached 11,000 ac-ft and draft 10,000 ac-ft curves. The rule set associated with this WCP is fully described in Appendix B.

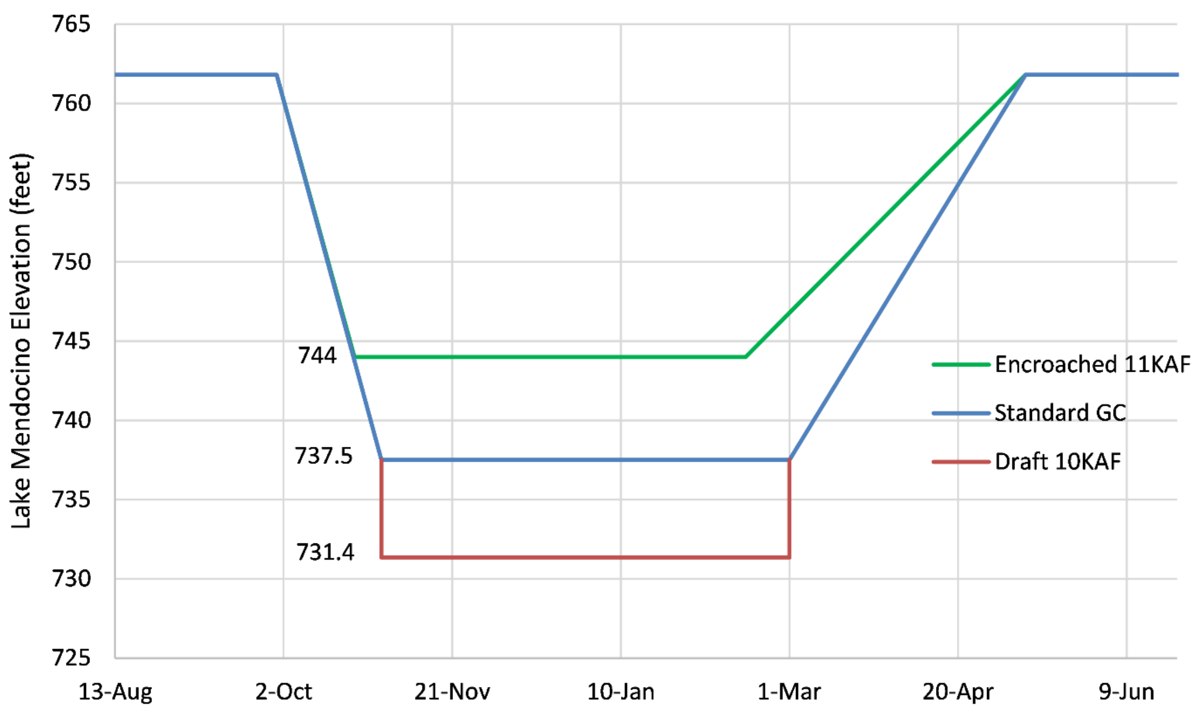

__Figure 3.5.__ Lake Mendocino guide curves for the Five-Day Deterministic Forecast WCP. The blue line is the baseline WCP guide curve. The green line allows for up to 11,000 ac-ft of conditional encroachment and the red line provides up to a 10,000 ac-ft draft into the conservation space to allow for major events.

3.3 WCP Performance Metrics

The Steering Committee defined in the HEMP the set of 16 metrics listed in Table 3.4 to evaluate the WCP alternatives consistently. Details associated with each metric, as well as the process for simulation and evaluation, are described in the HEMP (Appendix B).

Table 3.4. *Summary of performance metrics identified in the HEMP. (Details in Appendix B.)*

Metric	Metric Description
M1	Annual maximum flow frequency function at Hopland, Healdsburg, and Guerneville
M2	Annual maximum pool elevation frequency function of Lake Mendocino
M3	Annual maximum pool elevation frequency function of Lake Sonoma
M4	Annual maximum Lake Mendocino total release frequency function
M5	Annual maximum Lake Sonoma total release frequency function
M6	Annual maximum uncontrolled spill frequency function for Lake Mendocino
M7	Annual maximum uncontrolled spill frequency function for Lake Sonoma
M8	Expected annual inundation damage (EAD) at critical Russian River locations
M9	Expected annual potential (statistical) loss of life due to floodplain inundation at critical Russian River locations, assessed as "population exposed" (EAP)
M10	Reliability of water supply delivery, as measured by annual exceedance frequency of Lake Mendocino May 10 reservoir storage levels
M11	The ability to meet instream flows to support threatened and endangered fish during the summer rearing season, as measured by the annual exceedance of the number of days June through September flows exceed 125 cfs
M12	The ability to meet instream flows to support fall spawning migration, as measured by the annual exceedance of the number of days October 15 to January 1 flows exceed 105 cfs
M13	Impacts to the Bushay Campground during the rec season (Memorial Day through Labor Day), as measured by the annual exceedance of the number of days that Lake Mendocino water-surface elevation exceeds 750 ft (elevation of access road)
M14	Impacts to power production of the Coyote Valley Dam powerhouse
M15	Lake Mendocino bank protection, as measured by annual frequency of exceeding elevation 758.8 ft. (Later refined to capture the number of days above 758.8 ft)
M16	Impacts to hours of operation, as measured by the number of required gate changes

3.4 Procedure

Operation of each Lake Mendocino WCP alternative was simulated using an HEC Reservoir System Simulation (HEC-ResSim) model of the Russian River. The reservoir releases were then routed hydraulically using an HEC River Analysis System (HEC-RAS) model. The HEC-ResSim and HEC-RAS model results were then processed to evaluate the metrics defined in the HEMP (Table 3.4).

3.4.1 Study Boundary Conditions

The primary factor driving this analysis is the availability of historical ensemble forecast information (i.e., hindcasts) in the hydrologic dataset. The CNRFC of the National Weather Service has created a limited series of hindcasts and scaled ensembles. All alternatives analyzed used the same hydrologic dataset. This dataset includes:

- Historical reservoir inflow and downstream local flows. The local flows are computed by the CNRFC and Sonoma Water.

- Hindcasts for the period of record of 1/1/1985 through 9/30/2017. This period includes the largest annual events for WYs 1985 through 2017.
- Design events that represent events rarer than those seen in the hindcast period. Specifically, CNRFC created eight design events based on two scalings each of four historic event patterns. This data set includes reservoir inflows, coincident downstream local flows, and associated ensembles representing forecast information for the design event. The 8 design events are listed in Table 3.5. Details on the scaling process are discussed in Appendix F.

Further descriptions of the hindcast and ensemble development can be found in the *Development of Forecast Information Requirements and Assessment of Current Forecast Skill Supporting the Preliminary Viability Assessment of FIRO on Lake Mendocino* (Reynolds et.al., 2016).

Table 3.5. *Design events developed by the CNRFC for Lake Mendocino FIRO WCP evaluations.*

ID	Event Year	AEP/Scaling
1	1986	p=0.005 (200-year)
2	1986	p=0.002 (500-year)
3	March 1995	p=0.005 (200-year)
4	March 1995	p=0.002 (500-year)
5	1997	p=0.005 (200-year)
6	1997	p=0.002 (500-year)
7	2006	p=0.005 (200-year)
8	2006	p=0.002 (500-year)

3.4.2 Analysis Methods

Procedures for computing each metric were coordinated with Sonoma Water and HEC staff. These procedures are detailed in two technical memoranda titled *Proposed Procedure for Consequence Analysis* and *Procedures for Computation of Non-Consequence Metrics,* provided on 5/22/2020 (Appendix B).

3.4.2.a Non-Consequence Analysis Methods

The general procedure to assess the non-consequence metrics is captured in Figure 3.6. Here, "non-consequence" means those metrics that do not require HEC–Flood Impact Analysis (FIA) or HEC–Flood Damage Assessment (FDA) procedures.

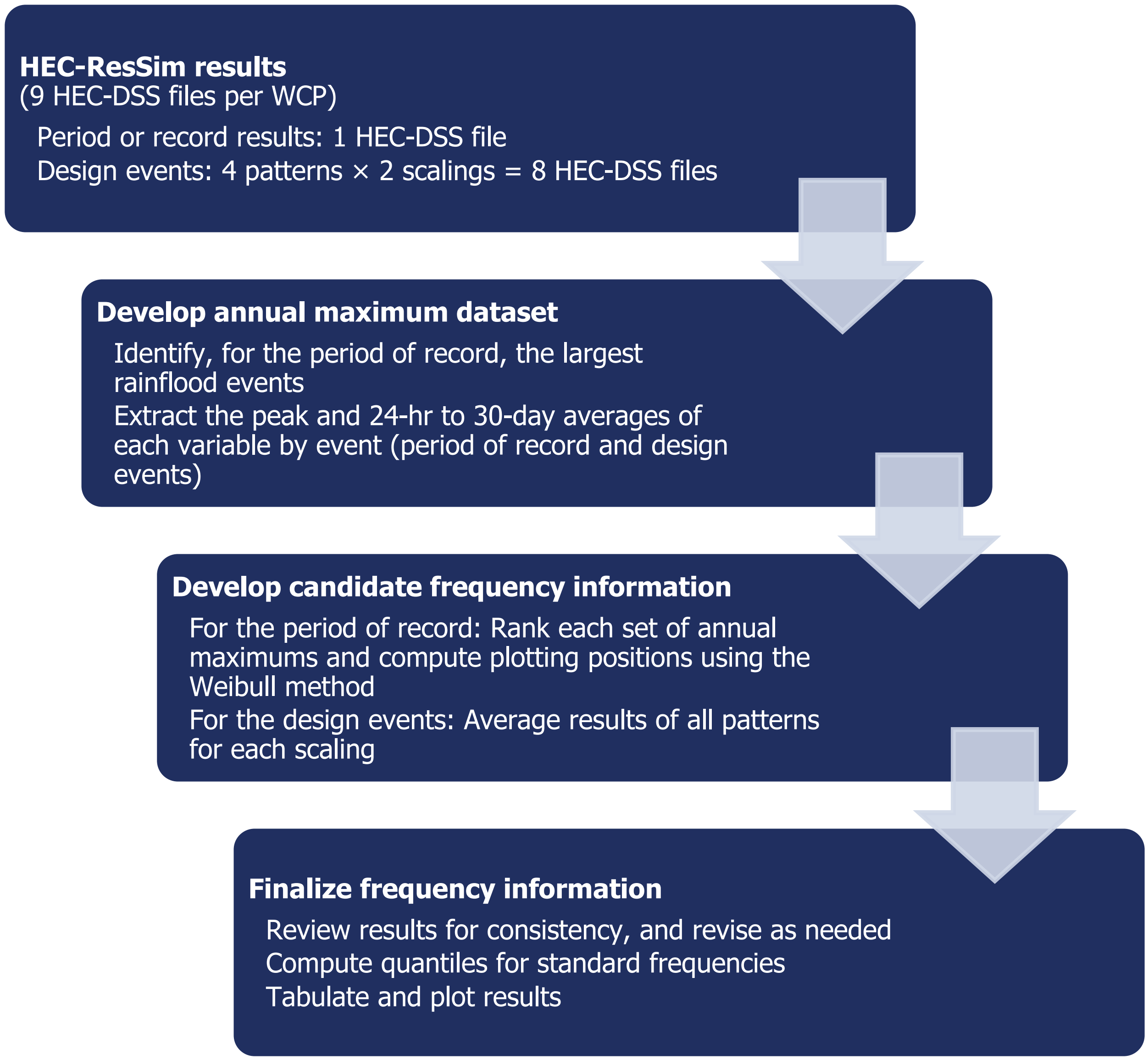

Figure 3.6. *Procedure to calculate M1 through M7. Note that the procedure for calculating M10 through M16 is the same, with the exclusion of the design events.*

3.4.2.b Consequence Analysis Methods

The methodology used historical streamflow information and hydrologic datasets from CNRFC hindcasts in addition to scaled event datasets, including associated ensembles, as input to HEC computer programs HEC-ResSim, HEC-RAS, HEC-FIA, and HEC-FDA. These programs were used to compute consequences for the baseline condition and proposed alternatives in the FVA. Figure 3.7 shows the general overall workflow for each alternative. Each of the steps listed below is more thoroughly discussed in the process document provided in Appendix B.

1. **Develop Floods of Record Dataset.** Reservoir outflows and local inflows from historical streamflow data were used to identify annual peak flow events for the period of record from WY 1985–2017. These floods of record were hydraulically routed and consequences (e.g., flood damage and life loss) for each annual peak flow were computed. For WCP alternatives that require forecast information, the hindcast dataset

was used as forecast information. The deterministic forecasts were approximated from the ensembles per a procedure developed by HEC (see Appendix B).

2. **Develop Design Events Dataset.** Design events, based on two historical event patterns scaled to match outflows for the p=0.005 (200-yr) and p=0.002 (500-yr) events, were used to determine reservoir outflow for the baseline condition and proposed alternatives. Reservoir outflows and local inflows were hydraulically routed and consequences (e.g., flood damage and population exposed) for each design event computed. For WCP alternatives that require forecast information, the ensembles associated with each event were used. The deterministic forecasts were approximated from the ensembles per a procedure developed by HEC (see Appendix B).
3. **Compute Annualized Consequences.** The outputs from Steps 1 and 2 were combined to create the necessary HEC-FDA input frequency functions for each of the event patterns. These were used to calculate expected annual damage (EAD) and Expected Annual Population at Risk (EAP) for each of the four event patterns. The EAD/EAP for the four event patterns were averaged to determine the final EAD/EAP of the chosen alternative.

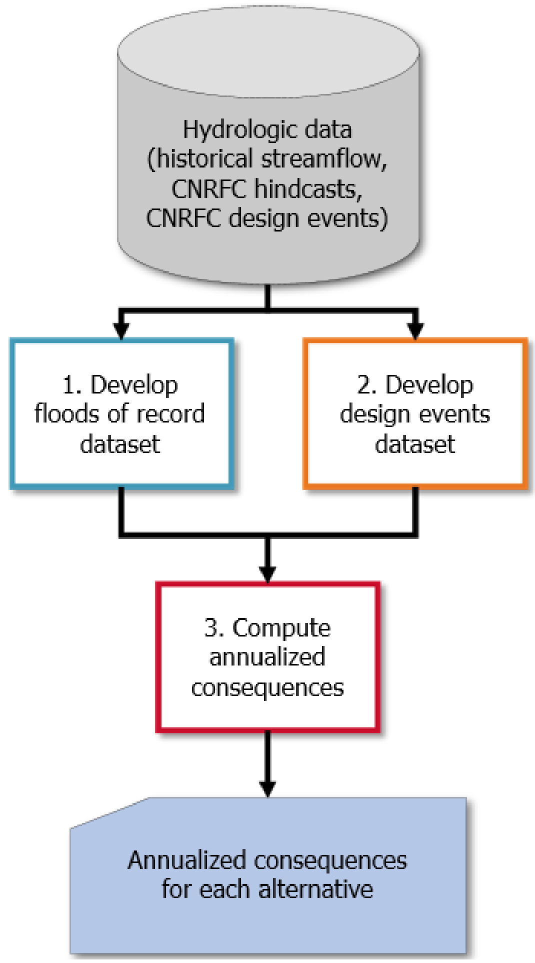

Figure 3.7. *Overview of proposed consequence analysis methodology for Lake Mendocino FVA.*

This methodology was repeated for each alternative.

3.5 Results

According to the HEMP, the efficacy of WCP alternatives must be evaluated using a set of measurable statistics that assess each alternative objectively. The Steering Committee defined in the HEMP a set of 16 metrics as listed in Table 3.4 above. A complete summary of all evaluated metrics is detailed in a technical memorandum titled *WCP Alternative Analysis Results and Metrics: Alternative Comparison,* dated 5/22/2020 (Appendix B).

3.5.1. Key Findings

After reviewing the analysis results for these 16 metrics, we identified eight key findings:

1. The annual frequency and magnitude of uncontrolled spills at Lake Mendocino are reduced compared to baseline for all FIRO WCPs as shown in Figure 3.8. and Table 3.6.

2. For all FIRO WCPs, as shown in Figure 3.9 and Table 3.7, the annual flow frequency quantiles at Hopland for events less frequent than the p=0.5 (1/2-yr) event are generally the same (within 1 percent of baseline) and decrease by up to 5 percent from baseline for the p=0.002 (1/500-yr) event.
3. The total EAD and EAP values for the Russian River are generally the same (within 1 percent of baseline) and may decrease slightly for all FIRO WCPs as shown in Figure 3.10 and Tables 3.8 and 3.9. However, we did find that EAD values for all WCPs along the reach from Hopland to Cloverdale showed slight (within 2 percent) increases from baseline. This increase in total EAD is because of increased damages to structures for specific events simulated. EAP values for this reach are generally the same (within 1 percent). Similarly, the reach including Dry Creek shows slightly (within 4 percent) increased EAD values for this reason. In addition, the Five-Day Deterministic Forecast alternative shows slight (less than 1 percent) increases in total EAD for the reaches of Santa Rosa and Monte Rio for the same reason.
4. The water supply reliability—as measured by the median (50th percentile exceedance) of May 10 storage—increases for all FIRO WCPs as shown in Figure 3.11.
5. The ability to meet instream flows for rearing or spawning habitat generally increases for all FIRO WCPs as exemplified in Figures 3.12 and 3.13.
6. All FIRO WCPs would negatively impact the ability to access Bushay Campground during the recreation season (Memorial Day to Labor Day) as shown in Figure 3.14.
7. City of Ukiah hydropower generation increases slightly (around 4 percent) for the Hybrid, Modified Hybrid, and Five-Day Deterministic Forecast WCPs, and decreases by 13 percent for the EFO WCP as shown in Figure 3.15.
8. There are no impacts on Lake Sonoma operations as shown in Figure 3.16.

The box and whisker plots that follow are configured to show the following:

- Maximum and minimum (whiskers)
- 25 percent to 75 percent range (box)
- Median (heavy horizonal bar)
- Mean (heavy dot)

The color labeling for WCPs is consistent across all figures and tables.

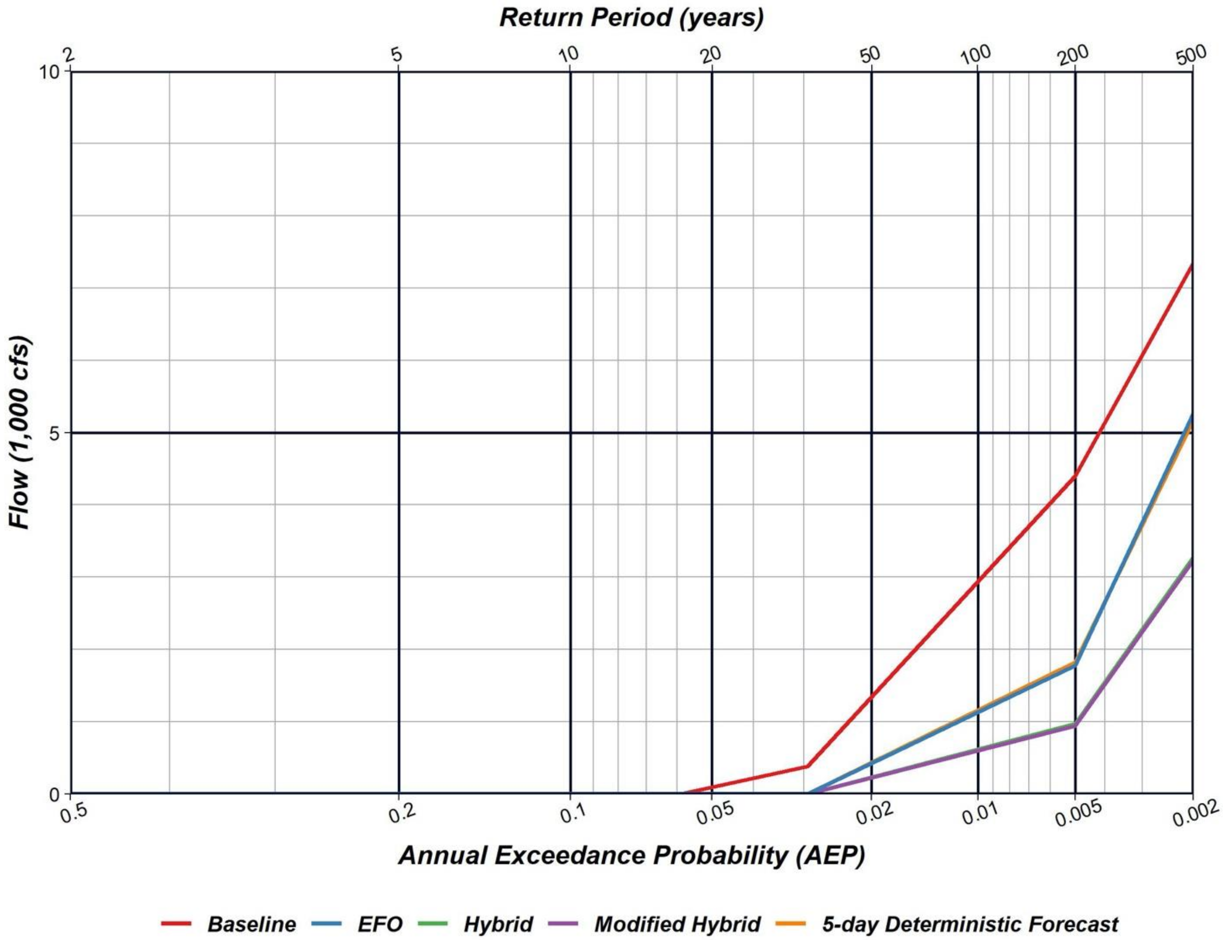

Figure 3.8. *Annual maximum uncontrolled spill-frequency in Lake Mendocino. The Hybrid and Modified Hybrid results are nearly identical (lower lines) and the Five-Day Deterministic Forecast and EFO results are also nearly identical (middle lines).*

Table 3.6. *Difference from baseline in annual uncontrolled spill frequency in Lake Mendocino.*

Annual Exceedance Probability	1/AEP	Difference in Annual Uncontrolled Spill Frequency Quantile (ft) and [%]			
		EFO	Hybrid	Modified Hybrid	Five-Day Deterministic Forecast
0.5	2	0 [0%]	0 [0%]	0 [0%]	0 [0%]
0.2	5	0 [0%]	0 [0%]	0 [0%]	0 [0%]
0.1	10	0 [0%]	0 [0%]	0 [0%]	0 [0%]
0.05	20	-94 [-100%]	-94 [-100%]	-94 [-100%]	-94 [-100%]
0.02	50	-916 [-68%]	-1,110 [-83%]	-1,116 [-83%]	-906 [-68%]
0.01	100	-1,807 [-61%]	-2,322 [-79%]	-2,338 [-80%]	-1,780 [-61%]
0.005	200	-2,621 [-60%]	-3,431 [-78%]	-3,456 [-79%]	-2,580 [-59%]
0.002	500	-2,082 [-28%]	-4,064 [-55%]	-4,111 [-56%]	-2,174 [-30%]

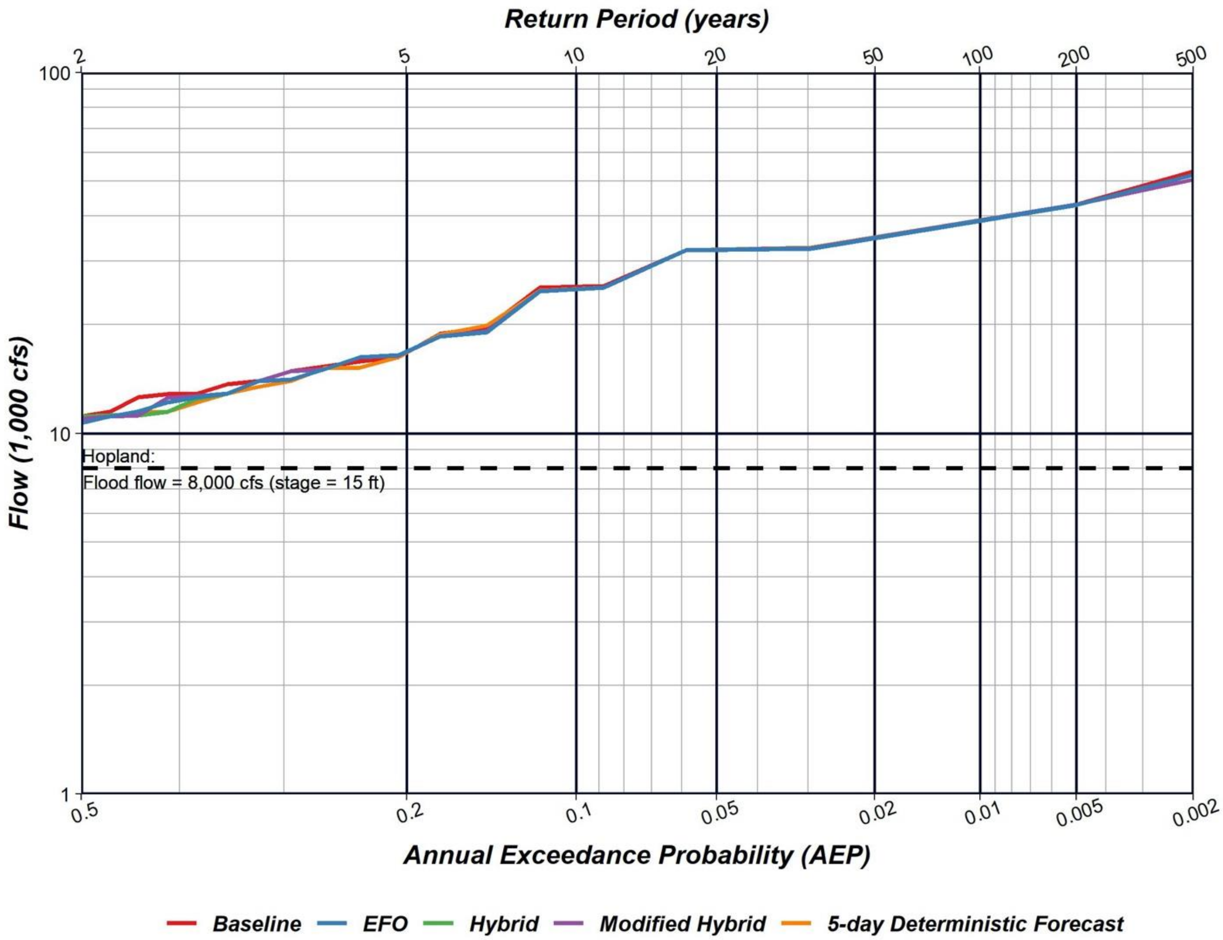

Figure 3.9. *Annual maximum flow exceedance probability at Hopland.*

Table 3.7. *Difference in annual maximum regulated flow frequency at Hopland.*

Annual Exceedance Probability	1/AEP	Difference in Annual Maximum Regulated Flow Quantile (cfs) and [%]			
		EFO	Hybrid	Modified Hybrid	Five-Day Deterministic Forecast
0.5	2	-466 [-4%]	0 [0%]	-171 [-2%]	-466 [-4%]
0.2	5	105 [1%]	73 [0%]	72 [0%]	-17 [0%]
0.1	10	-402 [-2%]	-403 [-2%]	-404 [-2%]	-374 [-1%]
0.05	20	-15 [0%]	-14 [0%]	4 [0%]	20 [0%]
0.02	50	-127 [0%]	-75 [0%]	5 [0%]	35 [0%]
0.01	100	-187 [0%]	-56 [0%]	-17 [0%]	-43 [0%]
0.005	200	-243 [-1%]	-38 [0%]	-38 [0%]	-115 [0%]
0.002	500	-1,335 [-3%]	-2,804 [-5%]	-2,804 [-5%]	-2,829 [-5%]

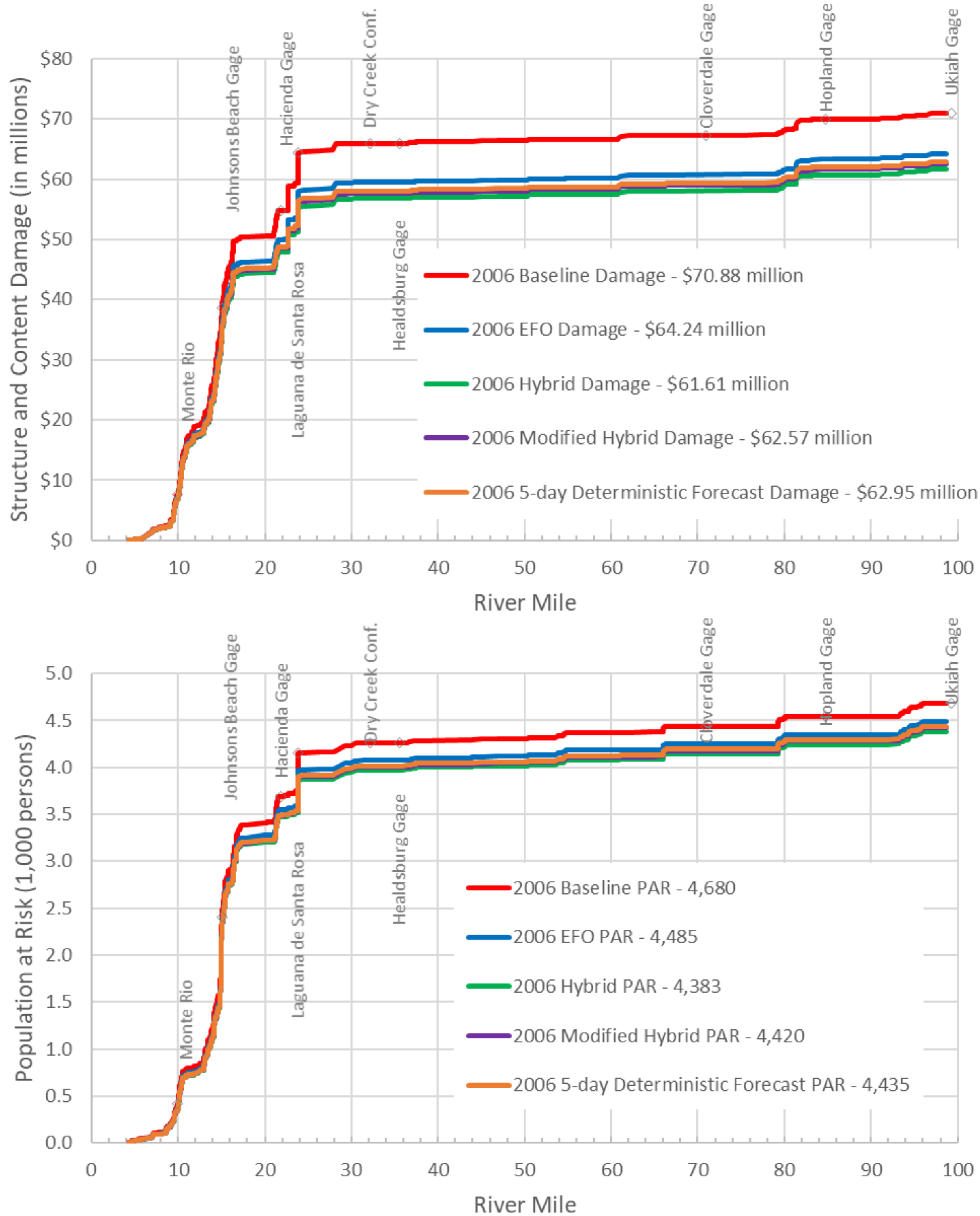

Figure 3.10. *Damage and population at risk (PAR) values along the Russian River for each WCP alternative for the historical 2006 event.*

Table 3.8. *EAD values for each WCP alternative.*

EAD ($1,000) by WCP Alternative					
Location	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
Hopland	104.1	101.1	98.5	100.6	103.7
Cloverdale	703.0	719.3	705.6	705.6	706.4
Geyserville	191.7	185.2	189.7	189.7	189.4
Healdsburg	542.2	532.2	533.1	535.0	540.8
Dry Creek	2.6	2.7	2.7	2.7	2.7
Windsor	265.6	259.6	258.5	258.5	260.2
Santa Rosa	1,121.1	1,119.9	1,104.0	1,100.5	1,122.8
Green Valley Creek	648.7	631.9	616.0	617.9	628.5
Guerneville	11,282.2	11,207.3	11,065.8	11,050.0	11,274.2
Monte Rio	369.8	366.7	364.5	363.8	370.1
Total EAD	**15,231.1**	**15,125.7**	**14,938.3**	**14,924.2**	**15,198.7**

Table 3.9. *EAP values for each WCP alternative.*

EAP (persons) by WCP Alternative					
Location	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
Hopland	15.3	14.7	14.6	14.7	14.9
Cloverdale	42.8	42.7	42.4	42.4	42.6
Geyserville	10.9	10.5	10.8	10.8	10.8
Healdsburg	48.4	48.2	48.3	48.3	48.5
Dry Creek	0.4	0.4	0.4	0.4	0.4
Windsor	39.9	39.9	39.9	40.0	40.2
Santa Rosa	101.5	100.8	99.2	99.1	101.5
Green Valley Creek	2.6	2.5	2.5	2.5	2.5
Guerneville	697.0	688.1	683.2	683.2	690.3
Monte Rio	21.4	21.3	20.9	20.8	21.2
Total EAP	**980.2**	**969.1**	**962.2**	**962.2**	**972.9**

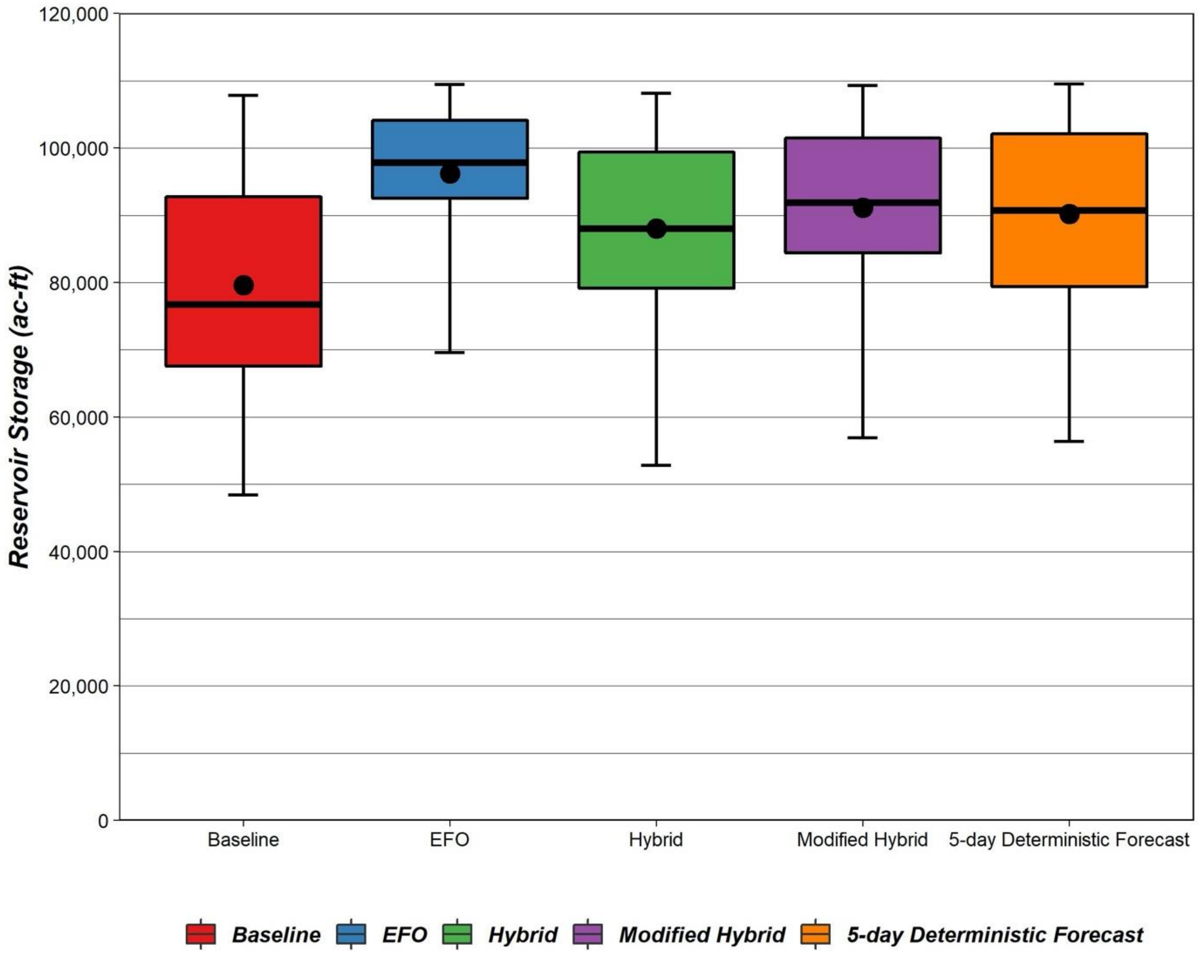

Figure 3.11. *Lake Mendocino storage on May 10.*

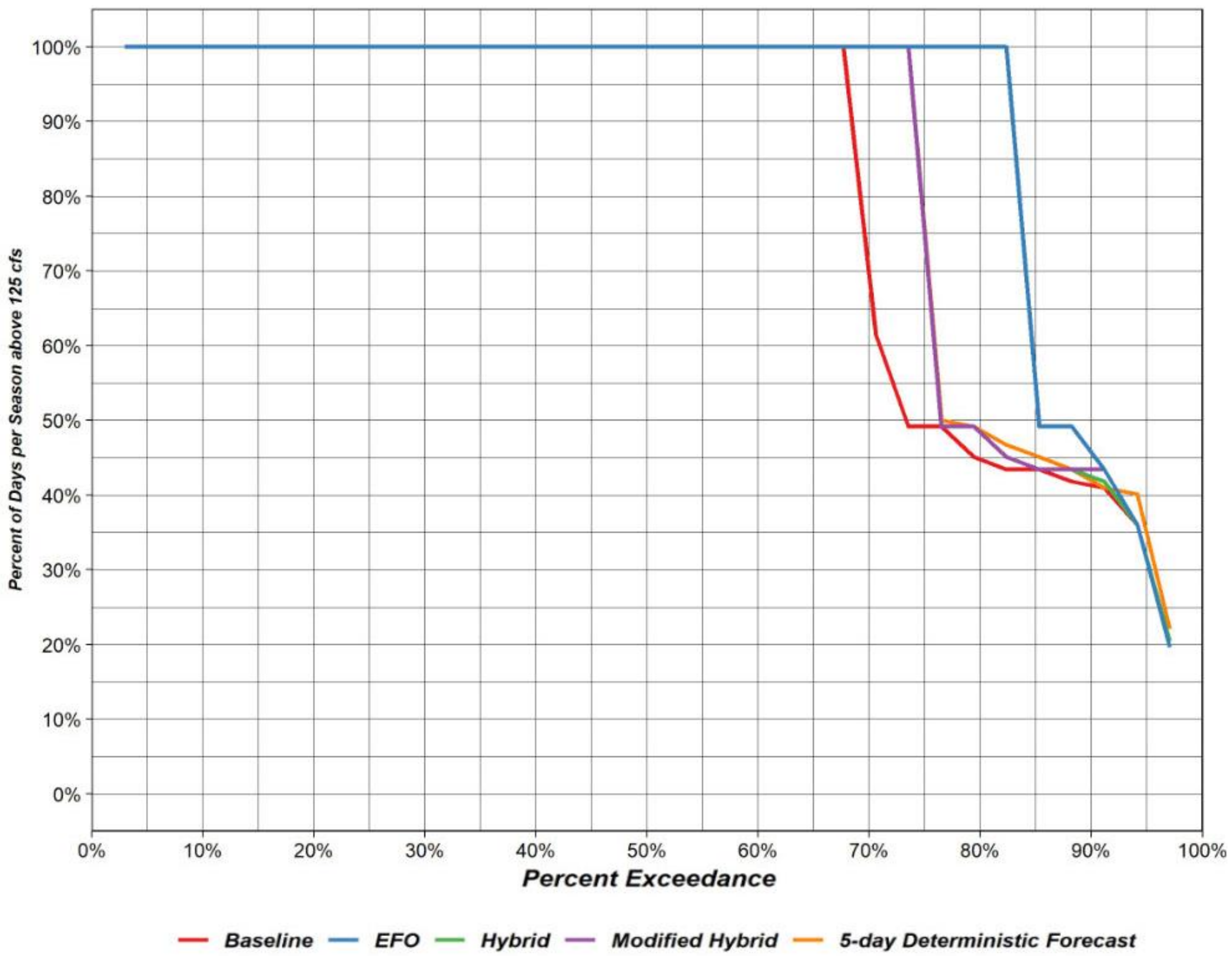

Figure 3.12. *Percent of days per season, June through September, in which flows satisfy 125 cfs at Cloverdale. (Higher is better.) Hybrid, Modified Hybrid, and Five-Day Deterministic Forecast models are nearly identical through 76 percent exceedance.*

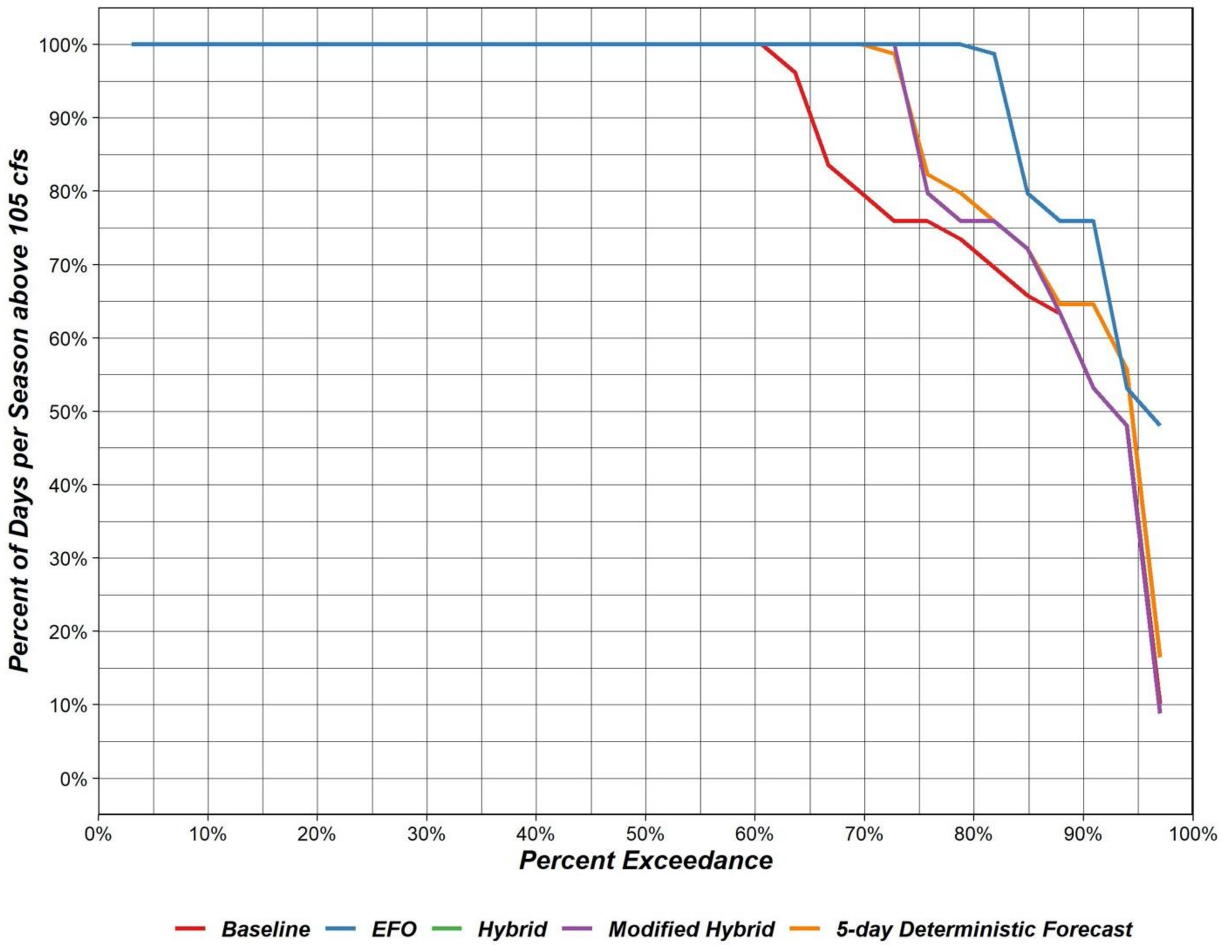

Figure 3.13. *Percent of days per season, October 12 through January 1, in which flows satisfy 105 cfs at Healdsburg. (Higher is better.)*

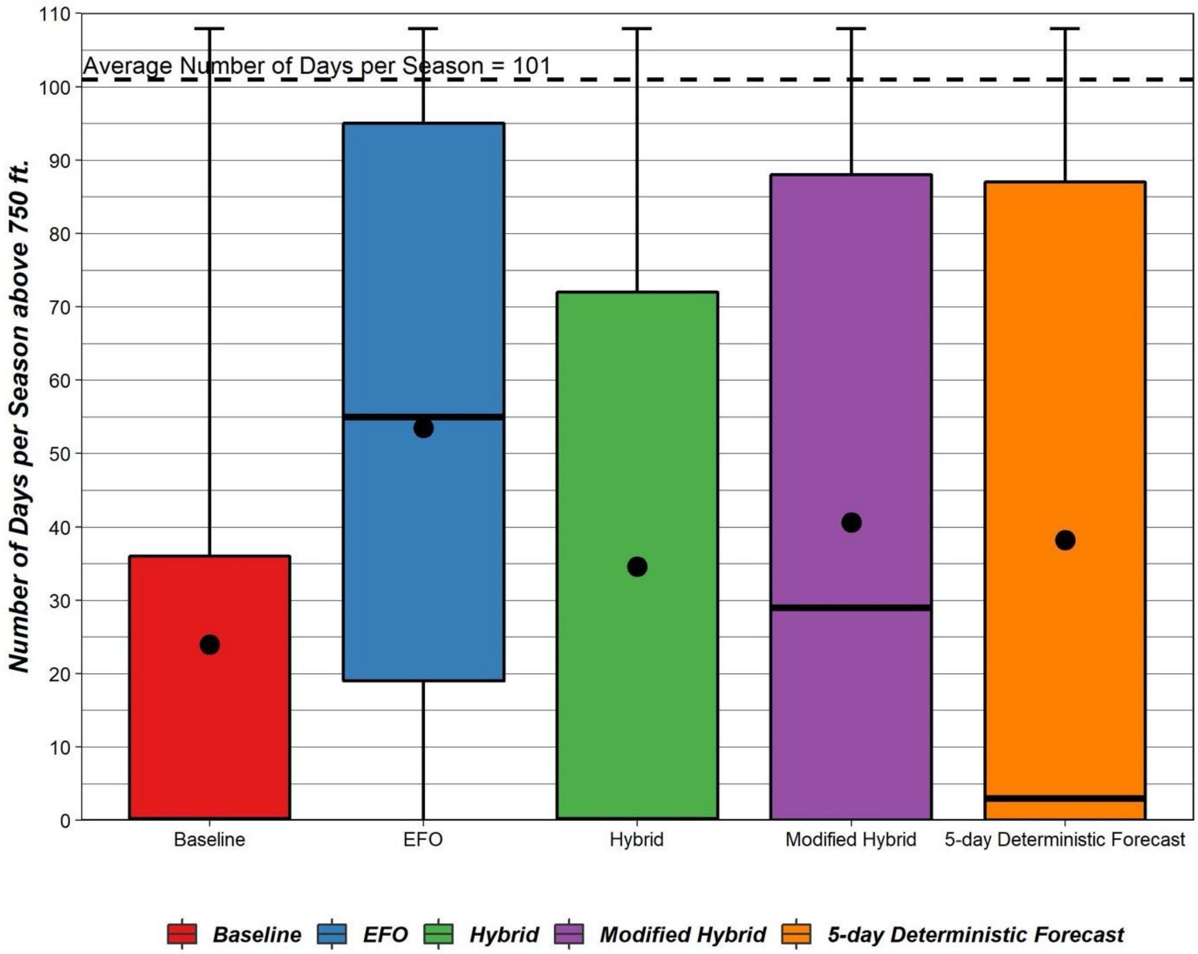

Figure 3.14. *Number of days per recreation season during which access to Bushay Campground is limited (pool elevation 750.0 feet is exceeded). (Lower is better.)*

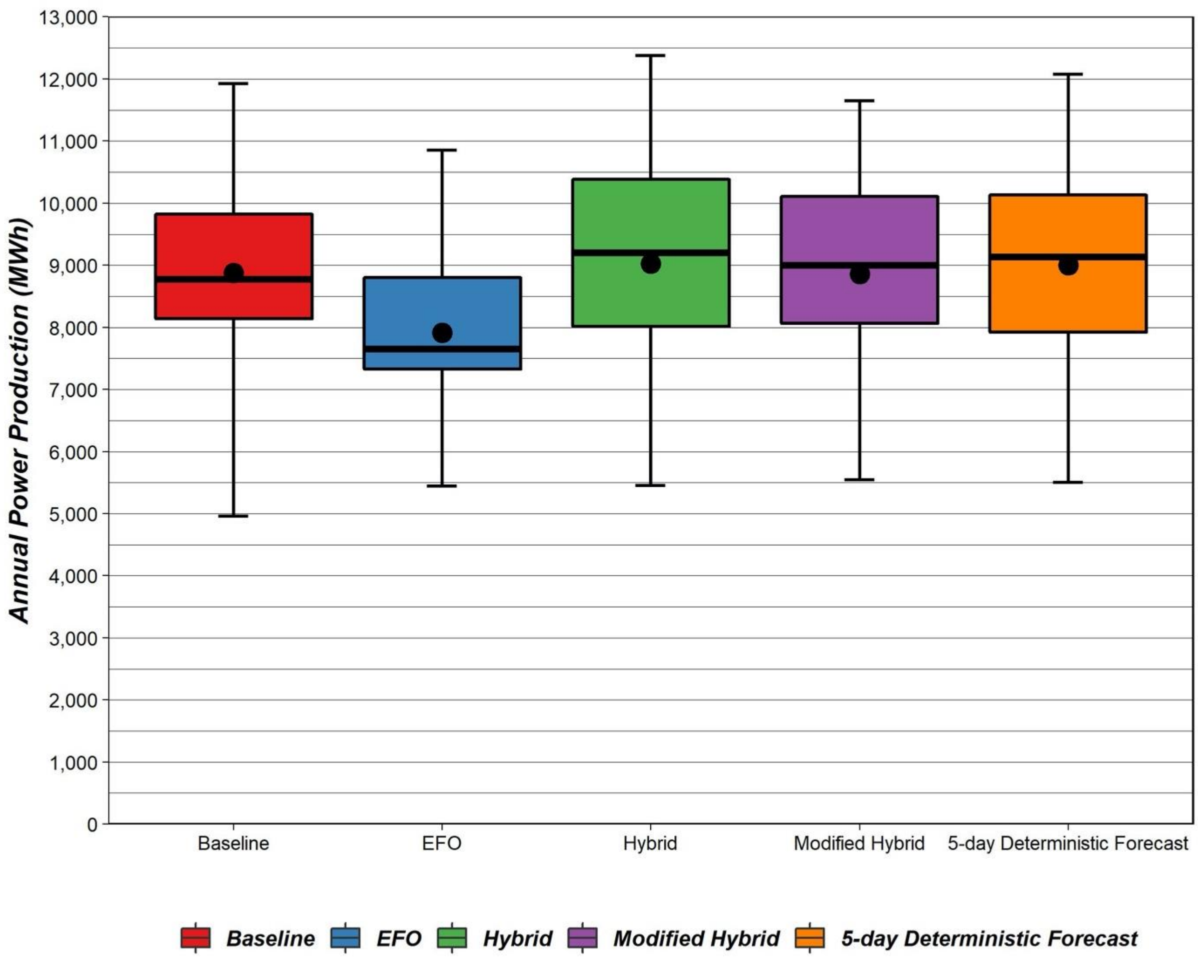

Figure 3.15. *Annual (calendar year) power production for Lake Mendocino. (Higher is better.)*

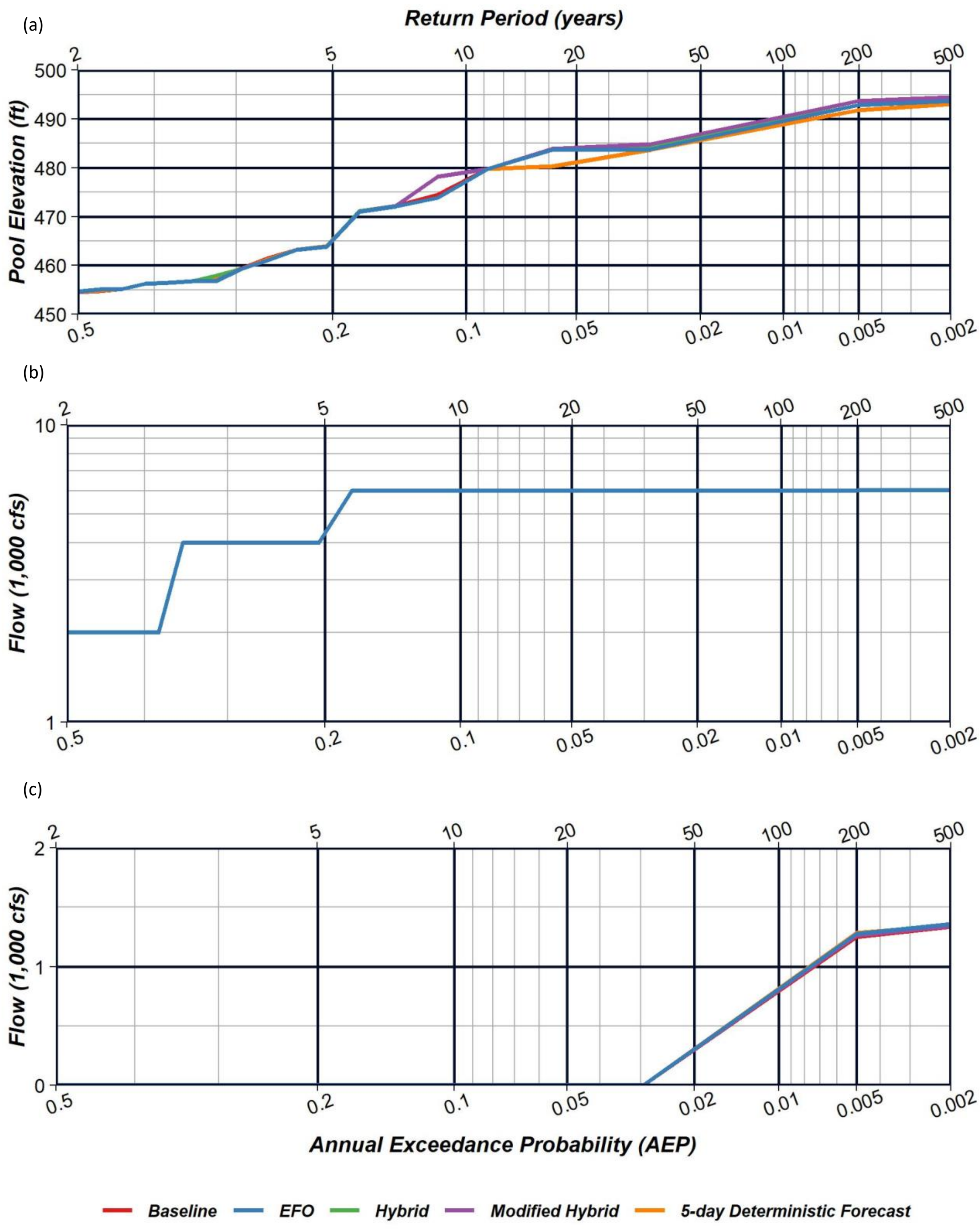

Figure 3.16. *Annual maximum (a) pool elevation, (b) total release, and (c) uncontrolled spill frequency functions at Lake Sonoma. Results for all alternatives are nearly identical in the bottom two plots.*

3.5.2 Making Sense of the Metrics

To summarize the evaluated metrics, a process was devised to rank each alternative for each metric. For several metrics, the process was complicated by multiple locations and WCP performance within the most important range of the frequency distributions. Additionally, practical "significant differences" needed to be established to allow for ranking WCPs the same when the outcomes were practically the same. Here, results that were within 1 percent were ranked the same. Finally, the metrics were grouped by (1) flood risk management; (2) water supply and environmental outcomes; (3) recreation, power production, and staffing impacts; and (4) impacts to Lake Sonoma operations. Tables 3.10, 3.11, 3.12, and 3.13 show the grouped and averaged rankings of each metric for each WCP. None of the alternative WCPs have a negative impact on Lake Sonoma as measured by metrics 3, 5, and 7. A ranking of "1" indicates better relative performance while a ranking of "5" indicates worse relative performance. Relative performance is also color coded from green ("1") to red ("5") with gradations in between.

Table 3.10. *Summary of flood risk management metrics.*

Rank of WCP alternative by flood risk management metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M1	5	3	1	1	4
M2	5	3	1	1	3
M4	5	3	1	1	4
M6	5	4	2	1	3
M8	1	1	1	1	1
M9	1	1	1	1	1
Average	**3.7**	**2.5**	**1.2**	**1.0**	**2.7**

Table 3.11. *Summary of water supply and environmental metrics.*

Rank of WCP alternative by water supply and environmental metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M10	5	1	4	2	3
M11	5	1	2	2	2
M12	5	1	4	2	3
Average	**5.0**	**1.0**	**3.3**	**2.0**	**2.7**

Table 3.12. *Summary of recreation, power, dam safety, and operations metrics.*

Rank of WCP alternative by recreation, power, dam safety, and operations metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M13	1	5	1	4	3
M14	4	5	1	1	1
M15	1	5	2	2	4
M16	2	1	3	4	5
Average	**2.0**	**4.0**	**1.8**	**2.8**	**3.3**

Table 3.13. *Summary of Lake Sonoma flood risk management metrics.*

Rank of WCP alternative by Lake Sonoma flood risk management metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M3	1	1	1	1	1
M5	1	1	1	1	1
M7	1	1	1	1	1
Average	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

3.6 Additional Robustness Testing

While developing the simulation plan for this evaluation, there was some concern surrounding the ability of candidate WCPs to effectively handle "back-to-back" events. Here, the WCP would need to effectively "recover" from an event in time to accommodate another. Recent experience in February 2019 elevated the importance of considering storm sequences. December 2005 was selected as the test period. Here, a large event preceded the January 2006 event used elsewhere in this analysis. This simulation and analysis, which was conducted for the baseline and the four FIRO WCP alternatives, showed results fully consistent with the period of record and scaled event analysis conducted previously. A full report on this work can be found in Appendix B under "Lake MendocinoFVA_RobustnessTesting.docx."

3.7 Summary

The design, simulation, evaluation, and management of the process that yielded the information provided in this section of the FVA was a massive effort completed by dedicated and talented individuals from Sonoma Water, HDR, HEC, and Robert K. Hartman Consulting Services. Key support was provided by the CNRFC and CW3E.

This evaluation indicates quite clearly that water supply reliability for Lake Mendocino can be improved without impacting—and while possibly enhancing—the flood risk management and environmental outcomes downstream. All the FIRO WCPs considered fully meet the objective as a significant improvement when compared to existing WCM operations. This evaluation provides an essential piece of information available to the Steering Committee in their decision to pursue a recommended FIRO WCP alternative in the update of the Lake Mendocino WCM.

Section 4. Interim Operations

The purpose of the Interim Operations effort was to gain insight and experience with selected Forecast Informed Reservoir Operations (FIRO) tools and approaches. Experience and insight gained could then be leveraged to refine the eventual proposed implementation in a formal Water Control Manual (WCM) update for Coyote Valley Dam and Lake Mendocino. The two fundamental components of Interim Operations were planned major deviations and decision support tools. Together, these components served the United States Army Corps of Engineers (USACE), Sonoma Water, and the Steering Committee and associated staff quite effectively.

The planned major deviations for water years (WYs) 2019 and 2020 provided an opportunity for the Corps and Sonoma Water to “try out” FIRO approaches without a long-term commitment. The decision support tools provided essential information to the operations staff.

4.1 Description and Analysis of Planned Major Deviations

USACE, via Engineering Regulation (ER) 1110-2-240, provides for three types of planned operational deviations from procedures described in the approved Water Control Plan (WCP): emergency, unplanned, and planned. For the purposes of the Lake Mendocino FIRO effort only *planned* deviations have been considered. ER 1110-2-240 provides guidelines rather than the specifics needed for field implementation. A USACE South Pacific Division Policy (Regulation No. 10-1-04) provides the details needed for implementation within the Division. This policy states:

> *A planned minor deviation is limited by i) flood control pool elevation will not vary more than 2 feet from what it would have been the water surface elevation under the approved Water Control Plan or ii) storage difference from approved Water Control Plan will not exceed 5% of the total storage.*

As such, a minor deviation for Lake Mendocino cannot exceed a change of 5 percent of 116,500 acre-feet (ac-ft) or 5,825 ac-ft from the approved WCP. Additionally, minor deviations are to last no more than 10 days unless coordinated with the South Pacific Division Senior Regional Hydraulics and Hydrology and Water Control Engineer.

Any proposed planned change that exceeds the minor deviation threshold is, by definition, a major deviation. Approval of planned major deviations must include a risk and uncertainty assessment to determine potential consequences. These larger changes also require some level of environmental impact assessment (National Environmental Policy Act compliance). ER 1110-2-240 also specifically states that major deviations should not be used as a substitute for an updated WCM. As such, repeated major deviations are discouraged unless the project team is actively working toward a WCM update.

4.1.1 WY 2019 Major Deviation

The major deviation that was implemented for WY 2019 began as a request package for WY 2018. The approval process took longer than anticipated and this request was instead redirected toward operations in WY 2019. A minor deviation, which allowed for 5 percent of total storage (5,825 ac-ft) was submitted, approved, and followed during WY 2018. The minor deviation request did not formally engage FIRO technologies under development.

The WY 2018 major deviation request was submitted to the Commander of the San Francisco District of the USACE on November 1, 2017. The request was made by the Lake Mendocino FIRO Steering Committee as opposed to Sonoma Water. This is an important distinction and may possibly be the first time that an interagency working group has requested a deviation in place of the local sponsoring agency. The request resulted in substantial work and coordination between USACE and Sonoma Water on environmental compliance. The request was approved by the South Pacific Division Commander on November 1, 2018.

The WY 2019 major deviation request included the following adjustments to the WCP as described in the 1986 version of the Lake Mendocino WCM. The changes are diagramed in Figure 4.1.

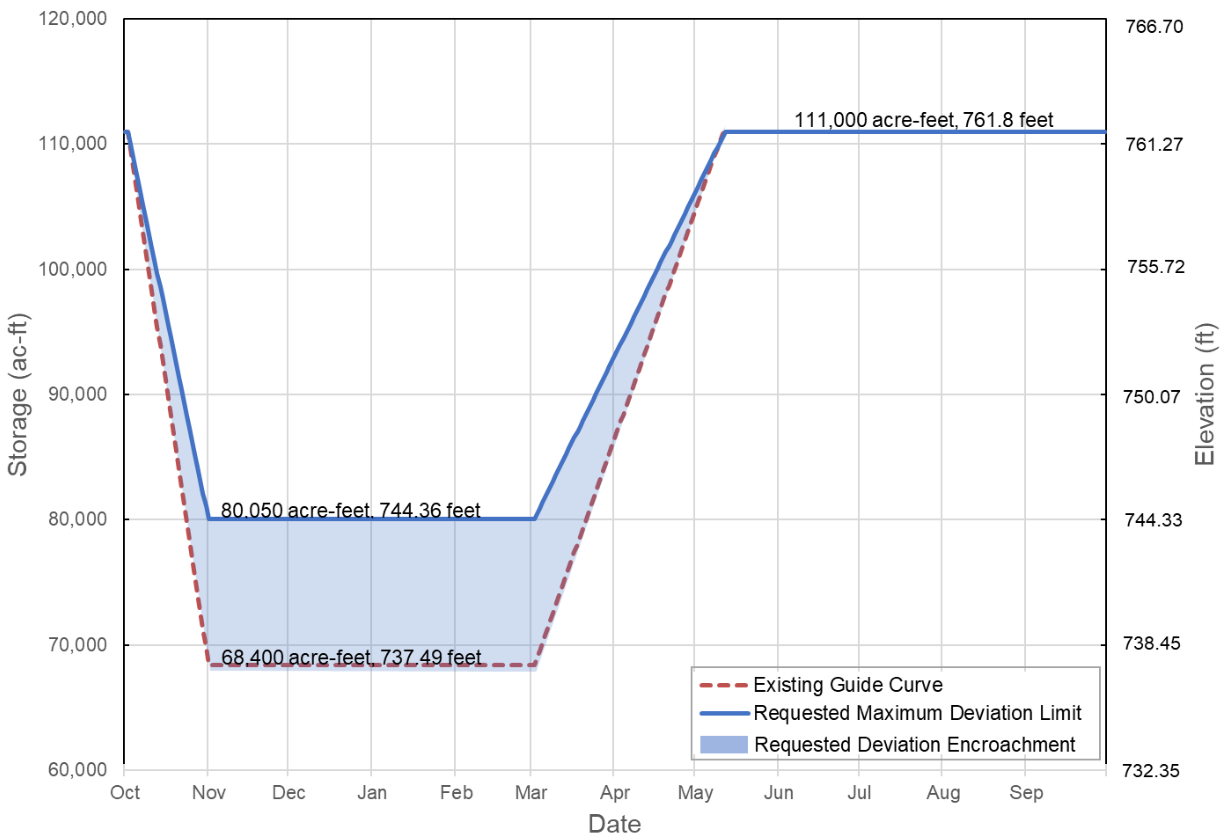

Figure 4.1. *Changes to Lake Mendocino WCP proposed for the WY 2019 (and WY 2020) major deviation.*

Although this language was not included in the WY 2019 major deviation request, the proposed changes reflected in the diagram include:

- Increase conservation pool storage by 11,650 ac-ft (November 1 through February 28)
- Decrease the conservation pool by 1,030 ac-ft per day if storage is above 80,050 ac-ft (starting October 1)
- Increase the conservation pool by 436 ac-ft per day (starting March 1)

It is important to note that even though the major deviation was approved, decisional responsibility for releases still resided with the San Francisco District whenever the storage was above the existing guide curve. The formal WY 2019 major deviation request can be found in Appendix C.

From the Preliminary Viability Assessment (PVA), we expect the benefits of FIRO to be most pronounced during either dryer years or when the bulk of the precipitation falls earlier in the winter season. WY 2019 was a wet year and the natural hydrology provided sufficient storage for water supply purposes. Nonetheless, the outcome from following the major deviation during WY 2019 was good and yielded valuable experience with FIRO tools and processes. As shown in Figure 4.2, storage was held higher than existing operations for much of the winter but was significantly drafted in response to forecast events in January and February. By the middle of March, storage was nearly 10,000 ac-ft higher than existing operations. Higher releases from mid-March through early April resulted in the storage intersecting the existing operations guide curve around April 6. The net result at the end of the winter season was no difference in storage over existing operations. Arguably, lower releases in early spring could have retained a sizeable portion of the excess storage on March 15. Nonetheless, a storage of 90,000 ac-ft on May 1 provided significant ecological and water supply benefits.

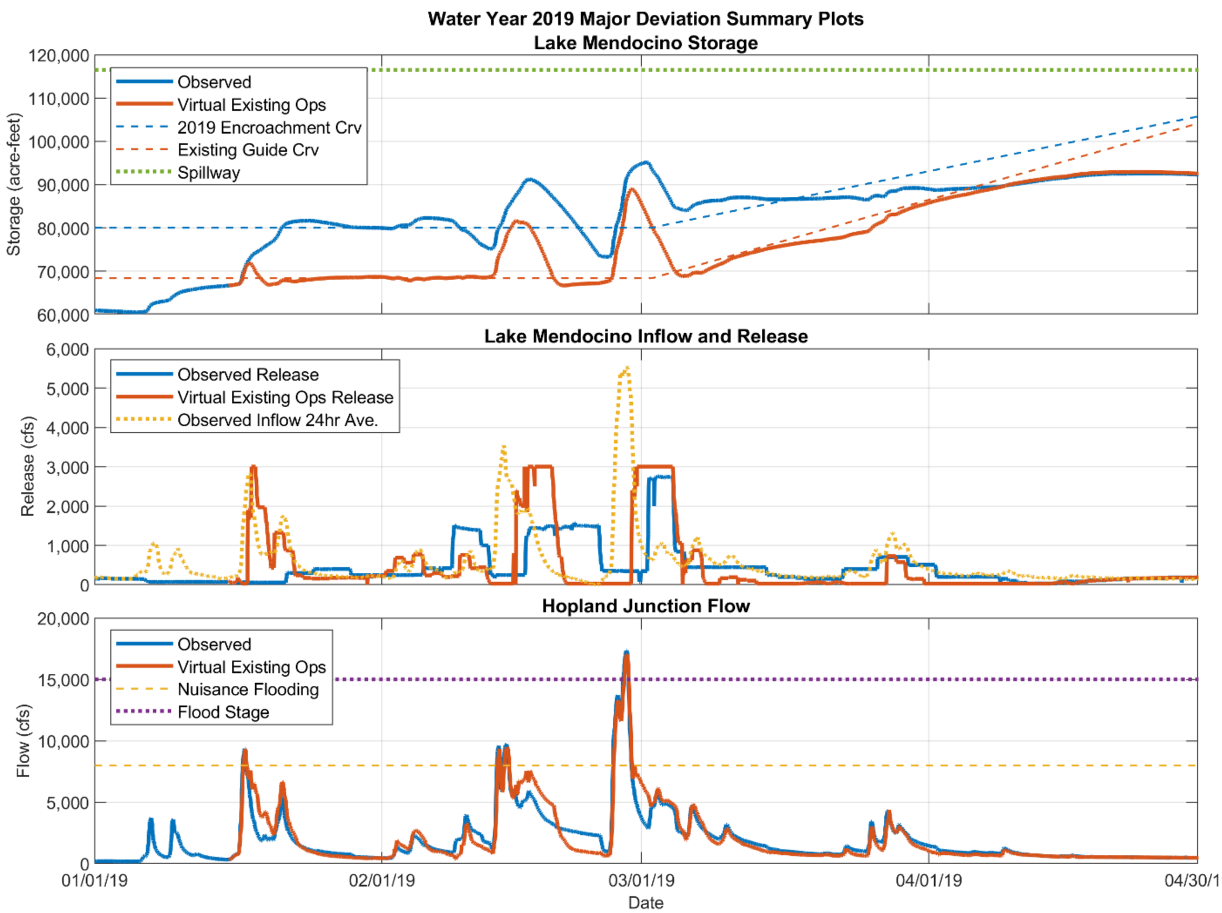

Figure 4.2. *Reservoir storage for Lake Mendocino during major deviation operations of WY 2019.*

Lessons learned from WY 2019 operations include:

- Lead time for flood events is extremely important. Reservoir operators think in terms of "time needed to get back down to the existing operations guide curve in advance of an event." In the second event during February 2019, the lead time was less than typically expected because forecasts failed to recognize that the AR would stall over the Russian River basin.

- Despite less-than-ideal forecasts, reservoir levels and releases were safely and effectively managed with no measurable increase in operational burden to the field staff.
- Water resources engineers generally do not have a strong understanding of atmospheric science. Consequently, decision support products should not assume that the user has a deep understanding of weather forecasting and model output interpretation.
- FIRO tools and San Francisco District operators successfully retained additional storage in Lake Mendocino through the bulk of the winter flood season while supporting downstream flood management objectives.
- Better tools and models are needed to predict and fully understand the volume of flood control space needed in advance of a forecast storm event.
- Operational avoidance of emergency spillway use exceeds that of the original design. An operation that results in spill would be considered a "failure" even though the project design expects spill for events in excess of P=0.02 (50-year return period).
- Working through a full season of operations under a major deviation can illuminate objectives and constraints not previously known to the full FIRO team. As an example, the local economic impact of keeping Lake Mendocino above 750 feet in the spring and preventing access to Bushay Campground was not previously known. However, this was temporary to that specific year as the campground not impacted by reservoir operations was occupied by victims of the 2017 Redwood Valley Complex wildfire (i.e., Federal Emergency Management Agency housing).

4.1.2 WY 2020 Major Deviation

Following WY 2019 operations, the FIRO Interim Operations Team spent considerable time reviewing the results and discussing possible scenarios for a WY 2020 major deviation request. Several new alternatives were considered and tested using data and forecasts from WY 2019 and the 1985–2010 hindcasts. These included raising the mid-winter conservation pool to 83,000 and 85,000 ac-ft and "cutting the corner" on spring refill by allowing greater storage after February 15. The analysis showed that "cutting the corner" on spring refill was most effective at increasing the storage at the end of the winter flood period. However, given the significant Russian River flood event in late February 2019 that was under-forecasted, the San Francisco District was reluctant to include it in the deviation request. In addition, this approach may have initiated a need for additional environmental review, which might have delayed approval beyond the start of the upcoming winter season. Consequently, a decision was made by the Lake Mendocino FIRO Steering Committee to submit a WY 2020 major deviation request that was identical to the request approved for WY 2019 with one minor change. This change would allow San Francisco District operators to draw the reservoir down into the existing conservation pool should FIRO decision support tools strongly indicate the need for additional reservoir storage for flood management operations. The decision to draft into the conservation pool would also be subject to approval by Sonoma Water leadership. The formal WY 2020 major deviation request can be found in Appendix C.

WY 2020 is an excellent example of a scenario where FIRO can provide improvement over existing operations. Precipitation in the Russian River basin was 4 percent of the average in October and 44 percent of the average in November. In December, the weather pattern changed, and the Russian River basin received nearly 150 percent of the average precipitation, with the basin above Lake Mendocino receiving closer to 100 percent of the average. January saw a return to dry conditions with less than half of average precipitation and February was literally dry (0 percent of average). Conditions remained much drier than average during March as well. Ukiah experienced the third driest winter in 127 years. There were only three ARs during the winter and all three occurred before mid-December. WY 2020 was exactly the sort of scenario where FIRO has the best opportunity to improve over existing operations—that is, drier than normal conditions for the second half of the winter season. Figure 4.3 shows a comparison of storage under the major deviation and existing operations during WY 2020.

It is important to note that trans-basin diversions from the Eel River through the Potter Valley Hydroelectric Project (PVP), owned and operated by PG&E, were elevated during February. FIRO allowed the capture of approximately 5,000 ac-ft of water in Lake Mendocino during a period of no precipitation or storm runoff. Based on the flood management rules in the existing WCM, this water would have been evacuated and eventually lost to the Pacific Ocean.

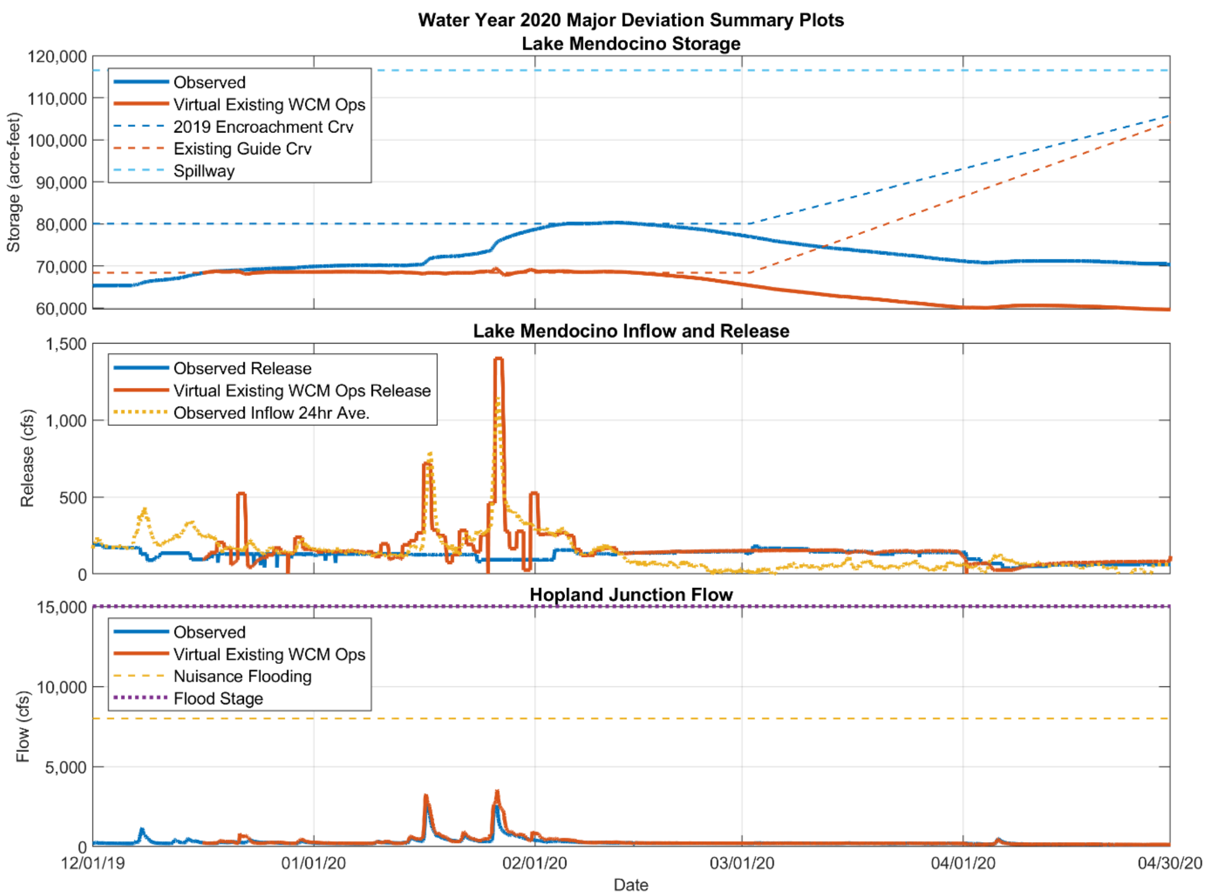

Figure 4.3. *Reservoir storage for Lake Mendocino during major deviation operations of WY 2020.*

Lessons learned from WY 2020 operations include:

- Every year provides a different set of circumstances for FIRO testing.
- As expected, the retention of early season storage can be extremely effective at mitigating the effects of a dry winter season.

- Communication between San Francisco District operators and Sonoma Water staff was extremely important to maintain instream minimums even while the reservoir was above the existing operations top of conservation level.
- Wintertime transfer of water from the PVP can be leveraged more effectively under the FIRO paradigm.
- Forecasts of dry weather were skillful and allowed operators to retain stored water per the approved major deviation.

4.2 Decision Support System and Situational Awareness

Decision support is central to FIRO. For water managers to effectively leverage forecast information, there must be a means for supporting their operational decisions. The process of developing decision support tools also provides an opportunity for researchers and developers to better understand the requirements placed on water operations to explore the nexus between information, uncertainty, and decision making.

The decision support tools developed and maintained or leveraged by the Lake Mendocino FIRO effort span the full range of weather and water forecasts as well as the direct application of those forecasts.

4.2.1 Interactive FIRO on California Data Exchange Center

This interface was modeled after the California Department of Water Resources (DWR) Forecast Coordinated Operations function on the California Data Exchange Center (CDEC). Figure 4.4 shows a schematic of the data and information flow.

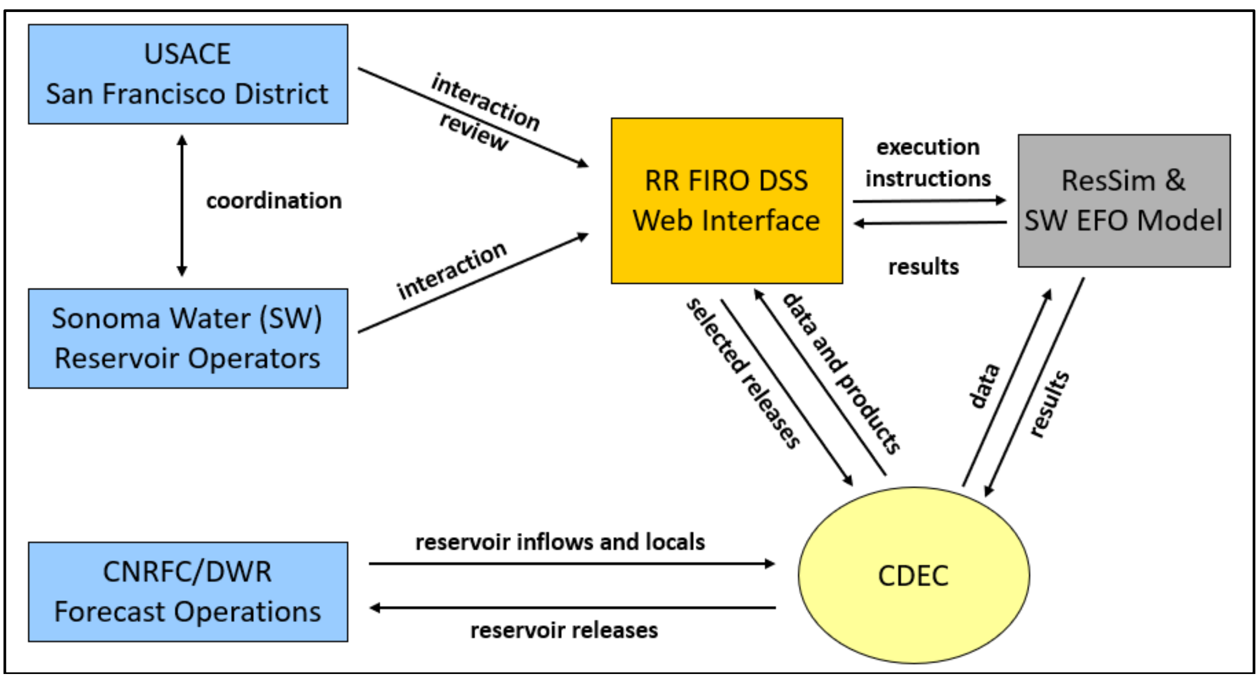

Figure 4.4. *Data and information flow for the CDEC FIRO interface.*

The interface (orange box) receives data through CDEC and has access to the Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) and Sonoma Water Ensemble Forecast Operations (EFO) models for suggesting and evaluating reservoir release strategies for

Lake Mendocino. Once selected, the release strategy can be transmitted to the National Weather Service California-Nevada River Forecast Center (CNRFC) and California Department of Water Resources (DWR) forecast operations for use in making forecasts downstream of the reservoir. Access is password protected and limited to Lake Mendocino FIRO partners. The selection and transmission of the release strategy is only available to the USACE San Francisco District.

The Russian River ResSim model supported on the CDEC interface (Figure 4.5) holds the system constraints and rule sets specified by the WCM and implemented by the San Francisco District. The Russian River ResSim model is effectively the "gatekeeper" to ensure that all reservoir releases are consistent with the physical and regulatory constraints.

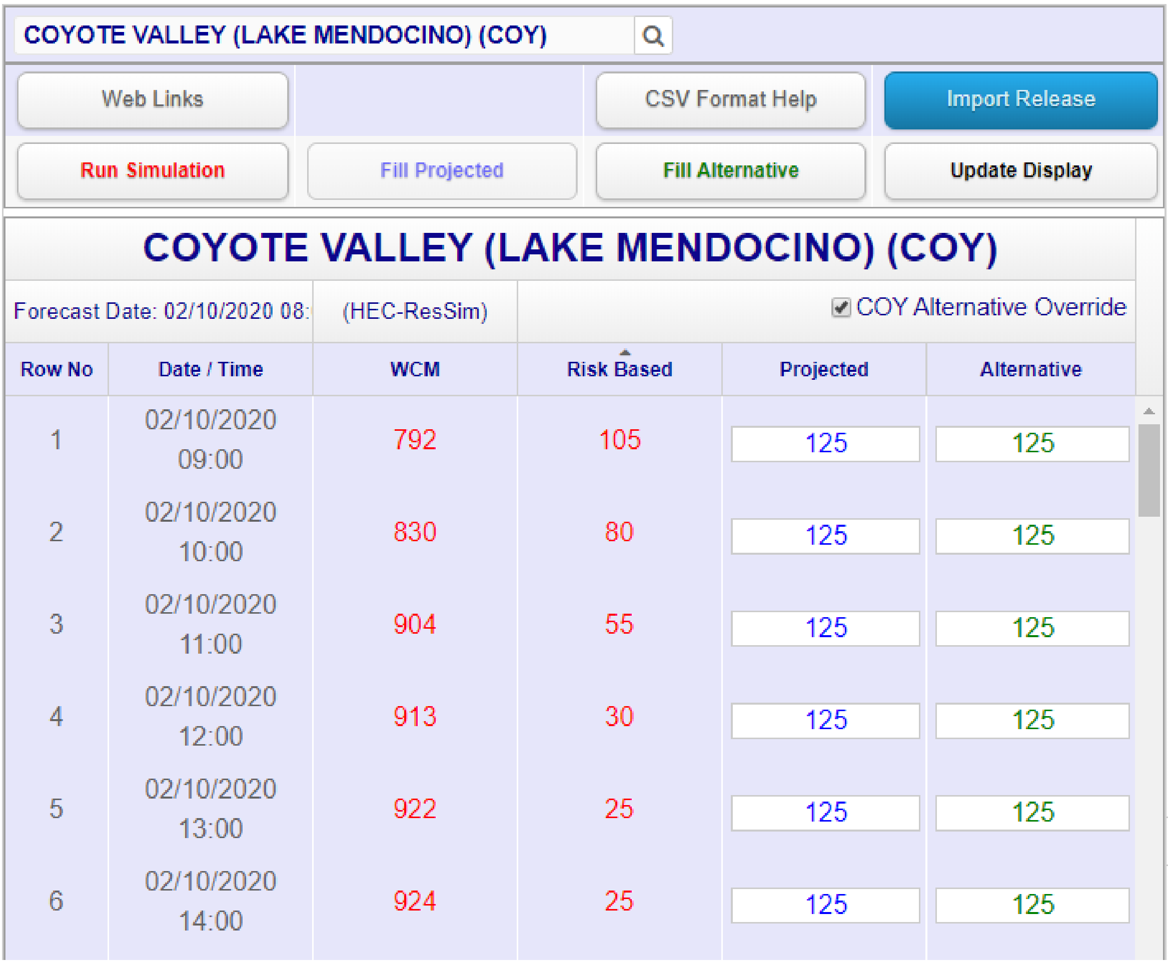

Figure 4.5. *Russian River ResSim model interface.*

The purpose of the interface is to provide realistic options for reservoir releases and to see the effects of the selected release decisions on downstream locations. Upon entry, the user has three options for selecting a future release pattern.

- As recommended by the WCM.
- As recommended by the Hybrid EFO model (Risk Based).
- As manually specified.

Options are provided to allow the user to fill the Projected and Alternative patterns with other columns. The Projected and Alternative can be manually edited as well. This allows the user to take advantage of a suggested release pattern while manually editing a few of the periods. Only the Projected release column can be sent to the CNRFC/DWR operations for inclusion in downstream forecasts. The user has the option to review the release for Warm Springs Dam as well, however there is no Risk-based option available.

When the user is satisfied with the contents of the Projected and Alternative column, the "Run Simulation" button can be selected to process the flows and review the impacts on the reservoir storage and downstream locations. When complete, the user has access to storage plots for Lake Mendocino and Lake Sonoma as well as downstream locations. If the results are not satisfactory, refinements can be made to the Projected and Alternative release columns and the simulations re-run. Figure 4.6 shows the simulation results for February 10, 2020. Note that Lake Mendocino has a storage of 80,260 ac-ft. This represents an encroachment into the traditional flood control pool of 11,850 ac-ft by virtue of the major deviation in effect. The WCM operations thus reflect a plan to release the storage above the 68,400 ac-ft TOC (top of conservation) for this time of year.

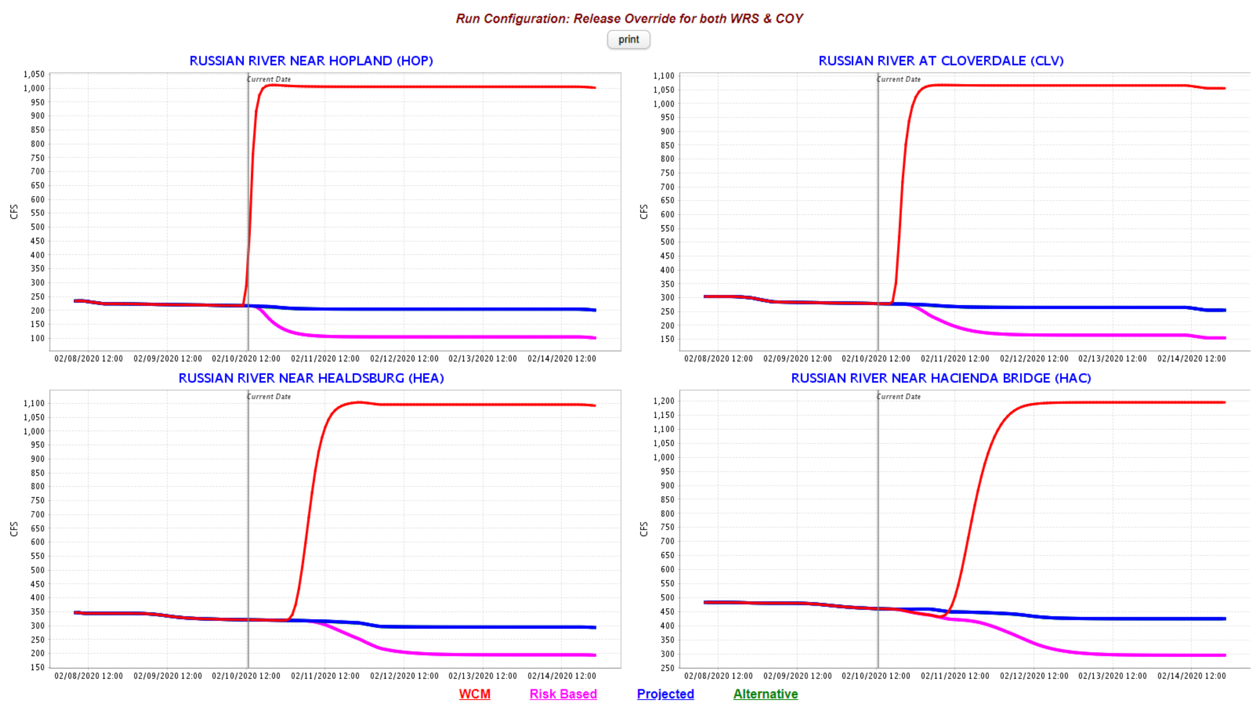

Figure 4.6. *Downstream projected flows with selected reservoir release strategies.*

For convenience, the interface also provides a set of links to commonly used forecast products and information provided by the CNRFC and CW3E. The links used for WY 2020 operations are shown in Figure 4.7.

CNRFC Web Interface

- Homepage - observed and forecast precipitation and temperature

Current Deterministic Forecasts

- 5-day Lake Mendocino Inflow
- 5-day Russian River – Ukiah
- 5-day Russian River – Hopland
- 5-day Russian River – Healdsburg
- 5-day Lake Sonoma Inflow
- 5-day Russian River – Guerneville

Current Ensemble Forecasts

- 10-day Accumulated Volume – Lake Mendocino
- 10-day Accumulated Volume – Lake Sonoma
- 10-day Inflow Probability – Lake Mendocino
- 10-day Streamflow Probability – Ukiah
- 10-day Streamflow Probability – Hopland
- 10-day Streamflow Probability – Healdsburg
- 10-day Inflow Probability – Lake Sonoma
- 10-day Streamflow Probability - Guerneville

CW3E Web Interface

- Ensemble Forecast Operations Results
- Access to all interactive forecast graphics
- NCEP GFS IVT Analysis for West Coast
- GFS Ensemble Probability IVT > 250 kg/ms (16 days)
- GFS Ensemble Probability IVT > 500 kg/ms (16 days)
- dprog/dT GFS Landfall Tool

Figure 4.7. *Links used for WY 2020 operations.*

4.2.2 CW3E Website

The CW3E website (cw3e.ucsd.edu), shown in Figure 4.8, provides both meteorological products as well as reservoir operations information. Commonly used meteorological products and graphics are linked through the CDEC decision support tool; however, users commonly access these directly through the CW3E menu system or through bookmarks. Details on the background, rationale, and development of specific AR products are provided in Section 5.

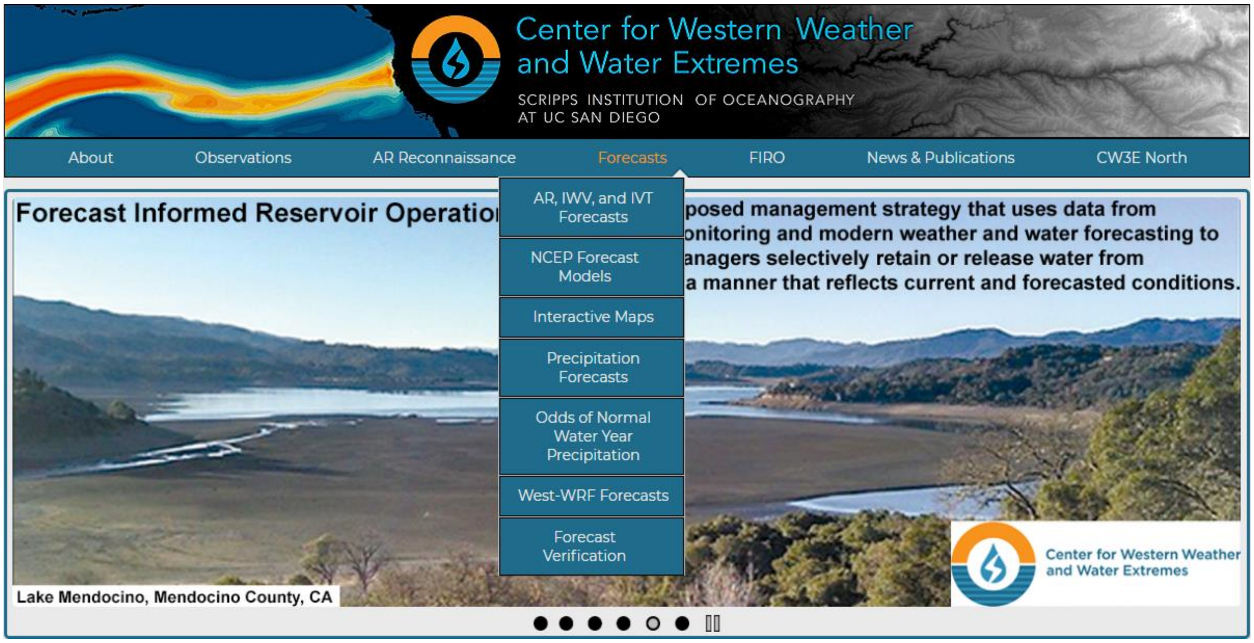

Figure 4.8. *CW3E website (cw3e.ucsd.edu).*

A pair of dedicated webpages were set up to support reservoir operation decisions and to compare alternative reservoir management alternatives. The web pages are not accessible through the CW3E web page, but can be accessed directly through a URL (and password) provided to the Steering Committee and key staff. The Major Deviation Operations webpage provides information on the current day's run of the multi-objective Hybrid EFO model. The Virtual Operations webpage provides a running comparison of results from several alternative reservoir management schemes.

4.2.3 Major Deviation Operations

The Major Deviation Operations webpage supports operations of Lake Mendocino by USACE and Sonoma Water consistent with the WY 2020 major deviation. Under the WY 2020 major deviation, forecast informed operations will typically be constrained to the region of the reservoir pool above the existing guide curve (68,400 ac-ft at mid-winter) and below the maximum encroachment curve (80,050 ac-ft at mid-winter). This scenario was developed to provide guidance to reservoir operations to inform forecast-based flood control releases when storage is within this "flood control encroachment pool." The webpage provides plot panels that reflect (1) the current release and (2) the release suggested by the multi-objective Hybrid EFO model. Here the user can see the previous five days as well as the next 15. Forecast inflow, storage, releases, and impacts downstream at Hopland and at Guerneville are provided for both scenarios. This is a "view only" website with no options for fine-tuning release decisions or sending release schedules to the CNRFC/DWR operations. An example of the Current Release Forecast plot is shown in Figure 4.9.

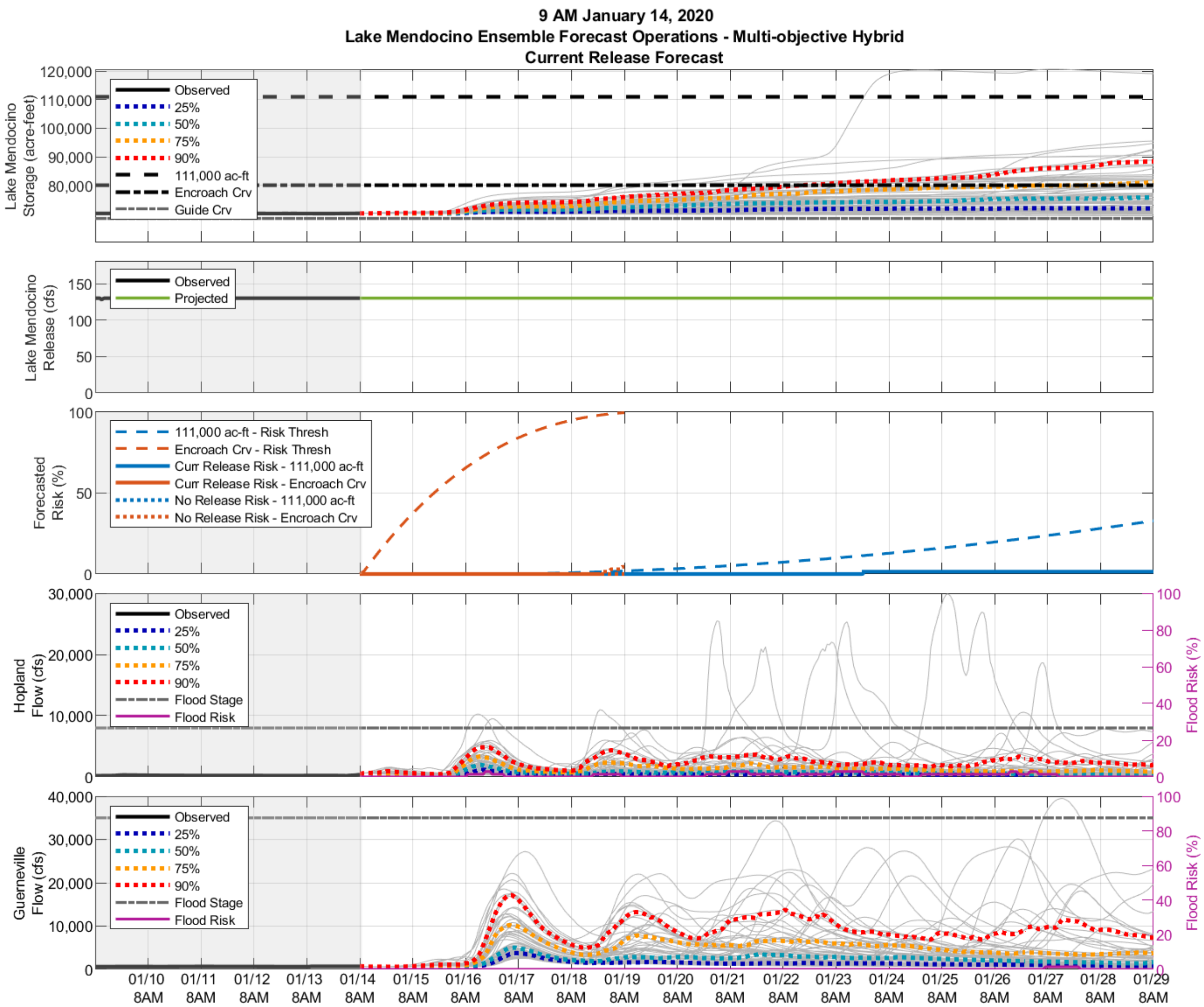

Figure 4.9. *Major deviation operations on the CW3E website.*

4.2.4 Virtual Operations

The Lake Mendocino FIRO Project is a mixture of research, investigation, and application. One of the ways that the project team members develop experience with new techniques involves experimentation. Some of the experimentation is real (e.g., major deviation operations) and some of it is virtual.

The purpose of the Virtual Operations webpage is to compare a set of alternative WCPs that have been developed for Lake Mendocino (see Figure 4.10). All but the baseline, contained in the existing Lake Mendocino Water Control Manual, leverage information from the streamflow forecasts of reservoir inflow and flow at downstream locations. All alternative WCPs must follow the same set of rules related to the physical attributes of the dam and constraints on release rates.

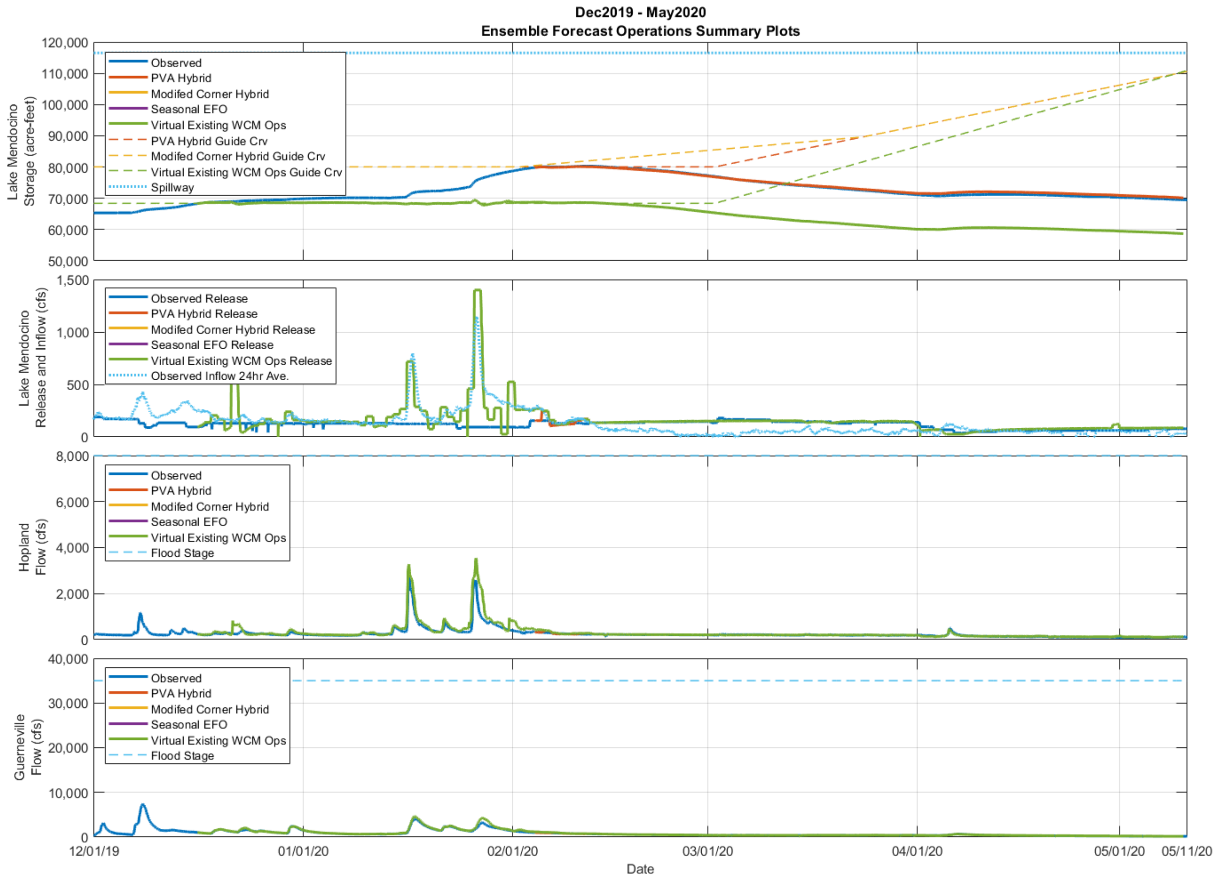

Figure 4.10. *Virtual operations on the CW3E website.*

The candidate WCPs simulated here include:

- Baseline WCM procedure (standard guide curve)
- Hybrid EFO (basis of WY 2019 and WY 2020 major deviations)
- Hybrid EFO with an early spring refill ("cutting the corner")
- Full EFO (no guide curve and seasonally adjusted risk curves)

All but the Baseline WCM procedure utilize streamflow forecasts and can make prereleases of stored water in the conservation pool for increased flood management operations if warranted by inflow forecasts. Drafting into the conservation pool requires the concurrence of Sonoma Water and National Marine Fisheries Service but is allowed for virtual operations. The flood operations engineer at USACE responsible for operations uses the WCP but is not strictly bound by its guidance. In this application, the guidance of each WCP is strictly implemented because operator interaction is not practical or feasible.

At the onset of a WY, all WCP seasonal results begin with the same storage and remain the same until storage increases and exceeds the Top of Conservation define in the baseline WCP. From this point forward, as differences in WCP releases occur, the virtual storages in the reservoir will begin to differentiate themselves. Each WCP then creates its own seasonal storage history as a function of its daily release decisions. It is important to note that the streamflow forecast issued at least daily is always the same for each of the alternative WCPs.

The plots in Figure 4.10 show the seasonal history of (1) Lake Mendocino storage, (2) Lake Mendocino releases, (3) streamflow at Hopland, and (4) streamflow at Guerneville for each WCP. The observed storage, inflow and release, and streamflow at Hopland and Guerneville are also shown for comparison.

4.3 Summary

The interim operations activities undertaken by the Lake Mendocino Steering Committee were essential components of the FVA process. Planned major deviations for Water Years 2019 and 2020 were requested by the Steering Committee and approved and utilized by the USACE San Francisco District. In both years (one wet and one dry) significant lessons were learned and substantial end-of-season storage gains over WCM operations were realized. The development and support of additional FIRO decision support system elements and situational awareness tools created key interactions within the "Research and Operations Partnership" (RAOP; Ralph et al. 2020) and supported operational reservoir release decisions.

Section 5. FIRO Gains Through Research, Studies, and Enhanced Observations

5.1 Introduction

The Lake Mendocino Forecast Informed Reservoir Operations (FIRO) Final Viability Assessment (FVA) stands on a foundation of extensive meteorological and hydrological research, development, engineering, decision support tools, forecast skill assessment and enhancement, quantitative risk studies, and real-world testing. This work has focused in particular on the atmospheric river (AR) storms that produce a majority of the Russian River watershed's precipitation—driving both beneficial water supply and flood hazards.

Section 5 summarizes three important aspects of the science behind FIRO:

- **Scientific advancements to date** that have made FIRO viable at Lake Mendocino.
- **Opportunities for further research and development** that could lead to even larger FIRO benefits at Lake Mendocino, and help to enable FIRO at other locations.
- **The coordinated approach that has made such progress possible**—a research and operations framework and partnership that can serve as a blueprint for future success.

5.1.1 Scientific Advancements that Contribute to FIRO's Viability at Lake Mendocino

The potential for FIRO at a given reservoir is defined by the reservoir's operational constraints and the characteristics of the watershed's hydroclimate. Hydrologic forecasts on the Russian River, including inflow forecasts at Lake Mendocino, benefit from the predictability of regional precipitation. Compared with the rest of the nation, short-range quantitative precipitation forecasts (QPF) are more skillful in the West during the winter season than in any other region in the United States (Sukovich et al. 2014). This forecast skill emerges from the dominance of ARs in the regional hydroclimate. More than two decades of studies on the sources of floods and water supply in the Russian River have consistently highlighted the dominant role of ARs (e.g., Ralph et al. 2006; Ralph et al. 2013). Ralph et al. (2006) concluded that every major flood in the Russian River's observational record had resulted from an AR—a fact that continues to this day. For FIRO to be successful in this region, hydrologic prediction must be linked to ARs. The Lake Mendocino FIRO project is taking advantage of significant advancements in AR predictability and hydrologic models focused on these extreme events.

This project has contributed to advances in understanding how ARs work physically (e.g., Cannon et al. 2020a), what distinguishes ARs that are mostly beneficial to water supply from those that are hazardous (creation of the AR scale by Ralph et al. 2019), how ARs impact FIRO information requirements (Weihs et al. 2020), and what tools can best observe and predict ARs and the streamflow they induce (e.g., Ralph et al. 2020). The box on the right lists four examples of recent innovations that have improved the underlying science to support FIRO.

Key Innovations Supporting FIRO at Lake Mendocino

Members of the Lake Mendocino FIRO partnership have advanced the underlying science in several ways, including by:

- Developing the Ensemble Forecast Operations decision support tool
- Creating the scale for AR intensity and impacts
- Inventing and operationalizing AR reconnaissance
- Building a regional weather model optimized for FIRO prediction needs

Knowing where ARs will hit and how much rain they may bring is essential for FIRO. Thus, FIRO at Lake Mendocino benefits from robust long-term investment in monitoring of ARs and associated precipitation as it moves through the watershed (White et al. 2013). A notable accomplishment in AR monitoring has been the development, testing, and operationalization of the Atmospheric River Reconnaissance (AR Recon) Program (Ralph et al. 2020). This program samples ARs offshore and transmits those data in real time to key global weather prediction models, including the National Weather Service's (NWS's) Global Forecast System (GFS), the Navy's NAVGEM model, and the European Centre for Medium-Range Weather Forecasts (ECMWF), where the data are assimilated and contribute to improved forecast skill. The Lake Mendocino FIRO team also identified and addressed gaps in monitoring within the Russian River watershed, especially at the coast for initial AR landfall and in the Lake Mendocino watershed (Sumargo et al. 2020b). Adding monitoring sites has been crucial to improving physical process understanding and the representation of those processes in atmospheric and hydrologic modeling.

Modern precipitation and streamflow forecasts benefit from the availability of multiple prediction methods and models. The FIRO team has built weather and streamflow forecast tools and decision support systems that leverage ensemble predictions. AR ensemble forecast tools (e.g., Cordeira et al. 2017) have been used by Lake Mendocino reservoir operators. Additionally, the creation of an Ensemble Forecast Operations (EFO) method (Delaney et al. 2020) represents a major contribution to FIRO and the future Lake Mendocino Water Control Manual (WCM) update while also enabling continued research and potential integration for improved forecasts into a future "FIRO 2.0" phase. This framework improves forecast accuracy by quantifying the modulating effect of land-surface conditions, especially of soil moisture, using observations and specialized hydrologic modeling (Sumargo et al. 2020a).

Sections 5.2 through 5.5 provide more detailed information about these efforts and additional advances in weather forecasting, observations, hydrology and water resources modeling, and FIRO benefits. Appendices D, E, F, G, and H provide further detail.

5.1.2 Potential Gains Through Additional Research and Development

The analysis of FIRO water control plans (WCPs) described in Section 3 and the outcome of interim operations described in Section 4 clearly show that FIRO is now viable at Lake Mendocino. Additional gains and flexibility to accommodate future climatic and regulatory uncertainty are also achievable. A future "FIRO 2.0" phase (as illustrated by Figure E.4 in the Executive Summary) will be important to further improve water supply reliability and adapt to a changing climate. Continued improvement will require support for enhanced observations and forecasting, modeling, and decision support tools. Sections 5.2 through 5.5 identify several specific areas where further research can lead to even greater gains from FIRO at Lake Mendocino. Some of these research investments could also help to make FIRO viable at other settings, particularly in other AR-dominated systems.

5.1.3 Research and Operations: A Blueprint for Success

The scientific advancements discussed in this section center on improving forecasts and their application in decision making. Prediction improvements are made through technological advancements (e.g., observation networks ingested into the forecasting system, updates to numerical forecasting and quantitative methods). The application of forecasts in decision making is implemented through designing robust decision support processes and tools with forecasters and operators, then ensuring wide usability of those tools through training and communication. All these types of advancements can benefit from a collaborative research and operations approach.

This project followed the initial strategies laid out in the Lake Mendocino FIRO Viability Assessment Work Plan (FIRO Steering Committee 2015) and the subsequent Preliminary Viability Assessment (PVA) (FIRO Steering Committee 2017). These plans were developed and executed using an organizing principle now recognized as a Research and Operations Partnership (RAOP; Ralph et al. 2020), led by UC San Diego's Center for Western Weather and Water Extremes (CW3E) and the U.S. Army Corps of Engineers' (USACE's) Engineer Research and Development Center (ERDC), which serve as research entities, in partnership with USACE South Pacific Division, San Francisco and Sacramento Districts, and the National Oceanic and Atmospheric Administration's (NOAA's) California-Nevada River Forecast Center (CNRFC), which serve as operational entities. Regulatory agencies and other stakeholders have also been involved in this effort to ensure consideration and alignment relative to their interests and roles. For example, the project team paid careful attention to ecosystem considerations in accordance with the Russian River Biological Opinion, a federal mandate for protecting vital salmon species in the river.

The Lake Mendocino FIRO partnership has brought operational practitioners and their mission requirements together with scientists and their innovations and discoveries to advance the knowledge, methods, and tools that support FIRO. This RAOP approach combines the rigor of established engineering testing protocols with the strengths of scientific studies and peer review to ensure the soundness of the technical foundation of FIRO at Lake Mendocino. At the core of this effort lies a well-established and successful operational framework (NWS/CNRFC); financial, human capital, and political support for scientific advancement; and a willingness to collaborate.

Figure 5.1 shows a conceptual pathway from research to operations for improved observations, models, and decision support tools. Beyond these information pathways, forecasters' and reservoir operators' expertise are essential to advancing FIRO. The RAOP approach has enabled research advancements while also ensuring that this knowledge can be operationalized to help forecasters and operators interpret observation and model guidance during extreme events. This tight connection of research to operations is a foundational element of FIRO at Lake Mendocino.

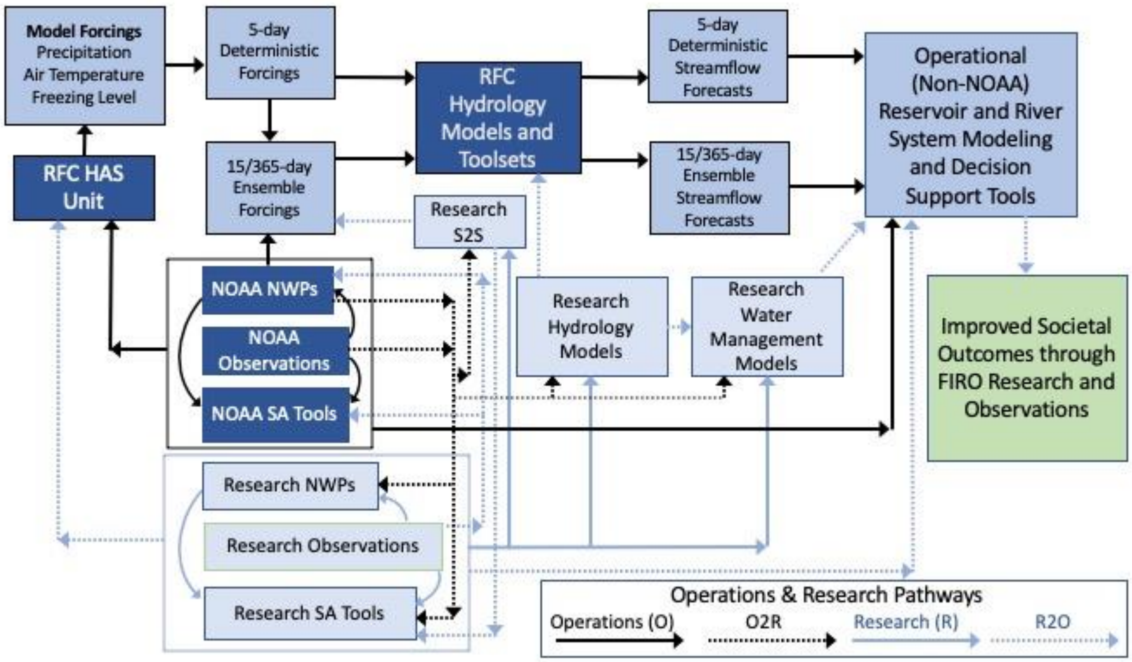

Figure 5.1 *Operations and research pathways concept as applied to streamflow forecasting in the Russian River basin.*

FIRO creates an environment where ongoing research investments in forecasts and their application leads to continually improving reservoir management outcomes. The RAOP approach is helpful in this regard. While many key tasks are defined by the specific technical requirements envisioned for FIRO, the RAOP also supports and empowers scientific inquiry that can lead to unexpected transformative advances underlying future enhancements in forecast skill, and ultimately greater reservoir operations flexibility. The current partnership can be extended to support additional WCM updates and push forecast skill forward to meet the requirements associated with FIRO 2.0 enhanced reservoir operations flexibility goals outlined in this FVA. This section describes many opportunities to apply the RAOP framework for continued improvement of reservoir management outcomes.

5.2 Weather Forecast Improvements

By linking hydrologic prediction to its atmospheric drivers, FIRO is able to leverage significant opportunities in AR prediction improvement stemming from research advancements in numerical weather prediction (NWP) models, process-based research, and decision support tool development. This approach to address both quantitative and qualitative pathways for hydrologic forecast improvement, targeting both incremental and transformative advances in hydrometeorological prediction, embodies the novel research and operations partnership that has come to define FIRO.

This section discusses current forecast procedures (Section 5.2.1) as well as several ways in which research to date has helped to improve AR forecasts, including:

- Improvements to zero- to seven-day forecasts, including development of the Weather Research and Forecasting Model (WRF) regional weather model for the western United States (Section 5.2.2).
- Machine learning for bias correction to reduce forecast error (Section 5.2.3).
- Development of decision support tools, such as the AR landfall tool and AR scale, as well as subseasonal-to-seasonal (S2S) forecast advancements (Section 5.2.4).

Section 5.2.5 summarizes opportunities for future gains, including several specific recommendations to build on the research conducted to date.

5.2.1 Current Forecast Procedures

Forecasting for the Russian River watershed—as in any area—uses a cascade of meteorological data and knowledge to generate a QPF product and then derive an operational streamflow forecast. The process begins with QPFs generated by NOAA's Weather Prediction Center (WPC) and culminates in streamflow forecasts produced by the CNRFC. These steps all benefit from knowledge, experience, and tools that help forecasters apply manual judgment to the forecasts they produce (Haynes and Souilliard 2010).

The forecast process for QPF at WPC follows the structure described in Olson et al. (1995). WPC QPF represents a continuous assimilation and assessment of observations, analyses, and model output. The forecaster uses models (e.g., National Centers for Environmental Prediction [NCEP] operational models), but also considers all available information and experience to decide which model is likely to be most correct for a given weather event. These decisions are based on extensive studies of model performance in predicting regional weather in the past (e.g., Wick et al. 2013 for ARs), known deficiencies that are relevant for a given event's driving meteorology (e.g., Martin et al. 2018), and model-to-model or run-to-run consistency (Olson et al. 1995). With all these pieces of information available, forecasters' manual production of operational QPF products often vary markedly from any individual NWP model's QPF. Manual forecasts have historically delivered a "value added" of 10–30 percent, depending on the model they are compared against and the conditions tested (Haynes and Souilliard 2010). Improvements in QPF accuracy are driven by a combination of increasing skill of NWP QPF, improvements in forecaster knowledge and training, and the availability of decision support tools (Reynolds 2003).

CNRFC forecasters generate the QPF used in their streamflow forecasts in a similar manner, refining WPC QPF with expert knowledge of their region of responsibility; region-specific forecast tools, including AR forecast diagnostics; and supplemental observations in the Russian River watershed (Section 5.3).

Given the reliance on data and decision support tools throughout the forecasting process, as described above, there are multiple pathways through which research products can help to improve QPF and streamflow forecasts in the Russian River watershed. This section further highlights the range of meteorological research advancements that have resulted from the FIRO development process, along with their pathways to supporting improved QPF and, ultimately, improved water management outcomes.

5.2.1.a Assessment of Operational Model Guidance

Forecasting extreme precipitation events over the western United States begins with NWP guidance from the NCEP suite of operational global and regional models and is supported by global models run operationally by other entities (e.g., the ECMWF model). The FIRO PVA for Lake Mendocino called for a quantitative assessment of the forecast skill of NWP QPF for the Russian River watershed, as it is a primary input into operational manually adjusted QPF generated by WPC. (Section 2 provides an assessment of the manually adjusted final CNRFC QPF product's skill.) Notably, the Global Ensemble Forecast System (GEFS) mean areal precipitation forecasts for the Russian River in 100 extreme events—defined as the 90th percentile of days with measurable precipitation—demonstrated that, although systemic biases in precipitation amount were apparent, the occurrence of an extreme event was well predicted out to five days, which was the maximum lead time evaluated. The lack of forecast "surprises" in the record reflects the large-scale signature of ARs, which indicates their potential impacts in advance of landfall. This general reliability of forecasts helps to make FIRO viable at Lake Mendocino.

Although Russian River precipitation forecasts are skillful at the lead times required for FIRO (Weihs et al. 2020), challenges in NWP remain that limit decision support for water management and hazard mitigation (Sukovich et al. 2014; Lavers et al. 2016). Many of these challenges relate to errors in the prediction of AR landfall position, intensity, orientation, duration (Wick et al. 2013; Lavers et al. 2016; Cordeira et al. 2017; DeFlorio et al. 2018; Nardi et al. 2018; Martin et al. 2018), and temperature (Henn et al. 2020). Nardi et al. (2018) performed a quantitative assessment of AR landfall location error across nine operational global models (including GFS and ECMWF) out to 14-day lead times over winter seasons for at least 10 years. The results demonstrated increasing errors of approximately 100 km per day of lead time, on average, with a five-day lead time error on the order of 500 km—a distance much larger than the scale of the Russian River watershed. These analyses also demonstrated considerable differences in skill across models, with no single model consistently outperforming the others for occurrence, intensity, and landfall location metrics.

Given the importance of documenting model skill for FIRO, the project team developed several automated and post-season verification tools that run in parallel with the near-real-time forecasting products. These verification analyses include a measurement of forecast accuracy for AR landfalls, precipitation amounts, and spatial extent. See Section 2.3.3 of Appendix D for detailed results.

5.2.2 Research to Improve Week One Forecast Skill

Beyond assessing current forecast skill, the PVA also recommended research to improve zero- to seven-day (week one) forecasts of extreme events at Lake Mendocino. While FIRO is possible with current forecast skill, a myriad of opportunities to further improve week one forecasts remain. Week one forecast research in support of FIRO builds upon the assessment of existing operational forecasts with:

- Research to improve global NWP forecast skill via assimilation of targeted observations.
- Studies to identify key physical processes that need to be resolved in NWP.
- Development of high-resolution forecast models.
- Development of forecast products focused on situation awareness.
- Post-processing and machine learning methods to bias correct NWP output.

- Testing of the design of ensemble systems to reliably quantify the prediction uncertainty.
- Development of unique model evaluation metrics for ARs and precipitation.

An example from Martin et al. (2019) helps to illustrate the transition of research findings to operational products and procedures through the pathways outlined in Section 5.1. This example—a case study—evaluated the sources of streamflow forecast error in the Russian River through the lens of atmospheric prediction ahead of an impactful AR event.

In the example case study from December 2014, a strong AR was accompanied by development of a secondary meteorological feature called a "mesoscale frontal wave." This feature modified the AR's intensity, duration, and precipitation generation, and it led to a significant flood event on the Russian River on December 14. The CNRFC deterministic streamflow forecast progression for December 10–13 exhibited rapid changes at short lead times, as the predicted peak of flow at Guerneville, located on the Russian River downstream of Coyote Valley Dam, increased by 8 feet between a forecast on December 8 and another on December 10. The forecast on December 10, the start of the event, ultimately exceeded observations by several feet (Figure 5.2). While these forecasts were still quite skillful in forecasting a major stage rise, the uncertainty was largely a function of the QPF, which resulted from poor representation of the AR and frontal wave in the NWPs. The forecast challenges in this case, including difficulties in representing the AR's intensity and duration, are used throughout this section to demonstrate how research to improve meteorological understanding of regional extreme events and their uncertainty in NWP—along with the development of tools that relay uncertainty in real time—has effected change in operational streamflow prediction and will continue to lead to improvements.

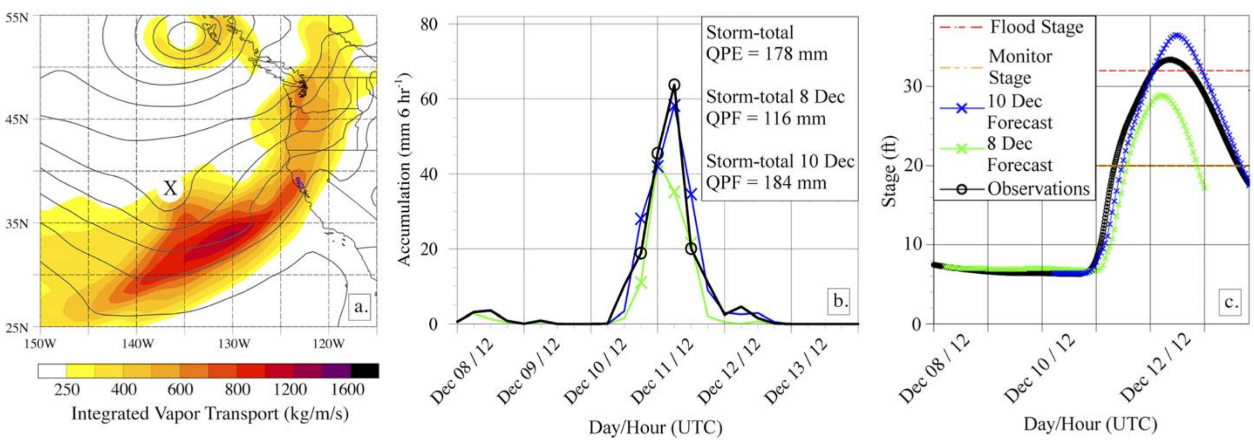

Figure 5.2. *Reanalysis of the AR conditions at 0000 UTC on December 11, 2014. The left panel shows integrated water vapor transport (IVT) (kg m^{-1} s^{-1}) and sea-level pressure (hPa; contours every 4 hPa from 974 to 1018 hPa). The "X" marks the location of a mesoscale frontal wave that modified AR conditions over the Russian River Watershed. The center panel shows the six-hourly accumulated RRW-mean areal QPF issued by CNRFC at 1200 UTC on December 8 (mm; green) and 1200 UTC on December 10 (mm; blue) and the CNRFC Quantitative Precipitation Estimate (QPE) (mm; black). Time on the x-axis refers to QPE valid time. The right panel shows the Guerneville river-stage forecast issued by CNRFC near 1200 UTC on December 8 (mm; green) and near 1200 UTC on December 12 (mm; blue), as well as observations from the river gauge (mm; black).*

5.2.2.a Research to Improve Numerical Weather Prediction and the Utility of its Output

NWP forecast skill is limited by uncertainty in a model's initial state, numerical approximations, physical process parameterizations, and subgrid-scale unresolved processes (Berner et al. 2015). The following subsections detail specific challenges related to each source of uncertainty and discuss research that has taken place to address them in an effort to bolster QPF skill for the Russian River. Importantly, uncertainty in AR forecasts and subsequent QPF varies across spatiotemporal scales, and any given event is generated by a unique combination of features and scale interactions with varying degrees of predictability.

5.2.2.a.i Model Initialization

A forecast is an estimate of the future state of the atmosphere generated by calculating how the current conditions (or "initial state") will evolve in space and time. As the atmosphere is chaotic, small errors in the initial state can lead to large errors in the forecast within hours to days (Lorenz 1969). Thus, AR prediction faces a primary challenge in that these features evolve over data-sparse oceans (Ralph et al. 2020). Zheng et al. (2020) described the measurement density and quality of various observational data sources over the Pacific (e.g., satellite radiances, satellite motion vector winds, GPS radio occultation, buoys, ships, aircraft) and found that deep cloud structures associated with ARs are responsible for significant data gaps in the regions that are most prone to forecast model initial condition sensitivity (Reynolds et al. 2019). This observation gap constrains the potential of data assimilation procedures to generate a high-fidelity initial state, which is unfortunate because data assimilation has been a major source of global NWP improvement in recent years (Majumdar 2016).

Weather reconnaissance dropsondes as part of AR Recon (described in detail in Section 5.3) expand upon a history of airborne observation targeting in other meteorological conditions (e.g., hurricanes), but with added flexibility in targeting strategies. Analysis of the impact of assimilating the dropsondes on operational forecast systems is ongoing, with positive results reported in Stone et al. (2020) and Lavers et al. (2020). So are efforts to improve assimilation strategies for reconnaissance data (e.g., Majumdar 2016). Due to the direct impact of dropsondes on forecast initialization (e.g., GFS and the ECMWF's Integrated Forecasting System background analyses), the pathway for AR Recon to influence FIRO is primarily through each model's representation of meteorological processes and evolution, which drive QPF guidance at WPC. In addition, studies to determine regions of forecast sensitivity in AR conditions (e.g., Reynolds et al. 2019; Demirdjian et al. 2020b; Lavers et al. 2020) aid further model development, operational AR Recon targeting procedures, and forecaster awareness. Revisiting the December 2014 event described above, the research that has guided AR Recon development and understanding of forecast uncertainties highlights how obtaining direct observations of wind and water vapor across the AR and in the vicinity of the developing frontal wave in an event such as this one would support the improvement of initial conditions in the NWP systems that contribute to QPF.

5.2.2.a.ii Parameterization

Beyond initial condition error, forecasts are plagued by model error that is partially attributed to parameterization (Berner et al. 2015). Physical process parameterization in NWP is necessary due to the computational expense of directly simulating a small-scale or exceedingly complex process, as well as insufficient knowledge on how to represent some of the processes mathematically (Warner 2011). With respect to the representation of ARs in global NWP, some of the relevant processes that are parameterized include cumulus convection, cloud and precipitation microphysics, the boundary layer, and turbulence. The fidelity of parameterization schemes in representing these processes has direct consequences on predicting AR impacts, as differences between parameterization schemes employed can be an important and confounding source of model divergence due to interdependencies between schemes and feedbacks with resolved processes. Drawing again from the 2014 example, sensitivity testing of model physics in Michaelis et al. (2020) led to changes in predicted AR development and precipitation amounts, indicating that the event's forecast uncertainty was partially attributable to parameterization.

Research at CW3E has targeted physical process parameterization uncertainty using land-based observations, including micro-rain radars, radiosondes, and gauges (deployed as part of FIRO and described in Section 5.3), to evaluate the representation of precipitation processes in ARs across NWP models (e.g., Martin et al. 2018; Cannon et al. 2020a; Michaelis et al. 2020). Specifically, considerable effort has been devoted to determining an optimal set of physics packages for AR prediction in the West (Martin et al. 2018). Assessing parameterization has also highlighted areas where operational models suffer systemic biases—for example, in representing orographic precipitation in the Russian River watershed. This information currently informs operations through an indirect pathway of CNRFC awareness of NWP bias, but it will eventually lead to quantitative improvements through improved physics packages for AR conditions and the development of high-resolution forecast models discussed in Section 5.2.2.b (e.g., Cannon et al. 2020a).

5.2.2.a.iii Grid Resolution

Model horizontal and vertical grid resolutions can present an additional source of error. A coarse model grid is often thought of as a limit to resolving precipitation impacts in a landfalling AR by failing to represent the complex topography that forces moisture ascent and precipitation generation. In the coast ranges of California, for example, a 0.5° (approximately 50 km) horizontal resolution model results in unrealistically low and smooth topography that does not force ascent of ARs with fidelity and consequently fails to produce realistic precipitation distributions. However, the influence of coarse model resolution on NWP extends beyond local precipitation forcing, as the model's effective resolution also defines the scale of atmospheric processes that can be resolved. For an approximately 50 km model grid, the effective resolution is on the order of several hundred km (Warner 2011), meaning that many important processes for AR development, including latent heating along fronts and sharp wind shear gradients (as in the case of the December 2014 event; Figure 5.2) are either poorly represented or entirely absent (Cannon et al. 2020b; Demirdjian et al. 2020a). Model error from unrepresented subgrid-scale processes can propagate upscale and lead to large errors in synoptic-scale meteorological features at even short lead times (Skamarock et al. 2014), affecting AR evolution in the range of zero to five days. Research by CW3E is guiding the NWP and observational communities towards addressing these challenges, with specific motivation coming from the need to improve forecasts of AR impacts in western U.S. watersheds.

5.2.2.b Regional Models

The prediction of regionally important physical processes on scales not adequately resolved by global models benefits from the use of limited area models that trade large-scale coverage for finer horizontal resolution. Numerous studies have used regional forecast models such as WRF (a community model developed by the National Center for Atmospheric Research and others; Skamarock et al. 2008) to explore precipitation processes in the western United States (e.g., Minder et al. 2011; Martin et al. 2018). The WRF modeling framework is also applied in near real-time for operational forecasting. The national High-Resolution Rapid Refresh (HRRR) (Benjamin et al. 2016), which employs 3 km horizontal resolution, is the most prominent example, as its data are available in real time to operational forecasters. Several other continental U.S. domain operational models also run at convective-resolving resolution.

CW3E runs a region-specific configuration of WRF over the western United States (West-WRF) in near real-time. West-WRF has been tuned in terms of physics parameterization, domain, and resolution (Martin et al. 2018) to specifically provide forecast guidance on the potential influences of mesoscale processes on landfalling ARs, to better represent the spatial variability of precipitation, and to discern localized impacts. Figure 5.3 shows the scale of grid cells in 3 km resolution regional models such as HRRR and West-WRF compared with a 0.5° global model ensemble grid. This illustration highlights the importance of resolution for simulating regional scale precipitation processes.

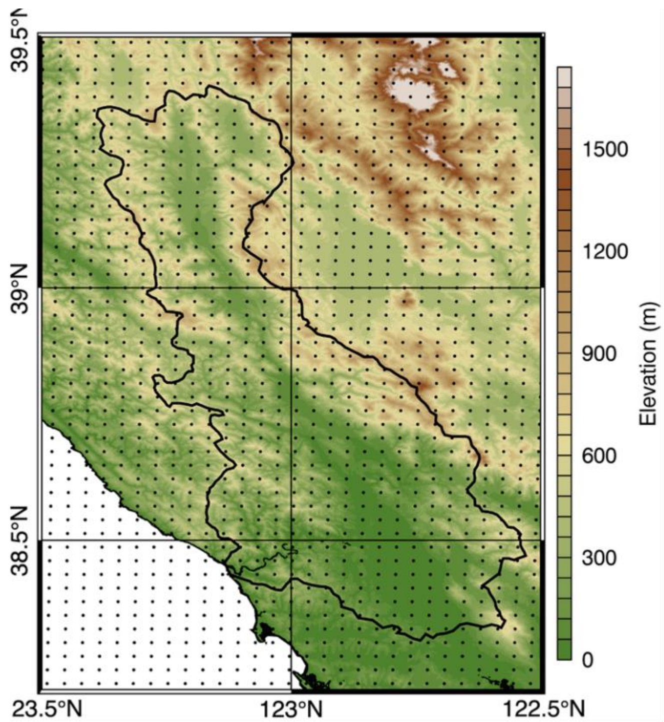

Figure 5.3. *The Russian River watershed's topography (shading) with a 0.5° grid (solid lines) and 3km grid (dots) overlaid. The coarse resolution grid is unable to resolve regional characteristics of the watershed.*

5.2.2.b.i West-WRF

West-WRF expands beyond the operational HRRR by enabling high-resolution forecasting and decision support tools to be tailored to the West and by providing 3 km resolution data out to five days—a longer lead time than is available from any similar mesoscale NWP model run nationally (see details in Section 2.3 of Appendix D). West-WRF near real time model runs have occurred every winter since 2015–2016, and its forecasts have been used by several partners, including NWS, municipal water agencies, and the California State-Federal Flood Operations Center (FOC). Notably, specialized West-WRF forecast products were provided to FOC during the flooding emergency on the Feather River at Lake Oroville Dam in 2017. The flexibility of the experimental model has proven useful in providing decision support tools in near real-time, providing an alternative source of QPF for hydrologic model predictions, and providing a platform for investigating ARs and their impacts and uncertainty in high resolution.

CW3E has developed several automated and post-season verification tools to run in parallel with the West-WRF near real-time forecasting system. These tools compare West-WRF with global forecast models as they evaluate forecast accuracy and model skill in AR landfalls, precipitation amount, and spatial coverage on daily, event, and seasonal time scales. These results highlight that:

- West-WRF predictions have a lower landfalling position error than GFS at up to a five-day lead (Figure 2.3.3a in Appendix D).

- West-WRF produced a smaller intensity error than GFS in weak ARs, but overpredicted AR intensity in strong events (Appendix D, Fig. 2.3.3b).

5.2.2.b.ii West-WRF Reforecast

An important part of understanding the utility of any given forecast is having a long-term record of how that forecasting system performed in previous extreme events. The lack of historical forecast information is a major drawback of the HRRR and several other mesoscale NWP systems that provide forecasts at high resolution over California. Accordingly, CW3E, using supercomputing resources provided by USACE-ERDC, developed a 34-year West-WRF reforecast to assess model skill in historical events. The reforecast effort additionally benefits FIRO by providing a potential higher resolution QPF to feed into CNRFC operational streamflow forecasts than what the NCEP/CNRFC system currently provides. Additional information on the development of the reforecast can be found in Appendix D, 2.3.5. To the best of the project team's knowledge, this is the only high-resolution regional reforecast effort at a climate time scale (30+ years) in the United States.

5.2.3 Machine Learning and Bias Correction

Calibrating forecasts entails post-processing to remove bias, which can improve the identification of extreme events or improve the representation of forecast uncertainty. Bias correction is possible if a sufficiently long forecast record exists, such as for reforecasts. Chapman et al. (2019) tested the utility of a convolutional neural network—a machine learning technique—to post-process a GFS reforecast of IVT over the Pacific. They demonstrated systematic error reductions out to five-day lead times, a critical forecast range for landfalling ARs. In this research, GFS predictions were improved by about 5 percent at the beginning of the forecast, and by more than 20 percent seven days out, when GFS performed worse than climatology. Effectively, the GFSnn (neural network) extends GFS's period of skillful predictions by approximately two days, based on root-mean-squared-error and other metrics. CW3E has run the GFSnn method in real time for the latter part of water year 2020 as part of the near real-time prediction systems, with results published on the CW3E website (https://cw3e.ucsd.edu/arcnn_ivt). CW3E is applying similar methods to the West-WRF reforecast to develop bias correction for near-real-time mesoscale forecasts of ARs and precipitation.

5.2.4 Decision Support

5.2.4.a Ensemble (Probabilistic) Forecast Guidance

The previous sections detailed how uncertainties in model initial conditions, numerical approximations, the representation of relevant physical processes, and effective resolution all limit the predictability of ARs. The objective of an ensemble forecast system is thus to account for these sources of error and to sample the forecast uncertainty space in an effort to identify the most likely weather outcomes. Various methods are used to design ensembles that can reliably quantify the prediction uncertainty, but the goal remains the same: to give the forecaster a better idea of what weather events may occur at a particular time. By comparing these different forecasts, the forecaster can better determine how likely a particular weather event is to occur. Disagreement between ensemble members or ensemble systems conveys model uncertainty to the forecaster, while member agreement instills confidence in a single forecast scenario.

CW3E developed the AR landfall tool to provide longer-range GEFS and ECMWF guidance on the probabilistic duration and timing of landfalling ARs up to 16 days in advance. The landfall tool diagram from February 20, 2019 (Figure 5.4a; also shown in Figure 1.9), for example, can be used to infer a high probability (p = 0.55 to 0.85, or 12 to 17 of 21 ensemble members predict IVT greater than 250) in AR landfall at the latitude of Bodega Bay on February 25–27 (five to seven days later). This particular event led to rapid changes in the hydrologic forecast for the Russian River, which can be interpreted through a lens of forecaster uncertainty about the duration of AR conditions. Lake Mendocino reservoir operators have used the AR landfall tool and plume diagram (Figure 5.4b) to prepare release scenarios. The forecasted intensity of AR conditions is also paramount to hydrologic impact prediction, and the AR plume diagram (Figure 5.4b) illustrates the spread in IVT magnitude across the ensemble of forecast models at a given location (the latitude of Lake Mendocino in this example) as a function of lead time.

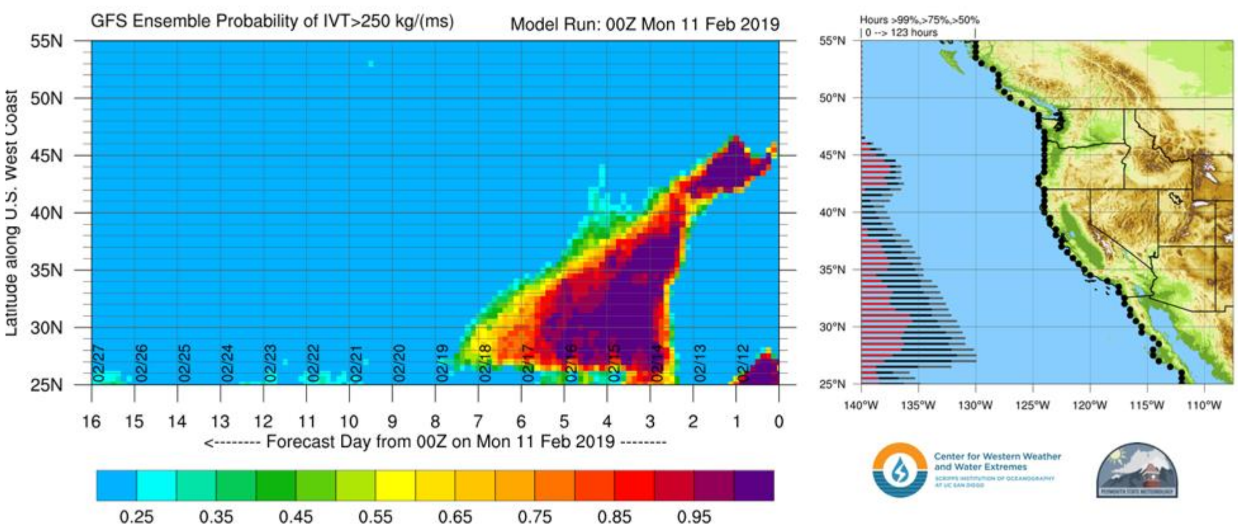

Figure 5.4. *The AR landfall tool (a) for a forecast on February 20, 2019, shows the probability of AR conditions according to lead time and latitude in the GEFS ensemble. The AR plume diagram (b) for the corresponding initialization time shows the IVT magnitude forecast from individual GEFS ensemble members (thin gray lines), the GEFS ensemble mean (green line), the control forecast (black line), and maximum and minimum members (red line and blue line, respectively). The plume diagram has been revised after feedback from the Lake Mendocino reservoir operator; a modified version showing +/-1 standard deviation is now displayed on the CW3E website.*

5.2.4.b The AR Scale

Despite the widely recognized importance of ARs, no concise method has existed for conveying the likelihood of benefits and hazards that communities face during a particular AR event. In response, CW3E and collaborators from academia, NWS, and the California Department of Water Resources (DWR) developed a scale for characterizing the strength and potential impacts of ARs (Ralph et al. 2019). This scale, available at https://cw3e.ucsd.edu/arscale, provides a crucial tool to assess flood potential before storms strike. Unlike other scales that focus primarily on damage potential, such as the Fujita scale for tornadoes or the Saffir-Simpson scale for hurricanes, the AR scale accounts not only for storms that can prove hazardous, but also for storms that can provide benefits to water supply (Ralph et al. 2019). In the context of FIRO, the AR scale provides a metric that distills forecast ingredients into a single number that can be used to convey a storm's potential water supply benefits and/or flooding hazards. Reservoir operators and forecasters use the AR scale in combination with other factors, such as antecedent condition and AR orientation, to fully assess each storm.

5.2.4.c Extended Range Decision Support Tools: S2S Research and Development

Demand for skillful forecasts of precipitation at lead times beyond seven days has been consistent for many decades across a variety of end user and applications communities. In California, this need is largely driven by the state's considerable year-to-year variation in annual precipitation (Dettinger et al. 2011). Recent advancements in forecasting models and innovative data analysis techniques have increased the potential for improved long-range prediction of physical quantities affecting water resource management over the western United States (DeFlorio et al. 2019). The PVA acknowledged the benefit of S2S forecasts, which provide two-week to at least two-month forecasts, and recommended that research to support S2S forecasts become part of the FIRO effort because of the high value of such forecasts to reservoir management. CW3E, in partnership with the NASA Jet Propulsion Laboratory, has conducted fundamental research with the ultimate goal of improving S2S lead-time forecasts of ARs and total precipitation and floods over California, including the Lake Mendocino watershed. Many of the S2S research efforts and associated online products that support FIRO leverage funding from California DWR. A list of S2S research and development accomplishments to date can be found in Appendix D, 2.4 and on the CW3E S2S forecast webpage (https://cw3e.ucsd.edu/s2s_forecasts).

5.2.5 Opportunities for Future Gains

Meteorological research for the FVA demonstrated that current forecasts are sufficiently skillful for FIRO implementation now, and led to additional advancements in understanding, predicting, and managing extreme precipitation events. This work has also shown the importance of several factors that go beyond just improving NWP products spanning a myriad of spatial and temporal scales. Leveraging the spectrum of NWP output into skillful, situationally aware forecast information also requires bias correction, development of decision support tools, utilization of observations, and effective communication with operators and stakeholders. The pathways through which forecast information is conveyed must be reliable and easy to access, and forecast products must be readily interpretable with sufficient background information to ensure that the material is used appropriately. Communication and partnership with CNRFC, reservoir operators, and stakeholders provides an opportunity for meteorological research to better support societal needs by tailoring forecast decision support tools.

Beyond the positive results presented above, the following recommendations identify opportunities for further improvements in forecasting for FIRO:

- Assess skill of new and updated models. NWP systems are not static. As models are upgraded and new systems come online (e.g., the Unified Forecast System), their skill should be assessed with FIRO-specific metrics.
- Conduct research to understand and resolve limitations in the predictability of ARs and extreme precipitation in recent events, and integrate findings into FIRO (e.g., via improved models or decision support tools).
- Continue collecting AR Recon observations—including high-vertical-resolution dropsondes, airborne radio occultation measurements, and buoy surface pressure—to improve model representation of the initial state of the atmosphere.
- Continue to assess and improve data assimilation in NWPs to best utilize AR Recon observations.

- Develop high-resolution probabilistic precipitation forecasts from West-WRF and create effective data visualizations for FIRO decision support.
- Develop machine learning algorithms to generate sharp and reliable probabilistic predictions, leveraging the recently developed high-resolution reforecast data set based on West-WRF.
- Explore hybrid dynamical-statistical methods and implement machine learning algorithms to improve S2S prediction of ARs and precipitation.
- Continue to work with forecast agencies, reservoir operators, and stakeholders to ensure that research addresses FIRO needs and that results are effectively transitioned to operations.

5.3 Enhanced Observations

Enhancing observations of the landscape and atmosphere supports the overall FIRO objective to use state-of-the-art monitoring to operate reservoirs and addresses the need identified in the PVA to develop new methods for data collection and monitoring. The PVA specifically called for observational enhancements, including additional soil moisture, precipitation, stream gauges, vertically profiling radars, radiosondes, and more. This augmentation of the existing instrumentation network in the Russian River supports watershed monitoring and provides crucial data to address research questions (Sections 5.2 and 5.4) and initialize models (Section 5.2.2.a.i), which will lead to improved forecasts. In addition, the observational datasets are critical to evaluating the skill of the models that produce the forecasts that are the foundation of FIRO (Sections 5.2 and 5.4).

This section describes key accomplishments in the realm of enhanced observations:

- Successful airborne reconnaissance field campaigns held during 2016, 2018, 2019, and 2020 to observe ARs before they make landfall on the West Coast and incorporate observations immediately into global operational NWPs (Section 5.3.1).
- Installation of a ground-based atmospheric sensor network for robust monitoring in near real-time throughout the watershed for all relevant conditions, including precipitation characteristics, integrated water vapor, soil moisture, streamflow, hydrogeochemistry, and more—complementing existing longer-term observations from other networks (Section 5.3.2).

These airborne reconnaissance and ground-based sensor network observations have been used to monitor the watershed in real time, and they have also been embedded into FIRO process-based research studies. Section 5.3.3 emphasizes the importance of maintaining these enhanced observation programs while also noting opportunities for continual improvement.

5.3.1 Atmospheric River Reconnaissance

AR Recon (Ralph et al. 2020) is an airborne field campaign designed to improve forecasting of impactful West Coast weather events at zero- to five-day lead times. AR Recon combines new observations, modeling, data assimilation, and forecast verification methods to improve the science and predictions of landfalling ARs. Principal Investigator Marty Ralph of CW3E, with support from NOAA Co-Principal Investigator Vijay Tallapragada, has formed and led the AR Recon program team, which comprises academic experts, global numerical weather prediction centers, forecasters, flight directors, and modelers. This team has organized the complex logistics of aircraft operations, crews, and dropsondes, and made the data they collect available in real time for ingestion into NWP models.

The AR Recon program measures AR conditions over the northeast Pacific using dropsondes from up to three aircraft simultaneously. AR Recon field campaigns in winters 2016, 2018, 2019, and 2020 deployed 1,312 dropsondes from aircraft during 32 missions. Details on AR Recon flight planning and targeting strategies can be found in Appendix D. The team has also used funding from NOAA and California DWR to deploy drifting buoys with pressure sensors, and it is currently testing novel airborne radio occultation observations. These efforts have resulted in development of new AR targeting and data collection methods to determine where data from AR Recon will most benefit forecasts (Figure 5.5).

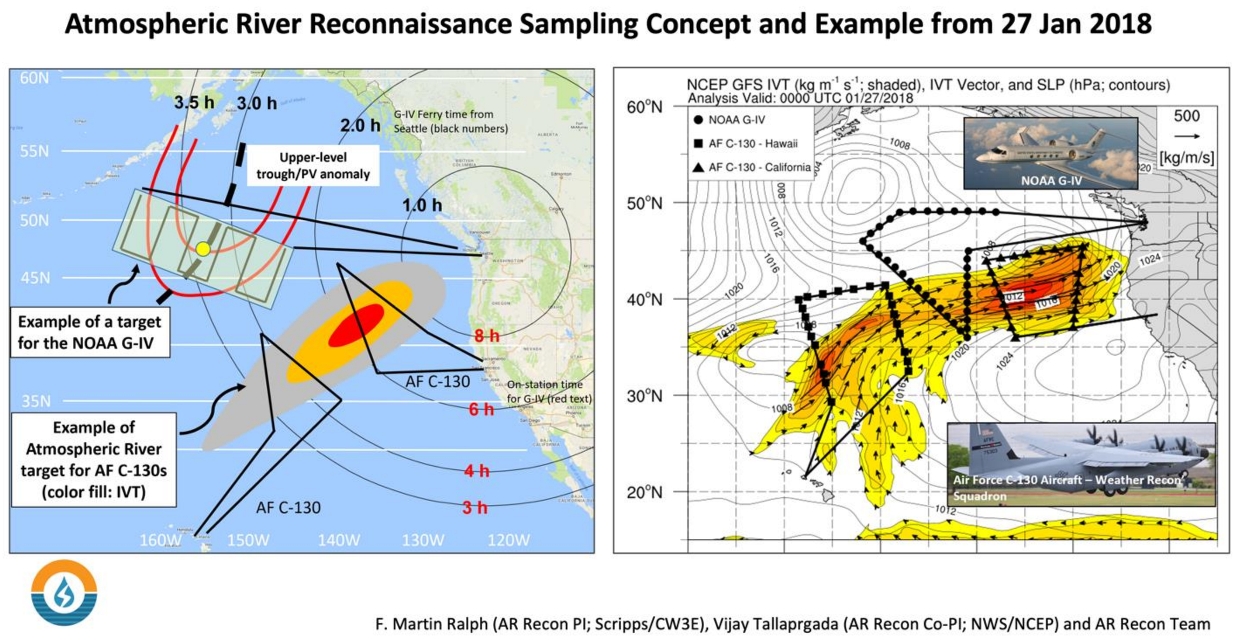

Figure 5.5. *AR Recon targeting concept and example using three aircraft sampling sensitive regions in and near the AR. In addition to physically based targeting, quantitative methods are used to identify regions of large initial condition error impacts, which largely match the location of the AR outlined here.*

AR Recon observations are assimilated in near real-time by global operational NWPs, and they are also being used to improve understanding of the physical and dynamical processes that define ARs. Assimilation and forecast impact experiments are ongoing, and better understanding of AR dynamics is emerging (see Section 5.2 and Appendix D).

In June 2019, the Office of the Federal Coordinator for Meteorology added AR Recon as a critical feature in its official National Winter Season Operations Plan to support improved outcomes for emergency preparedness and water management in the West. This was the first update to the document since 2014 and was largely based on the successful demonstration of the forecast benefits from, and execution of, missions during 2016, 2018, and 2019. In 2020, additional edits explicitly acknowledged the leadership of CW3E and NOAA and the importance of AR Recon in helping to address western weather and water needs.

Modeling and data assimilation work is conducted under the auspices of the AR Recon Modeling and Data Assimilation Steering Committee. Appendix D lists the members of this Steering Committee, which formalizes the collaboration between CW3E and several leading global operational NWP centers to quantify the added benefit provided by the dropsondes using data denial hindcasts. The Steering Committee has developed Terms of Reference for participating organizations and is developing and executing a five-year work plan for AR Recon data assimilation efforts. The results indicate that AR Recon data have significant beneficial impacts, with per-observation impacts more than double those from the North American radiosonde network (Stone et al. 2020). A comprehensive listing of results to date relevant to Lake Mendocino FIRO goals can be found in Appendix D.

5.3.2 Ground-Based Sensor Network

The Lake Mendocino FIRO project has led to—and benefited from—enhancements to existing hydrometeorological monitoring efforts in the Russian River basin. This newly enhanced, multi-agency monitoring network in the basin upstream from Lake Mendocino now collects observations of events of all strengths that bring precipitation to the watershed. This network has been named the Russian River Hydrometeorological Observing Network (RHONET; see Sumargo et al. 2020b, Section 5.4, and Appendix D). The increase in station density is a major accomplishment of the Lake Mendocino FIRO initiative (Figure 5.6).

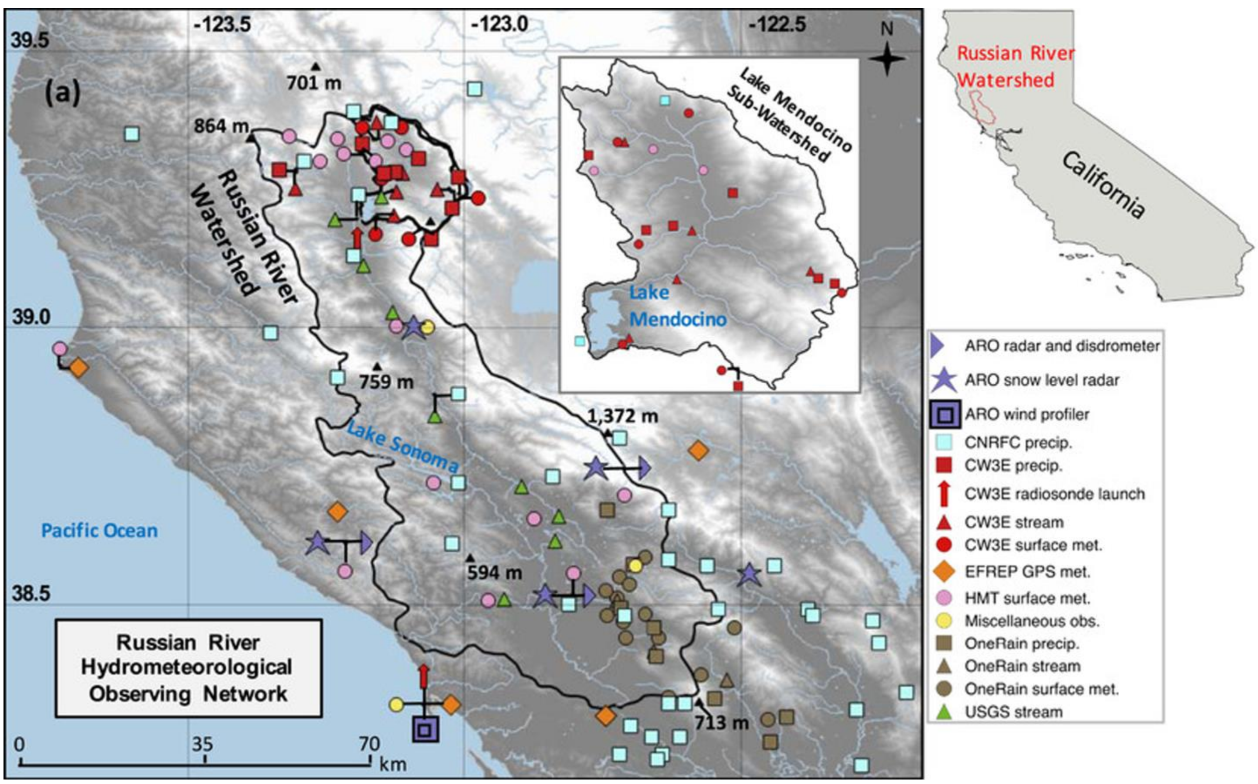

Figure 5.6. *RHONET in and around the Russian River watershed (from Figure 1, Sumargo et al. 2020b).*

RHONET instrumentation provides near real-time observations of atmospheric conditions within the watershed that are of operational value to NWS forecasting partners. These data are also useful for model verification and answering scientific questions about AR-driven precipitation in the watershed. Distributed atmospheric, precipitation, soil moisture, and streamflow observations help to quantify the magnitudes and spatial variability of water vapor transport, precipitation, soil moisture, and streamflow rates during AR events. Soil moisture observations provide critical information on the antecedent wetness state of the watershed, which has implications for the runoff produced by precipitation events. Precipitation observations can be used to develop forcing data products to drive the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) and WRF-Hydro models. Streamflow observations are essential to calibrate and verify the models. Section 5.4 and Appendix E provide more details about hydrologic modeling.

Most of the stations report in near real-time on the CW3E website and also transmit data to other appropriate data repositories, including the California Data Exchange, NOAA Physical Science Laboratory, and Meteorological Assimilation Data Ingest System. Recent additions to the network include two radar stations and, during storms, two radiosonde release locations. Data from the radiosondes are transmitted to the World Meteorological Organization's Global Telecommunications System, so they can be assimilated into global operational NWPs, akin to the AR Recon efforts described in Section 5.3.1. Radiosonde data are also provided directly to interested NWS Offices in the Western Region, including Monterey, Eureka, Sacramento, and Reno (Appendix D).

5.3.3 Opportunities for Future Gains

The efforts to enhance observations throughout the FIRO project have significantly improved monitoring capabilities within the watershed. The network is sufficient to support FIRO viability if maintained at current (2020) levels (see Sumargo et al. 2020b, Section 2 of this document, and references cited therein). Ongoing quantification of the benefits of AR Recon data for AR forecasts shows that continuing this international, multi-agency effort is critical to improve forecasts as part of FIRO. Observing the atmosphere before, during, and after extreme events is fundamental to the research to support FIRO, and useful to partners making real-time forecasts (Section 5.3.2). Continued efforts to maintain the current observations are important to supporting FIRO at Lake Mendocino to implement the FVA and future WCMs.

The following observation-related recommendations would help to enhance the benefits of FIRO:

- Continue to integrate monitoring data into modeling and analysis studies to improve process-based understanding of ARs and their impacts, particularly as it relates to streamflow.
- Continue storm-based sampling with airborne reconnaissance and ground-based radiosondes to directly feed into operational numerical weather prediction models to improve the representation of the initial state of the atmosphere.
- Maintain RHONET to support long-term process understanding, model improvements, and eventually model inputs for improved hydrologic predictions.
- Upgrade all hydrometeorological stations to report in near real-time to maximize the utility of the data.
- Continue data dissemination to the NOAA Hydrometeorology Testbed, California Data Exchange Center, the Global Telecommunications System, and other users as they are identified.
- Evaluate the sensor network regularly to identify potential gaps that can be addressed to maximize FIRO benefits. Examples might include additional streamflow and soil moisture instrumentation in the lower part of the basin.
- Continue to look for partnerships to expand the utility of RHONET to overcome the perception of diminishing returns for long-term network operation.

5.4 Hydrology and Water Resources Engineering

FIRO depends on having skilled streamflow forecasts and leveraging them effectively. This process requires hydrologic models that support reliable streamflow forecasts, and it also requires the use of risk-based reservoir models that allow reservoir operators to use streamflow forecast information effectively. More broadly, the software that USACE uses to evaluate WCP alternatives needs to be able to consider forecasts and their uncertainty. This section describes efforts to advance streamflow forecasting and their use in the following ways:

- Improvement of streamflow simulation and prediction through the application and evaluation of contemporary hydrologic models (Section 5.4.1). This provides a pathway for transformative operational changes that may lead toward improved FIRO outcomes in the future.
- Refinements to the EFO model and its application (Section 5.4.2). These refinements allow reservoir operators to more effectively leverage forecast streamflow ensembles, and they improve representation of operational conditions—both physical and policy conditions. This leads to more robust analyses and improved WCM application.
- Enhancements to USACE Hydrologic Engineering Center (HEC) models to ensure that USACE can robustly evaluate and ultimately accept FIRO WCPs for potential application in WCMs (Section 5.4.3).

Section 5.4.4 summarizes recommendations for future efforts in all these areas.

5.4.1 Hydrologic Modeling

Improvements in tracking, understanding, and predicting the hydrology of the Russian River basin provide a stronger basis for Lake Mendocino FIRO. Hydrologic models can be improved with good observational data, careful calibration, and realistic representation of local hydrologic and hydrogeologic conditions. The Lake Mendocino FIRO team has made significant progress in this area, such as by:

- Implementing a multi-agency observation network in the Russian River basin above Lake Mendocino, with measurements including rainfall, soil moisture, streamflow, and hydrogeochemistry.
- Developing, calibrating, and verifying WRF-Hydro and GSSHA distributed hydrologic models of the Lake Mendocino watershed.
- Developing infrastructure to ingest West-WRF meteorological forcing into GSSHA and WRF-Hydro.
- Developing a novel calibration technique using distributed soil moisture information to set parameters in the WRF-Hydro gridded hydrologic model.

Project team members continue to investigate new hydrologic modeling capabilities and hydrologic observations to identify ways to improve streamflow forecasts associated with AR events over the Lake Mendocino watershed. These investigations support the FIRO objective to better operate reservoirs for authorized purposes using precipitation and hydrologic forecasts. The Lake Mendocino FIRO project team specifically addressed the PVA’s recommendation to evaluate emerging watershed and runoff forecast systems such as the NOAA National Water Model (NWM) and USACE’s GSSHA model. These enhanced watershed runoff models represent key physical processes, including surface-groundwater interactions, and integrate uncertainty associated with observations, model states and model formulation, and future meteorological forcings. This subsection provides a high-level overview of hydrologic modeling efforts to support the FVA. A more detailed description can be found in Appendix E, along with supporting technical reports.

5.4.1.a Russian River Hydrometeorological Observing Network (RHONET)

As described in Section 5.3.2, the newly enhanced multi-agency RHONET monitoring network collects data associated with extreme AR events that lead to flooding in the Russian River basin. This network supports FIRO by providing observations to better understand atmospheric and hydrological processes in the basin, as well as forcing data for developing hydrologic models. Thus, RHONET supports hydrologic model development, calibration, and coupling with West-WRF.

5.4.1.b GSSHA Model

As part of the Lake Mendocino FIRO project, CW3E and ERDC demonstrated a state-of-the-art atmospheric and hydrologic modeling system formed by coupling the West-WRF and GSSHA models for the upper Russian River watershed above the Hopland gauge. West-WRF meteorological forcing drives the GSSHA model, which is a physics-based, spatially explicit hydrologic model that continuously simulates processes relevant to the hydrologic response of a watershed. Processes modeled include rainfall distribution, canopy interception, surface retention, evapotranspiration, vertical infiltration, two-dimensional overland flow, one-dimensional channel flow, two-dimensional groundwater flow for the unconfined aquifer system and surface water-groundwater interaction, lake/reservoir levels, and snow accumulation and melt.

Specific research questions focused on better understanding the physical hydrologic processes in the watershed; assessing the ability of the GSSHA model to simulate streamflow, reservoir levels, and soil moisture; assessing the impact of model resolution on these parameters; assessing the ability of the GSSHA/West-WRF system to forecast hydrologic conditions; and determining a water balance for the watershed. Through this research, CW3E completed the following tasks:

- Gathered, analyzed, and prepared existing data; filled historical data gaps with RHONET data.
- Developed hydrologic models of varying resolutions.
- Coupled the hydrologic models to the West-WRF atmospheric model.
- Calibrated and validated the models using streamflow, reservoir level, and soil moisture records.
- Developed a water balance for the watershed and reservoir.
- Incorporated the GSSHA model into the UCAR data assimilation system.
- Assessed the impact of utilizing assimilation for GSSHA modeling, specifically at Lake Mendocino.

Comparison of pre- and post-CW3E data collection efforts indicated that enhanced observations set greatly improved the calibration of the GSSHA model. Verification of the calibrated model indicated that the GSSHA model, when forced by observed precipitation, could simulate daily streamflow with a high degree of confidence during the 2018/2019 rainy season (Figure 5.7). Streamflow forecasts driven with short-term West-WRF forecasts were good for day one, deteriorated at day three, and were poor by day five. Analysis indicated a bias in West-WRF precipitation, with volumes decreasing as the forecast lead time increased. Study details are available in Appendix E.

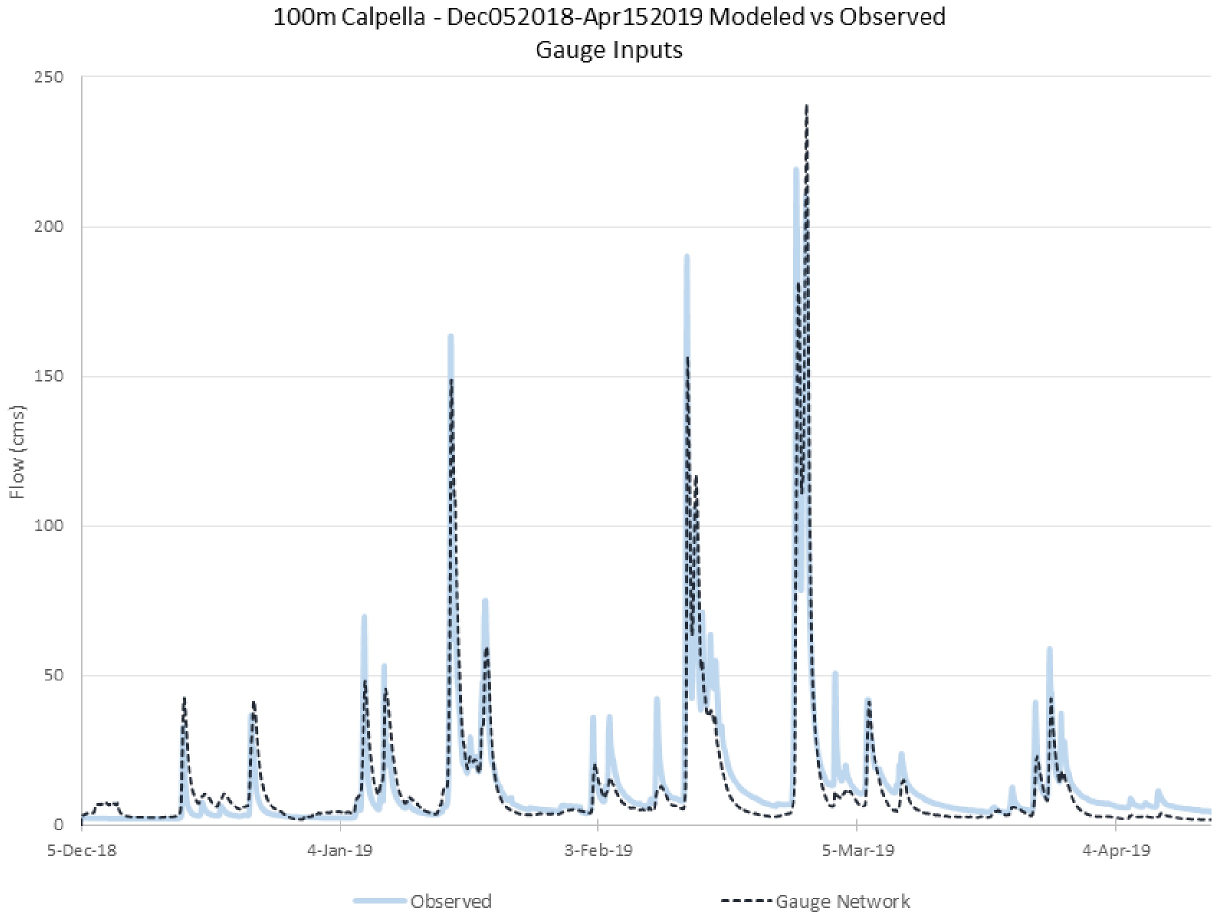

Figure 5.7. *Comparison of GSSHA model simulated (black dashed line) and observed (blue solid line) flow using observed precipitation.*

Although GSSHA was not the hydrologic model used to evaluate FIRO WCPs, the research described here provides a path, beyond the FVA, towards improved operational forecasts. Meteorological-hydrological model coupling schemes can improve future FIRO outcomes through more contemporary and modern hydrologic modeling schemes. Section 5.4.4 provides several specific recommendations in this regard.

5.4.1.c WRF-Hydro

The Lake Mendocino FIRO team explored the WRF-Hydro model as a potential pathway for transformative change leading to improved streamflow predictions in support of FIRO testing and potential implementation. CW3E used the Lake Mendocino watershed region of the National Center for Atmospheric Research's WRF-Hydro v5.0 (1 km), mirroring the configuration of the NWM, a hydrologic model developed by NOAA's Office of Water Prediction (https://water.noaa.gov/about/nwm). A combined West-WRF and WRF-Hydro system is particularly advantageous for FIRO because the WRF-Hydro model is available nationwide through the NWM. This means that the hydrologic model used is part of (and leverages) the national efforts and resources associated with the NWM. WRF-Hydro offers an opportunity to scale the use and investments of distributed hydrologic modeling from an official national tool. Model skill in simulating streamflow and soil moisture were evaluated in the watershed, using forcings from the National Land Data Assimilation System v2 as well as West-WRF output.

Although WRF-Hydro captures synoptic-to-annual variations in soil moisture, calibration is needed because the model underestimates diurnal and local variations. A new calibration technique that uses distributed soil moisture information has been developed to improve soil parameters representation in WRF-Hydro. Specifically, the project team has used sensitivity analysis to determine which model parameters affect soil moisture simulations the most and, therefore, should be addressed (i.e., modified) in calibrating the model. Thus far, the team has explored the sensitivities for 13 model parameters and identified the parameters that exert strong control on soil moisture, channel roughness, and runoff and infiltration rates in the Lake Mendocino watershed. Initial results suggest that important parameters are moisture maximum, beta exponent, saturated soil hydraulic conductivity, runoff/infiltration rate, and Manning's Roughness.

Soil moisture observations collected through RHONET have been used to capture spatial, temporal, and depth variations in soil moisture and runoff characteristics. Some applications that have been enabled by the availability of these observations include characterizing the soil wet-up and dry-down processes during AR events and WRF-Hydro model calibration. Particularly, the availability of observation at six depths (5, 10, 15, 20, 50, and 100 cm) at each observation site has helped reveal the different soil moisture behavior between the shallow (5–20 cm) and deep (50–100 cm) layers. Capturing these two distinct behavioral layers is important to determine the soil depth below which the influence of evapotranspiration diminishes and the saturation dynamics change, which the model should emulate. In addition, soil moisture samples from the two-minute observations have also helped capture the soil field capacity, the point above which groundwater has had the capability to recharge and exfiltrate, leading to increased runoff. For instance, Sumargo et al. (2020a) found that runoff was about 2.6 times greater in precipitation events where the antecedent soil moisture had reached field capacity. Furthermore, this study also found that soil moisture responses to precipitation events were well correlated on seasonal timescales, but highly variable at event timescales. These results highlight the importance of sampling the different soil moisture characteristics at different sites within the watershed, which control runoff responses in important tributaries. Calibration methods will be designed and evaluated with these specific observational characteristics in mind. Additional information about these studies is available in Appendix E.

5.4.2 Reservoir Management Tools

As part of the PVA, Sonoma Water developed an innovative reservoir model, called the EFO model, that incorporates official ensemble streamflow predictions of inflows to Lake Mendocino and downstream contributing areas and applies a risk-based approach to calculate appropriate flood-control release responses (Delaney et al. 2020). The ensemble streamflow predictions used by the model are issued up to four times a day by CNRFC using the Hydrologic Ensemble Forecast System. The EFO model simulates each member of an ensemble streamflow prediction individually to forecast system conditions and calculate the risk of reaching critical operational (storage) thresholds. The EFO model is described in the Lake Mendocino PVA and in Delaney et al. 2020 (Appendix F). The simulation and evaluation of the EFO completed for the PVA had several shortcomings that have been addressed through the research and development associated with this FVA.

Accomplishments of this effort include:

- Modification of the EFO computational time step from daily to hourly.
- Extension of EFO-model considerations downstream to Guerneville, as the PVA analysis stopped at Healdsburg.
- Scaling of selected historical events (1986, 1995, 1997, and 2006) to 100- and 200-year return period levels to explore model and system performance associated with extreme events.
- Risk curve refinements, explorations, and evaluations reflecting optimization, seasonality, and multiple objectives.

The details of this work are provided in Appendix F. These efforts were essential to the results described in Sections 3 and 4.

5.4.3 USACE HEC Software

For USACE to more broadly-adopt FIRO-based WCPs as described in Sections 3 and 4, tools are needed to adequately evaluate changes in risk associated with the proposed alternatives. The guidance document Engineer Regulation 1105-2-101 requires USACE to adopt a risk framework in which the values of all key variables, parameters, and components of flood risk management studies are subject to analysis of their variability and uncertainty. As a result, USACE requires probabilistic analysis of a broad range of variables, including precipitation characteristics, reservoir operations, and hydraulic parameters. Existing USACE-HEC tools can already incorporate uncertainty in key flood risk variables to a great extent, including input and parameter uncertainty in the hydrologic modeling software HEC-HMS and the reservoir modeling software HEC Reservoir System Simulation (ResSim). In addition, the HEC Watershed Analysis Tool (WAT), a planning tool that integrates other HEC software, performs Monte Carlo simulations in support of uncertainty analysis.

The advent of FIRO adds another type of input data that HEC software tools must be able to accept and apply forecasts and their uncertainty. Forecast uncertainty is an essential component of risk when the forecasts affect reservoir operations, and ensemble forecasts add a further dimension to software tool development. The ability to ingest and use ensemble forecast data and pass corresponding model results between software applications is a significant challenge, given the sheer volume of data involved. For example, a representative ensemble forecast data set consists of daily forecasts (one per day) of hourly time steps, for a 14-day forecast period with approximately 60 traces at each location. A 50-year record of these data for six model input locations corresponds to 13 gigabytes of storage.

Another challenge is the need to look beyond the historical record of forecasts and observations at larger synthetic events to evaluate changes in flood risk corresponding to changes in reservoir operations. HEC-WAT currently supports evaluation of thousands of flow or precipitation events, with the goal of defining model results across the full probability space. However, these synthetic events do not have associated forecasts. Methods of generating meaningful artificial ensemble streamflow forecasts are being developed as part of a separate research effort. In the interim, HEC has developed a simple ensemble generation method based on actual flows and precipitation. While the patterns are not expected to closely mimic actual forecasts, they will produce the correct error distributions.

5.4.4 Opportunities for Future Gains

5.4.4.a Hydrologic Modeling

The project team embraced interagency collaboration to develop and test GSSHA and NWM hydrology models to support FIRO. These efforts helped to improve understanding and the structure of hydrologic models and forecasts by integrating observations, model development and verification, and ensemble development. These improvements will provide context for transformative changes in operational hydrologic modeling and operational practices in the future, which will lead to improved FIRO outcomes. Recommendations to enhance hydrologic modeling benefits to FIRO include:

- Maintain RHONET to support long-term process understanding, model improvements, and eventually model inputs for improved hydrologic predictions.
- Develop methods to produce representative ensembles that more fully capture meteorological and hydrological uncertainty.
- Focus on hydrologic model improvements that will be beneficial across multiple watersheds, as FIRO extends beyond Lake Mendocino.
- Analyze West-WRF and NWM re-analyses and observations to improve understanding and representations of pre- and post-storm land surface and drainage processes and fluxes that control soil moisture dry-down and wet-up rates.
- Analyze the influence of spatial variation in meteorological and hydrological variables on the contributions that various tributaries make to the total flow into Lake Mendocino.
- Focus forecast validation efforts on lead times of greatest utility for FIRO decision support.
- Continue soil moisture calibration efforts.
- Develop an operational version of the GSSHA model to be tested at Lake Mendocino, improve application with West-WRF by calibrating to different West-WRF lead times and/or bias-correcting the West-WRF forecast, and improve the GSSHA model by parallelizing more processes and developing a data assimilation version of the model.

5.4.2.b Reservoir Management Tools

Given the importance of the EFO model to FIRO implementation, continued research, exploration, and improvement beyond that developed for the FVA is warranted to realize achievable gains and improve potential transferability to other systems. The following EFO model recommendations will benefit FIRO as applied to Lake Mendocino and elsewhere:

- Develop and optimize risk tolerance curves to incorporate more sophisticated optimization methods.
- Explore multi-objective approaches to improve storage reliability, flood risk reduction, and other authorized purposes.
- Reorganize and generalize the EFO code to facilitate development of EFO models for other reservoir systems.
- Develop a methodology for generating synthetic ensemble forecasts—consistent in character with those operationally issued by CNRFC—to evaluate and optimize EFO over a wider range of hydrologic possibilities.

5.4.4.c USACE HEC Software Enhancements

HEC began work in fall 2019 to develop software tools needed to support the use of ensemble forecasts. These ongoing efforts are critical to FIRO development and the envisioned integration of FIRO WCPs in future WCMs within the next one to two years. The major HEC software development tasks necessary to support evaluation of ensemble forecasts consist of:

- Creating ensemble forecast data storage capability.
- Adding the ability to visualize ensemble forecast data.
- Modifying HEC-HMS and HEC-ResSim to use ensemble forecast data.
- Modifying HEC-WAT to support analyses using ensemble forecast data.
- Validating tools for a test watershed.
- Developing user and technical documentation.

5.5 Benefits

Economic assessment was a critical part of this project, given the desire to implement FIRO in a way that maximizes benefits to a wide range of water users and stakeholders. To this end, ERG, Inc., with the input of Sonoma Water and members of the Steering Committee, conducted an assessment to quantify economic benefits of FIRO for dam operations, water supply, environment, recreation, and hydropower. The relative benefits of the FIRO alternatives were compared in the hydrologic engineering management plan (HEMP). The analysis described here puts the relative benefits in monetary terms so policy makers and decision makers can understand the payoff resulting from modest investments in FIRO.

The team also conducted a flood risk management study to quantify FIRO's benefits for flood risk management, as well as a detailed assessment to ensure that FIRO operations will have no negative impacts on fisheries—and, if possible, will provide positive benefits. This fisheries analysis was critical because the Russian River provides habitat for a threatened population of Chinook salmon, in addition to other temperature-sensitive salmonid species such as steelhead trout.

This section summarizes methods and results for the following analyses:

- Economic benefits associated with various water uses, as well as reduced operation, maintenance, and replacement costs (Section 5.5.1). For this analysis, the team compared baseline operations with EFO and Modified Hybrid Operations—the two options that performed the best according to the HEMP metrics. The Modified Hybrid alternative results in total estimated annual benefits of $9.4 million. The EFO alternative has estimated total annual benefits of $9.9 million.
- Flood risk management (Section 5.5.2). This study found no significant difference between the baseline and the FIRO alternatives when measuring damages to structures and contents of structures. However, when considering population at risk in addition to these damages, all FIRO alternatives significantly reduce risk upstream of Hacienda Bridge, near Guerneville.
- Water temperature effects on fisheries (Section 5.5.3). This analysis concluded that EFO and Modified Hybrid Operations would offer the greatest benefits.

- Frequency of high flows, which can affect migratory cues for anadromous fish species (Section 5.5.4). This flow study did not assess benefits but, rather, concluded that FIRO is unlikely to negatively affect Chinook salmon.

More detailed results can be found in Appendices G and H. Section 5.5.5 suggests additional analyses that could improve understanding of the benefits of FIRO.

5.5.1 Economic Assessment of FIRO Benefits

This analysis assesses the economic benefits of FIRO under Modified Hybrid Operations and the EFO alternative, compared with baseline operations. Six benefits were quantified using methods developed by ERG, with input from economists at CW3E, the U.S. Bureau of Reclamation, USACE, Highland Economics, NOAA Fisheries, and HDR, Inc. The benefits assessed were:

- Irrigation water supply
- Municipal and industrial water supply
- Hydropower
- Fisheries
- Recreation
- Operation, maintenance, and replacement costs

FIRO impacts on Lake Mendocino water levels form the basis of all benefits assessments. Water levels were estimated using data from a 33-year hindcast from January 1, 1985, through September 30, 2017 (Table 5.1). For each benefit, the team calculated the average annual amount over this hindcast period. All benefits are presented in 2019 dollars. When necessary, the Bureau of Labor Statistics' Consumer Price Index for All Urban Consumers (CPI-U) was used to convert figures to 2019 dollars.

Table 5.1. *Summary of marginal average annual FIRO benefits (1,000s of 2019 dollars).*

Benefit Type	Modified Hybrid	EFO
Total	$9,361.4	$9,872.2
Agriculture water supply [a]	$114.1	$118.4
Municipal and industrial water supply	$2,674.6	$2,778.9
Hydropower [b]	-$1.9	-$43.8
Fisheries [c]	$5,726.4	$5,726.4
Recreation	$802.7	$1,239.2
Reduced operation, maintenance, and replacement costs	$45.5	$53.0

[a] This analysis is expected to underestimate total benefits because it only reflects the average marginal value.

[b] The negative annual benefit is due to the retention of a WCM rule in FIRO alternative simulations that terminates hydropower production at reservoir elevations above 755 feet to prioritize flood control operations. This rule would likely be eliminated with any FIRO alternative, resulting in positive hydropower benefits.

[c] This estimate uses the cost to raise the height of Coyote Valley Dam as a proxy for benefits. The alternative method using water transaction prices results in larger values.

5.5.1.a Irrigation Water Supply

In general, water used for frost protection of wine grapes and for crop irrigation can result in improved quality and quantity of agricultural goods, which leads to an economic benefit from avoided crop losses. FIRO can help attain that economic benefit by using better forecasting and allowing reservoir operations to change based on the predicted incoming flow.

The analysis focused on wine grapes because they are the dominant crop in the region. Results for wine grapes were then extrapolated to other crops. Depending on the crop, the value of an acre-foot of water ranges up to $634.

To estimate the additional FIRO water supply for irrigation, the volume below the target storage level was used as a proxy for water scarcity. The amount by which FIRO can reduce this deficit then represents a benefit in the form of increased water reliability. Average annual increases in water reliability were 1,480 and 1,536 acre-feet for the Modified Hybrid and EFO alternatives, respectively. For the purposes of this estimate, half of the additional reliability was attributed to irrigation and half to municipal and industrial users.

The results showed average annual benefits of $114,079 under the Modified Hybrid alternative and $118,394 under the EFO. In times of low seasonal runoff, benefits could exceed $775,000 annually.

5.5.1.b Municipal and Industrial Water Supply

FIRO operations at Lake Mendocino could increase the reliability of water supplies for municipal, commercial, and industrial users (hereinafter, "municipal and industrial"). To quantify this increase, the project team used a revealed preference approach to estimate the demand curve for municipal and industrial water and used the price elasticity of demand to quantify changes in consumer surplus due to an increase in water reliability. The price elasticity of demand is a measure of the change in the quantity of a good or service demanded based on a change in the price of that good or service—in this case, water. Elasticity was then used to generate a demand curve and calculate how price might change due to a change in water reliability. By comparing the old and new prices and quantities, it is then possible to calculate the change in consumer surplus. Section 5.5.1.a above described the change in water availability, half of which was attributed to municipal and industrial users.

The project team estimated an increase in consumer surplus of $2.7 million under the Modified Hybrid alternative and $2.8 million under the EFO. For comparison, the team also conducted a sensitivity analysis that assumed no change in price because of the increase in water reliability. Under these conditions, the Modified Hybrid will lead to an estimated annual benefit of $1.04 million, and the EFO a benefit of $1.08 million.

5.5.1.c Hydropower

The project team calculated the benefit from hydropower by multiplying the average wholesale electricity price ($/MWh) by the power generation (MWh) for each of the alternatives. This analysis used the following inputs:

- Historical wholesale price data compiled for the Northern California hub (NP-15). This study used the weighted average daily price for NP15 EZ Gen DA LMP Peak electricity from 2010 to 2019 to estimate average monthly prices.
- Daily hydroelectric power production values as determined in the HEMP analysis.

In aggregate, the Modified Hybrid and EFO alternatives are predicted to generate $1,868 and $43,750 per year less in benefits, respectively, compared with baseline operations. This decrease occurs because the simulation of FIRO alternatives retained a WCM rule that terminates power generation above elevation 755 feet to give priority to flood control operations. This rule would likely be eliminated with any FIRO alternative, resulting in positive hydropower benefits for the Modified Hybrid and EFO alternatives.

5.5.1.d Fisheries

By increasing the water level stored in the reservoir, FIRO may reduce water temperature and improve streamflow at times that are critical for migration and spawning, thus benefiting fisheries. Additionally, it could allow better controlled releases from Lake Mendocino, which will reduce turbidity. To monetize this benefit, the project team conducted an abbreviated least-cost alternative analysis. This method considers alternative projects that would result in the same impact as the proposed project. The cost of the least-cost alternative that would achieve the same goal is then used to estimate the benefit. A full least-cost alternative analysis would consider all feasible options that would achieve the same impact on fisheries. Because conducting a full least-cost alternative analysis was beyond the scope of this project, the team selected an alternative that has been previously considered, such that some cost information was available.

The economics team consulted with fisheries experts to identify temperature and streamflow as the key salmonid metrics that can be correlated with FIRO operations. Raising Coyote Valley Dam would achieve similar impacts to temperature and streamflow, and consequently similar benefits to salmonid populations. Raising the dam has been considered in the past, although this option is not actively being considered. However, this is an appropriate alternative to consider for the purposes of this report.

Based on guidance from Sonoma Water, the team assumed that raising the dam by 6 feet would result in roughly equivalent streamflow and temperature benefits for fisheries as FIRO alternatives. The cost to raise the dam by 6 feet has not been calculated in an engineering study. To estimate that cost, the project team used the estimated cost to raise the dam by 36 feet and applied assumptions to approximate the cost for a 6-foot increase. If the dam is expected to last 50 years, the annualized value discounted at 2.75 percent would be $5.73 million.

5.5.1.e Recreation

FIRO can lead to increases in quantity and quality of recreation at Lake Mendocino and on the Russian River. The project team estimated the increased level of recreational activity due to increased water levels at Lake Mendocino using multivariable regression analysis, then applied unit day values to those increased recreation levels.

The USACE provided data on historical recreational usage. Using these data, the project team developed a use estimating model to evaluate how usage would change under FIRO operations. Ordinary least squares regressions were used to determine the relationship between surface area and monthly recreation. The analysis used three log-log models for three types of recreation: camping, boating and fishing, and general recreation.

Analysts applied coefficients to the estimated daily storage levels at Lake Mendocino from October 2001 until September 2017 under the baseline and FIRO alternatives. They averaged monthly predictions over the 16-year period and then multiplied by 12 months to reflect the annual average. FIRO’s impact on recreation is the difference between the predicted recreational levels under the baseline and the two FIRO alternatives. Average annual visitation increases by approximately 18,000 people under the Modified Hybrid alternative and 27,000 people under the EFO alternative.

Next, a dollar value needs to be placed on the increased recreational usage. This analysis used unit day values from Bowker et al. (2009), adjusted to 2019 dollars. These adjusted unit day values range from $23 to $92, depending on the activity. The value of increased recreation is then calculated as the product of the increased levels of recreation and unit day values. Benefits under the Modified Hybrid alternative total slightly more than $800,000 per year, while benefits under the EFO alternative total $1.2 million per year.

5.5.1.f Reduced Operation, Maintenance, and Replacement Costs

FIRO may result in a reduction in the cost of environmental reviews because there may be fewer Temporary Urgency Change Petitions. Each of these petition costs approximately $250,000. Using data from 1985 to 2017, the project team identified instances where FIRO could have avoided these petitions. The team estimated that the Modified Hybrid approach would reduce the prevalence of these events by 18.2 percent and the EFO alternative would reduce the prevalence by 21.2 percent. This results in an estimated annual average savings of $45,400 for the Modified Hybrid alternative and $53,000 for EFO.

5.5.2 FIRO Flood Risk Management Improvement Potential

The project team developed and engineered the FIRO WCP alternatives to avoid negative impacts on flood risk management. However, the alternatives achieved incidental benefits to flood risk management as well as environmental objectives over the baseline WCM procedures. This section describes the incidental benefits provided to flood risk management by applying WCPs that leverage streamflow forecasts.

Flood risk management benefits (Table 5.2) will most likely accrue for more extreme flood events where the original design of the WCM was expected to result in emergency spillway activation (e.g., greater than a 0.02 annual exceedance probability or a 50-year event). This incidental flood risk management benefit is an important adaptation tool, as the frequency of extreme events is expected to increase in the coming decades (Dettinger 2016; Gershunov et al. 2019).

Table 5.2 compares expected annual damage (EAD) from inundation for baseline and FIRO WCP alternatives. The project team computed EAD through a Monte Carlo sampling of the stage-frequency curves derived from the hydraulic routing of the simulated regulated streamflow at multiple locations. Damages are accrued through the intersection of inundation with known structures and assets.

Table 5.2. *EAD values for each WCP alternative in $1,000.*

EAD ($1,000) by WCP Alternative					
Location	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
Hopland	104.1	101.1	98.5	100.6	103.7
Cloverdale	703.0	719.3	705.6	705.6	706.4
Geyserville	191.7	185.2	189.7	189.7	189.4
Healdsburg	542.2	532.2	533.1	535.0	540.8
Dry Creek	2.6	2.7	2.7	2.7	2.7
Windsor	265.6	259.6	258.5	258.5	260.2
Santa Rosa	1,121.1	1,119.9	1,104.0	1,100.5	1,122.8
Green Valley Creek	648.7	631.9	616.0	617.9	628.5
Guerneville	11,282.2	11,207.3	11,065.8	11,050.0	11,274.2
Monte Rio	369.8	366.7	364.5	363.8	370.1
Total EAD	**15,231.1**	**15,125.7**	**14,938.3**	**14,924.2**	**15,198.7**

The analysis found no significant difference between the baseline and any of the FIRO WCP alternatives. However, there are other ways to measure and represent impacts on flood risk management. In a simulation of the January 2006 flood event, all of the FIRO WCPs significantly reduce damage and populations at risk upstream of Hacienda Bridge (near Guerneville), and the reduction is largely eliminated in the lower portion of the watershed where the magnitude of Lake Mendocino releases is small compared with the natural unregulated flow in the basin (Figure 5.8).

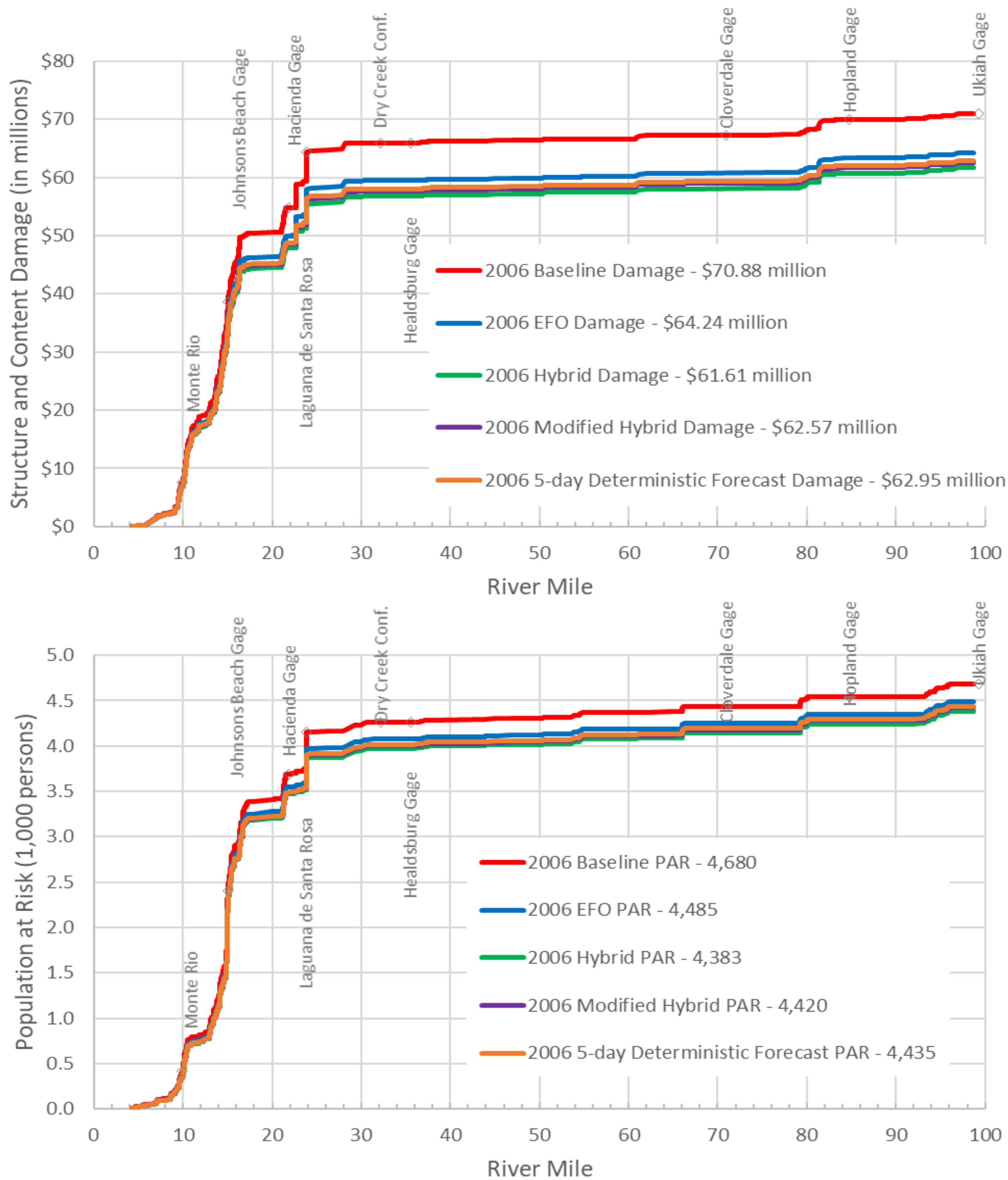

Figure 5.8. *Damage and population-at-risk values along the Russian River for the baseline (red) and each FIRO WCP alternative for the historical January 2006 flood event.*

Preventing uncontrolled releases through the emergency spillway is a potential measure of flood risk management effectiveness. Figure 5.9 shows the annual maximum pool elevation frequency function for Lake Mendocino. Here, the baseline (red) shows spillway activation at an annual frequency of approximately 0.03 (about one in 33 years), while the FIRO WCP alternatives show spillway activation significantly less often. Given the emphasis on avoiding emergency spillway use, this represents a significant benefit to flood risk management.

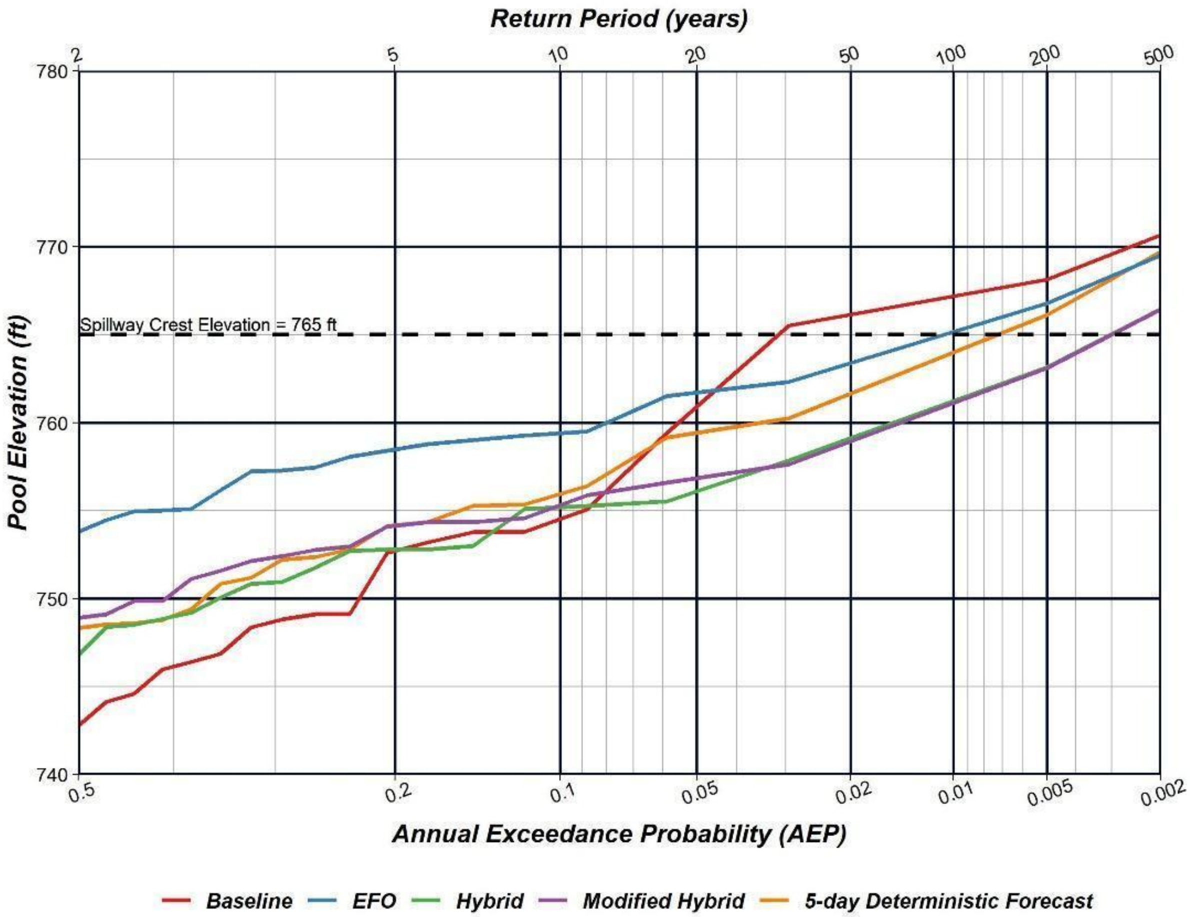

Figure 5.9. *Annual maximum pool elevation frequency function for Lake Mendocino.*

5.5.3 Lake Mendocino and Upper Russian River Water Temperature Model

Chinook salmon are native to the Russian River and are part of the California Coastal Chinook Evolutionarily Significant Unit, which was listed under the federal Endangered Species Act as threatened in 1999. Steelhead trout are another important salmonid species in the Russian River. These fish need cold, clean water to thrive. Thus, the Lake Mendocino PVA recommended: *"Water quality in the reservoir should be evaluated in terms of sediment load and temperature stratification as a component of further evaluation of water availability. The ability to maintain a 'cold water pool' and release cooler water in late summer for salmonid migration should be evaluated."*

The project team addressed this PVA recommendation by modeling scenarios to answer the question, "How would water temperature conditions in the 'cold water pool' in Lake Mendocino influence the upper Russian River cold water tailrace (zone or reach) below the reservoir, and to what extent downstream?" To answer this question, the team investigated the effects of different reservoir storage levels to gain a better understanding of reservoir operation effects on cold water pool storage in Lake Mendocino and associated water temperatures in the upper

Russian River mainstem during the juvenile steelhead trout summer rearing season and the adult Chinook salmon fall migration period.

NOAA Fisheries has monitored upper Russian River stream temperatures and water temperature at different depths in Lake Mendocino during summer and fall since 2015. The team focused on observed data from two recent water years with dry (2015) and wet (2019) conditions. Based on these data, the study team developed a machine learning modeling approach to estimate stream and reservoir water temperatures that influence the quality of salmonid habitat within the upper Russian River.

In general, temperatures in the cold-water zone of the reservoir and upper Russian River tend to be lower for the scenarios with higher reservoir storage levels during the warm summer and early fall months. Conversely, temperatures in the cold-water zone of the reservoir and upper Russian River tend to be higher for the scenarios with lower reservoir storage levels during this same dry-season period. Modeling results demonstrated the benefits of higher reservoir storage levels to maintain cooler water temperatures during the juvenile steelhead trout summer rearing season through the fall adult Chinook salmon migration period. This study corroborates the HEMP assessment of FIRO alternatives, which showed that EFO, followed by the Modified Hybrid, ranked most highly compared with baseline operations, according to the two fisheries metrics used in the HEMP.

NOAA Fisheries has continued its efforts to monitor stream temperature in the upper Russian River and water temperature at different depths in Lake Mendocino during summer through fall 2020. These new oncoming data will provide valuable information to improve the machine learning modeling approach. Although the overall performance of the model is good, there are months in which the performance of the model needs to be improved. Therefore, NOAA Fisheries will perform additional analysis, including selecting the number of lag days for different months or seasons, performing additional training and validation processes, and performing a sensitivity analysis to find the most relevant inputs to the model for different months or seasons.

5.5.4. Environmental Factors Affecting Russian River Chinook Salmon Adult Migration

Sonoma Water has monitored adult fall run Chinook salmon since 2000. Sonoma Water operates a seasonal dam on the Russian River and uses underwater video cameras to count Chinook salmon as they move upstream (Chase et al. 2007). The annual adult population ranges from approximately 1,400 to 6,700 fish (Martini-Lamb and Manning 2014). Adult Chinook have been observed in the Russian River from August through February, with peak migration from October 15 to December 31 (Sonoma Water 2016). Chinook spawning takes place from November through January (Sonoma Water 2008). Chinook have been observed ascending the river when instream flow is as low as 135 cfs at the U.S. Geological Survey (USGS) stream gage 11467000 at Hacienda, and adult Chinook salmon can traverse the upper Russian River when flow is as low as 105 cfs at USGS gage 11463980 near Healdsburg (Smith 2013).

The FIRO project team assessed whether FIRO will negatively affect migration cues by resulting in fewer moderate to high flow events that trigger adult Chinook salmon upstream migration. To explore this hypothesis, the team compiled daily video counts of Chinook salmon along with daily summaries of multiple environmental conditions to determine if Coyote Valley Dam flood control releases were an important factor in triggering upstream migration of Chinook salmon. Daily fish counts were compiled from the underwater video cameras and considered along with daily average flow from dam releases; daily average flow from the USGS stream gages at Hopland, Healdsburg, and Hacienda Bridge; rainfall at the Venado; and stage at the USGS gage at the Highway 1 Bridge near Jenner. Jenner Visitor's Center gage data were used to identify occurrence of river mouth closures, which temporarily block Chinook salmon from entering the Russian River from the Pacific Ocean. In all, the project team investigated 17 years of Chinook migration data and 19 years of environmental data.

This study concluded that FIRO is unlikely to negatively affect the timing of upstream movement of Chinook salmon or the river conditions required for safe passage. Flood releases during the fall are uncommon and are not the typical environmental cue that triggers Chinook to migrate upstream in the Russian River. Seasonality, the absence of a barrier beach at the river mouth, and rain events are likely more typical environmental cues that encourage Chinook salmon to migrate upstream.

5.5.5 Opportunities for Future Gains

The economic benefits estimation demonstrated significant benefits of FIRO at Lake Mendocino. While this study represents a screening level assessment, more in-depth analysis is recommended for more precise benefit determinations. In particular, for fisheries, willingness-to-pay estimates could generate a more reliable estimate than the least-cost method. And, while readily available literature was used to estimate the relationship between water levels and recreation activity, a more extensive review and compilation of the literature, coupled with a Lake Mendocino-specific survey, would be beneficial. This study did not estimate FIRO costs compared with other methods of ensuring water supply reliability. Understanding cost savings of FIRO compared with methods such as infrastructure improvement would go further than this benefits estimation to fully understand the economic impacts of FIRO. Finally, adapting these benefits methods for multiple-reservoir systems is recommended as a next step, as multi-reservoir systems are very common. Lake Sonoma and Lake Mendocino are managed together, for example, and if FIRO is applied to Lake Sonoma in the future, this step should be undertaken.

To better assess FIRO effects on Chinook Salmon adult migrations, the project team recommends continued monitoring of adult Chinook salmon upstream spawning migrations; spawning migrations and spawning activity specifically related to FIRO operations (fall/spring water storage capture and releases); and Chinook salmon population trends in the Russian River. To better understand the relationship between temperature in Lake Mendocino and the upper Russian River, the project team recommends continuing to monitor temperature conditions within Lake Mendocino and the upper Russian River (spring through fall) and establishing temperature thresholds for summer rearing juvenile steelhead trout and adult Chinook salmon for the upper Russian River.

5.6 Conclusion

The data collection and research summarized above and in more detail in Appendices D through H have formed a foundation for FIRO at Lake Mendocino. Extensive observations in the Russian River Watershed demonstrate the importance of observations to verify and initialize models as well as study hydrometeorological conditions important for FIRO. The project team has also developed direct applications to illustrate the viability of FIRO, in addition to demonstrating approaches to improve forecasts and integrating research into forecast tools and benefits estimates to enhance FIRO opportunities.

Initial implementation of FIRO at Lake Mendocino is not a singular event. FIRO creates an environment where ongoing research investments in forecasts and their application yields ever-improving reservoir management outcomes. Ideally, FIRO represents a commitment to continue to conduct research and operationalize it for continual improvement. The research conducted and reported as a part of this FVA is emblematic of this commitment and represents the beginning of the next phase of FIRO for Lake Mendocino.

Section 6. Implementation Strategy

The implementation strategy for Lake Mendocino Forecast Informed Reservoir Operations (FIRO) is structured around driving the results from this Final Viability Assessment (FVA) into an updated Water Control Manual (WCM) where benefits associated with improved water supply reliability and flood risk management can be incorporated and grow over time. The updated WCM will take time to develop, get approved, and be implemented. To realize the immediate gains demonstrated through the Lake Mendocino FIRO project, a major deviation will be requested to cover the time needed to update the WCM manual. The strategy also includes the selection of an initial Water Control Plan (WCP) based on the results of the evaluation described in Section 3, leverages lessons learned through planned major deviations described in Section 4, and a creates a pathway for continued improvement over time as advances in science and technology promote and leverage improved forecast skill as described in Section 5. Finally, the United States Army Corps of Engineers (USACE) process for updating the WCM needs to be initiated and followed with the required level of resources to complete it within a reasonable timeframe.

6.1 Five-Year Major Deviation

Members of the FIRO Steering Committee have requested USACE approval of a multi-year planned major deviation to store additional water above the existing guide curve for the Coyote Valley Dam Lake Mendocino WCM within the shaded region shown in Figure 6.1. This request is the same as the approved major deviations granted by USACE for WY 2020, with the addition that pre-releases by USACE in advance of storm events into the water conservation pool would be allowed under certain conditions, as was provided for in the WY 2020 major deviation. Such pre-releases would be allowed if (1) such a release is recommended by the FIRO decision support tools and (2) Sonoma Water is consulted about the pre-releases and approves of the action in coordination with National Marine Fisheries Service. If approved by USACE, this would result in a maximum additional storage of 11,650 acre-feet between November 1 and February 28. Figure 6.1 shows the existing guide curve for the Coyote Valley Dam Lake Mendocino WCM and the proposed maximum deviation limit. With the Steering Committee recommendation to pursue the Modified Hybrid Ensemble Forecast Operations (EFO) model as the initial WCP in the WCM update, efforts are being made to reflect this plan in the multi-year major deviation. The Modified Hybrid EFO model allows spring refill to begin on February 15th rather than March 1 as shown in Figure 6.1.

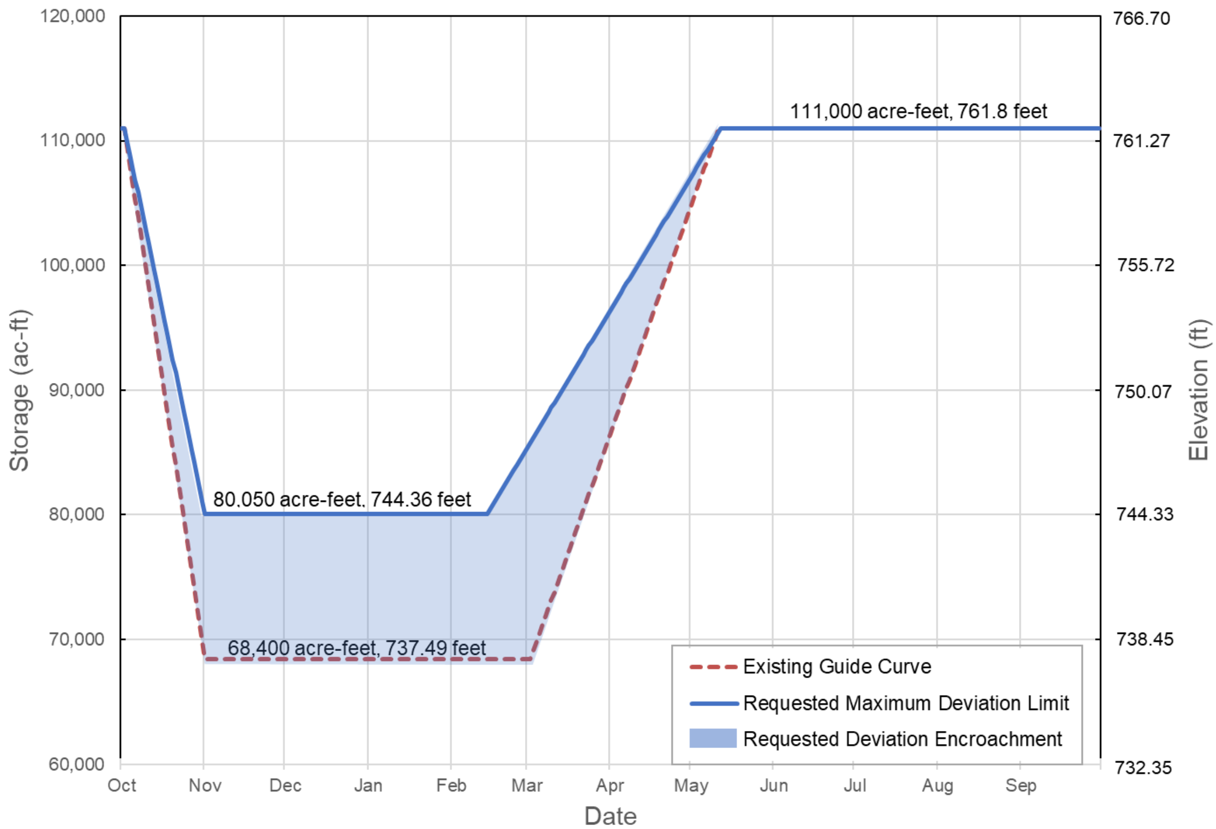

Figure 6.1. *The existing guide curve (red dashed line) and the proposed maximum deviation limit of the flood space encroachment.*

As part of the planned major deviation, members of the Steering Committee will also request that USACE include and leverage the Modified Hybrid EFO alternative developed by Sonoma Water as part of the tools and protocols USACE uses to manage reservoir operations at Lake Mendocino. Based on operational hydrologic ensemble of streamflow forecasts provided by the NWS California-Nevada River Forecast Center (CNRFC), current reservoir storage, and current and anticipated downstream conditions, the alternative provides a recommended release to help inform operational decisions. The formulation and performance of this alternative is described in Section 3 with additional detail in Appendix C.

The formal request and supporting documents for the 5-year major deviation are provided in Appendix D.

6.2 Initial Proposed WCP: Modified Hybrid EFO

The Modified Hybrid EFO model was chosen for the initial WCP of the updated Lake Mendocino WCM. This FIRO alternative:

- Ranks favorably across all metrics compared to baseline (current operations) and other WCP alternatives
- Can be feasibly implemented through either integration or adaptation to USACE standard decision tools, such as the Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim)

- Explicitly uses the uncertainty in streamflow forecasts
- Has a pathway for growth with improving forecast skill and model refinements

Section 3 describes a rigorous process through which four FIRO WCP alternatives were compared to the baseline WCP defined in the 1986 update of the Lake Mendocino WCM. The four FIRO WCP alternatives leveraged streamflow forecasts (Section 2), adhered to a strict set of constraints, and were simulated over a common historical period and for common design events. This evaluation framework allowed for direct comparison through a set of 16 metrics for flood risk management, water supply reliability, environmental condition, recreation, hydropower, dam safety, and workload.

All four of the FIRO WCPs were effective in improving water supply reliability while retaining, or even enhancing, flood risk management and environmental objectives relative to current baseline operations. In addition, all four FIRO WCP alternatives had no negative impact on the operation of Lake Sonoma. Improvements in water supply reliability were measured through metric 10, as the May 10 storage annual exceedance. Figure 6.2 shows the results of metric 10. At the 50 percent level (median), the EFO model provides a 27 percent increase over baseline operations while the other FIRO alternatives provide 15 to 19 percent improvement. This improvement persists across the more important drier years (50 percent exceedance and above).

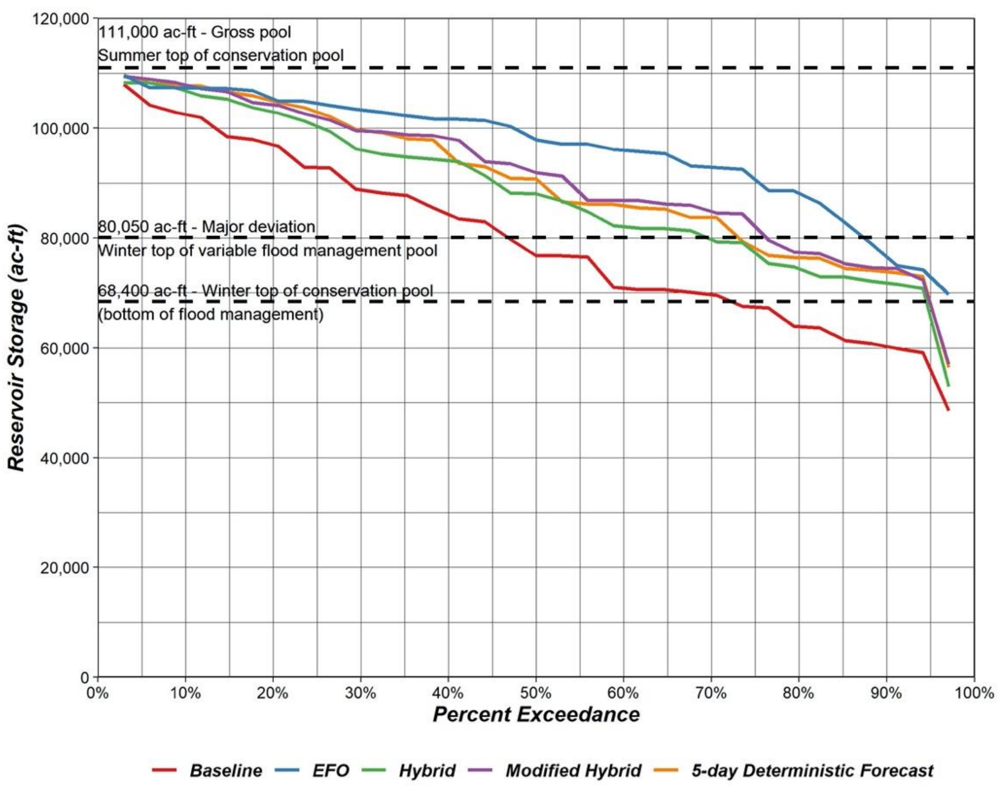

Figure 6.2. *Improvements in water supply reliability as measured by metric 10, May 10 Lake Mendocino storage exceedance. Results from the evaluation are reported in Section 3.*

Table 6.1 shows the expected annual inundation damage (EAD) for the baseline and four FIRO WCP alternatives. This summary suggests there is no significant difference in EAD due to operations any of the FIRO WCPs tested. This was expected as the major impact areas are well downstream of Lake Mendocino, where uncontrolled runoff dominates the flooding. Together, Lake Mendocino and Lake Sonoma only control about 15 percent of the Russian River drainage area.

But EAD does not really tell the complete story. Figure 6.3 shows the annual maximum pool elevation frequency for Lake Mendocino associated with the alternatives. Here we can see that all of the FIRO WCPs reduce the frequency for which the reservoir elevation exceeds the sill of the emergency spillway compared to the Baseline WCM and that the Hybrid and Modified Hybrid alternatives provide the lowest frequency of annual spillway activation.

Table 6.1. *EAD summary by location for the Russian River below Lake Mendocino. Results from the evaluation are reported in Section 3.*

EAD ($1,000) by WCP Alternative					
Location	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
Hopland	104.1	101.1	98.5	100.6	103.7
Cloverdale	703.0	719.3	705.6	705.6	706.4
Geyserville	191.7	185.2	189.7	189.7	189.4
Healdsburg	542.2	532.2	533.1	535.0	540.8
Dry Creek	2.6	2.7	2.7	2.7	2.7
Windsor	265.6	259.6	258.5	258.5	260.2
Santa Rosa	1,121.1	1,119.9	1,104.0	1,100.5	1,122.8
Green Valley Creek	648.7	631.9	616.0	617.9	628.5
Guerneville	11,282.2	11,207.3	11,065.8	11,050.0	11,274.2
Monte Rio	369.8	366.7	364.5	363.8	370.1
Total EAD	**15,231.1**	**15,125.7**	**14,938.3**	**14,924.2**	**15,198.7**

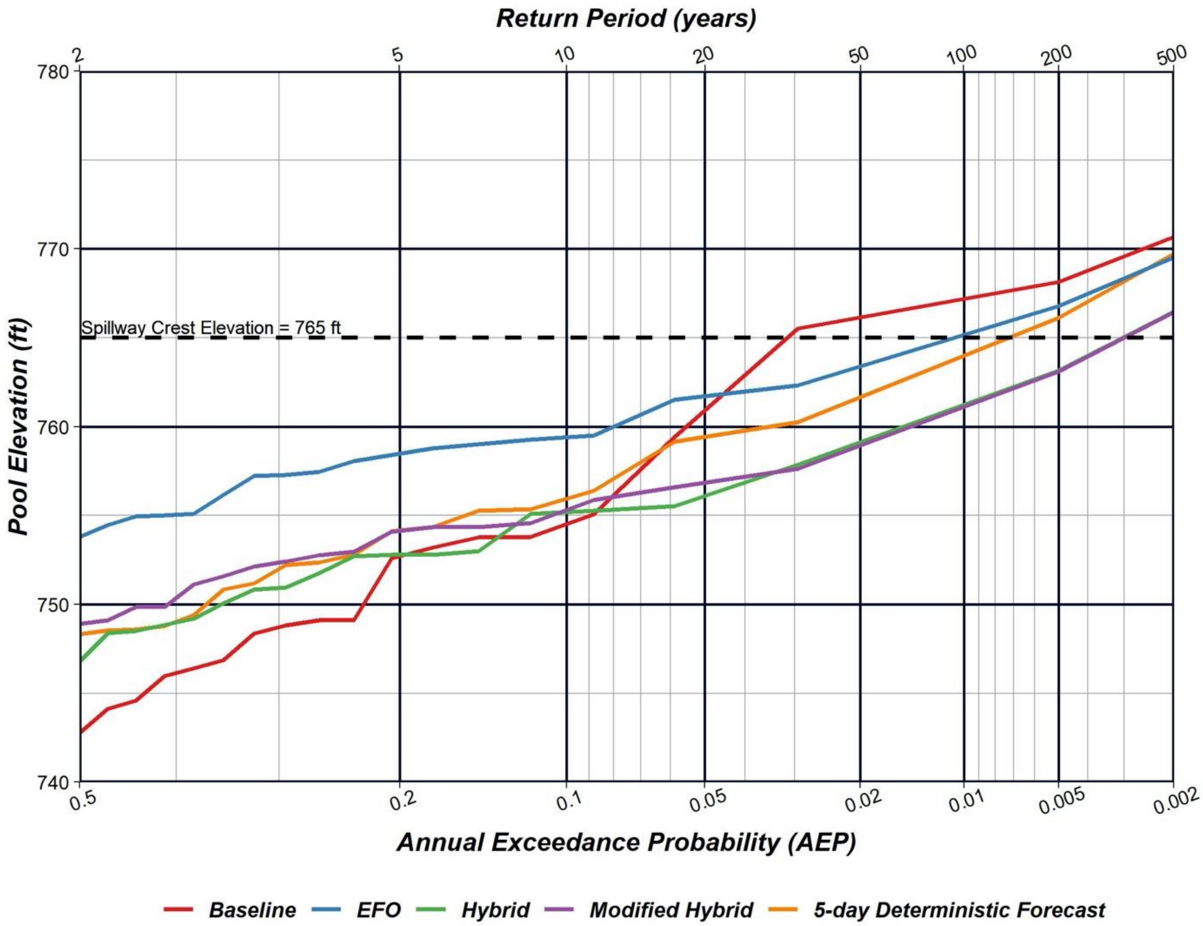

Figure 6.3. *Frequency of annual maximum pool elevation for Lake Mendocino. Results from the evaluation are reported in Section 3.*

As a part of the Section 3 evaluation, the 16 metrics were objectively ranked from 1 (most effective) to 5 (least effective) among the five alternatives (four FIRO and the Baseline WCM) and summarized into flood risk management, water supply reliability, environmental condition, and other objectives. Table 6.2 shows the results from this objective summarization process. Details on the process are available in Appendix B.

Table 6.2. *Summary of objective metric ranking process.*

Rank of WCP alternative by flood risk management metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M1	5	3	1	1	4
M2	5	3	1	1	3
M4	5	3	1	1	4
M6	5	4	2	1	3
M8	1	1	1	1	1
M9	1	1	1	1	1
Average	**3.7**	**2.5**	**1.2**	**1.0**	**2.7**

Rank of WCP alternative by water supply and environmental metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M10	5	1	4	2	3
M11	5	1	2	2	2
M12	5	1	4	2	3
Average	**5.0**	**1.0**	**3.3**	**2.0**	**2.7**

Rank of WCP alternative by recreation, power, dam safety, and operations metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M13	1	5	1	4	3
M14	4	5	1	1	1
M15	1	5	2	2	4
M16	2	1	3	4	5
Average	**2.0**	**4.0**	**1.8**	**2.8**	**3.3**

Rank of WCP alternative by Lake Sonoma flood risk management metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M3	1	1	1	1	1
M5	1	1	1	1	1
M7	1	1	1	1	1
Average	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

In addition to the objective rankings, participants of the June 2, 2020, briefing on the Section 3 results were asked to rank the performance of each WCP alternative (four FIRO and the Baseline WCM) as the results for each metric were presented. Sixteen individuals participated in the ranking, with half being Steering Committee members. The results from this ranking are shown in Table 6.3 There was a high level of consistency between the objective and participant ranking results.

__Table 6.3.__ Summary of participant rankings from June 2, 2020, briefing.

Average votes of WCP alt by flood risk management metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M1	4.0	2.0	1.5	1.4	2.1
M2	4.3	3.4	1.5	1.5	3.0
M4	4.5	2.8	1.3	1.0	2.8
M6	4.5	3.4	1.3	1.0	3.1
M8	3.9	2.6	1.4	1.3	2.6
M9	4.1	2.0	1.3	1.3	2.2
Average	**4.2**	**2.7**	**1.4**	**1.3**	**2.6**

Average votes of WCP alt by water supply and environmental metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M10	5.0	1.0	2.7	2.1	2.4
M11	4.9	1.1	2.4	2.4	2.3
M12	4.9	1.2	2.8	2.4	2.3
Average	**4.9**	**1.1**	**2.6**	**2.3**	**2.4**

Average votes of WCP alt by recreation, power, dam safety, and operations metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M13	1.6	4.4	2.9	3.1	2.9
M14	2.0	4.4	1.7	1.9	1.7
M15	1.3	4.8	2.2	2.0	2.6
M16	2.2	1.2	2.9	3.0	4.3
Average	**1.8**	**3.7**	**2.4**	**2.5**	**2.9**

Average votes of WCP alt by Lake Sonoma flood risk management metrics					
Metric ID	**Baseline**	**EFO**	**Hybrid**	**Modified Hybrid**	**Five-Day Deterministic Forecast**
M3	2.2	1.7	2.0	1.9	1.8
M5	1.1	1.1	1.1	1.1	1.1
M7	1.4	1.3	1.1	1.1	1.1
Average	**1.6**	**1.3**	**1.4**	**1.4**	**1.3**

Even though the rankings are quite similar, the selection of an initial WCP for the Lake Mendocino WCM update is not straightforward. The value and weight of individual metrics will naturally vary with the primary interest of the individual. Further, more than half of the metrics (9 of 16) reflected flood risk management objectives, while only one reflected water supply reliability. For a more equitable comparison across metrics, the rankings from the June 2, 2020, briefing were grouped and summarized in Table 6.4.

Table 6.4. Summary participant rankings grouped by objective.

Category	Baseline	EFO	Hybrid	Modified Hybrid	Five-Day Deterministic Forecast
Flood Risk Mgt. (M1-9)	4.3	2.3	1.3	1.2	2.5
Water Supply Rel. (M10)	5.0	1.0	2.7	2.1	2.6
Environmental (M11-12)	4.8	1.2	2.4	2.3	2.3
Other (M13-16)	1.7	3.6	2.3	2.4	2.8

From here, the narrowing of candidate FIRO WCP alternatives was accomplished through (1) a refocusing on the original objective of improving water supply reliability and (2) implementation limitations. From Table 6.4, the EFO model provides the greatest improvement in water supply reliability without impacting flood risk management objectives. It also provides good support to environmental objectives (metrics 11 and 12). "Other" objectives are not as well met, but the impacts are either manageable, can be mitigated, or are less important.

The EFO model is, however, beyond the limits of reservoir operator confidence needed for implementation at this time. As such, the EFO model was eliminated as the recommendation for the initial WCP. Of the remaining three FIRO WCPs, the Modified Hybrid ranked highest in improving water supply reliability and environmental metrics, while performing about the same as the other WCP alternatives with respect to flood risk management and the recreation, dam safety, hydropower, and workload metrics.

Interestingly, the only difference between the Hybrid and the Modified Hybrid models is the shape of the FIRO Space (see Section 6.3). For the Modified Hybrid, spring refill can begin on February 15, while the Hybrid must wait until March 1. The Five-Day Deterministic Forecast WCP also allows for spring refill to begin on February 15.

6.3 FIRO Adaptive WCP Framework: FIRO Space Concept

From the very beginning, the FIRO project has embraced research and the notion that research-inspired improvements in forecast skill could be naturally leveraged by a FIRO WCP without the need to update the WCM for every incremental forecast skill improvement. From this notion, the Steering Committee developed the following definition of a FIRO WCP:

> *A Water Control Plan (WCP) that allows for an adaptable and bounded FIRO Space. The magnitude of the FIRO Space is defined by the demonstrated streamflow forecast skill, operational constraints, and procedures that leverage that skill to maintain or enhance defined flood risk management objectives for the project. The process and procedure for reevaluating and updating the FIRO Space is described in the WCM.*

It is interesting that this definition only mentions flood risk management objectives, while the primary objective of the Lake Mendocino FIRO project is to improve water supply reliability. This is because procedures that affect release decisions from the flood control pool are of much greater interest to the USACE than releases from the conservation pool, where a local sponsoring agency (Sonoma Water in this case) has that authority.

This definition has several elements that require further description and explanation**:**

- The FIRO Space is adaptable.
- The FIRO Space is bounded.
- Its magnitude is defined by:
  - Demonstrated streamflow forecast skill
  - Operational constraints
  - Procedures that leverage skill to achieve project objectives
  - Reservoir operator confidence
- WCM describes the process for reevaluating and updating the FIRO Space.

Figure 6.4 provides a conceptual diagram of FIRO Space for Lake Mendocino. Here, the space allows for conditional storage in the established flood control pool as well as conditional evacuation of a portion of the conservation pool as described in Section 3. The FIRO Space in Figure 6.4 also holds the ability for the space to increase as forecast skill and reservoir operator confidence improves.

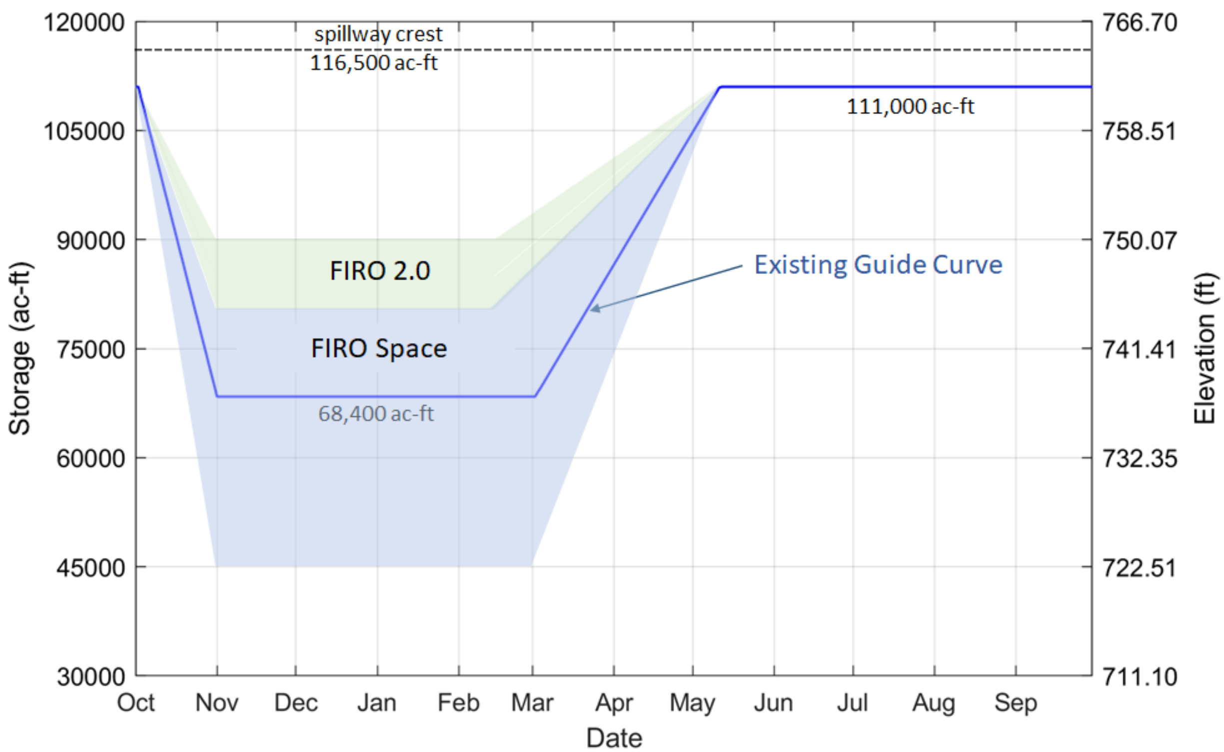

Figure 6.4. *Conceptual FIRO Space for Lake Mendocino.*

The concept of a FIRO Space does not change the defined seasonal variation of the flood control and conservation pools (blue line in Figure 6.4.). The USACE still makes all release decisions when the pool is above the Top of Conservation (TOC) and Sonoma Water makes all release decisions when the pool is at or below TOC. With existing WCM operations, any storage above TOC is evacuated as soon as safely feasible. Under a FIRO WCP, the release decision is *informed by* the forecast of future conditions (e.g., weather and streamflow forecasts) and decision support tools and models.

6.3.1 Bounded

A bounded FIRO Space is important for several reasons. First, an unbounded FIRO WCP (i.e., the EFO WCP alternative) is not considered viable by USACE. Second, there are numerous physical and programmatic limitations that necessitate reasonable bounds. These include project authorized purposes, physical conditions, flood risk management objectives, dam safety objectives and concerns, the confidence of approving officials and reservoir operators, and compliance considerations with the National Environmental Policy Act (NEPA) and the California Environmental Quality Act (CEQA).

6.3.2 Magnitude

The magnitude (size) of the FIRO Space is limited by the bounds described above, but is also subject to the demonstrated forecast skill, operational constraints, and the efficacy of procedures that leverage the forecast skill in the release decision making process. It is important to note that it is the *combination* of forecast skill and forecast application that yields improved operational outcomes for the reservoir, as shown in Figure 6.5.

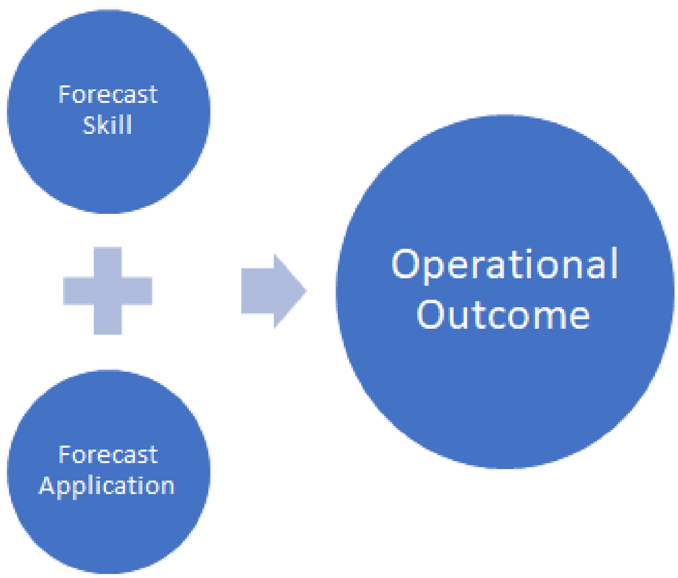

Figure 6.5. *Both forecast skill and forecast applications (e.g., reservoir modelling) are needed to produce improved operational outcomes for reservoirs.*

6.3.3 Adaptable

Being flexible or adaptable means having the ability to adjust to changes that occur over time. Changes could result from baseline conditions such as climate change or federal and state regulations, forecast skill improvements, or observational enhancements. The underlying premise of FIRO is that forecast skill will improve over time with effort and investments in science and observing systems (per Section 5). As this materializes, adaptation is envisioned in two ways. First, greater forecast skill will allow for storage retention at higher levels in the FIRO Space and a reduction of “false alarms” will reduce cases where the evacuation of storage was not necessary. Second, the bounds of the FIRO Space could be expanded (e.g., FIRO 2.0 in Figure 6.4).

Figure 6.6 is a conceptual diagram that shows how this might happen for Lake Mendocino where improvements in water supply reliability are sought while maintaining, or possibly enhancing, flood risk management and environmental outcomes.

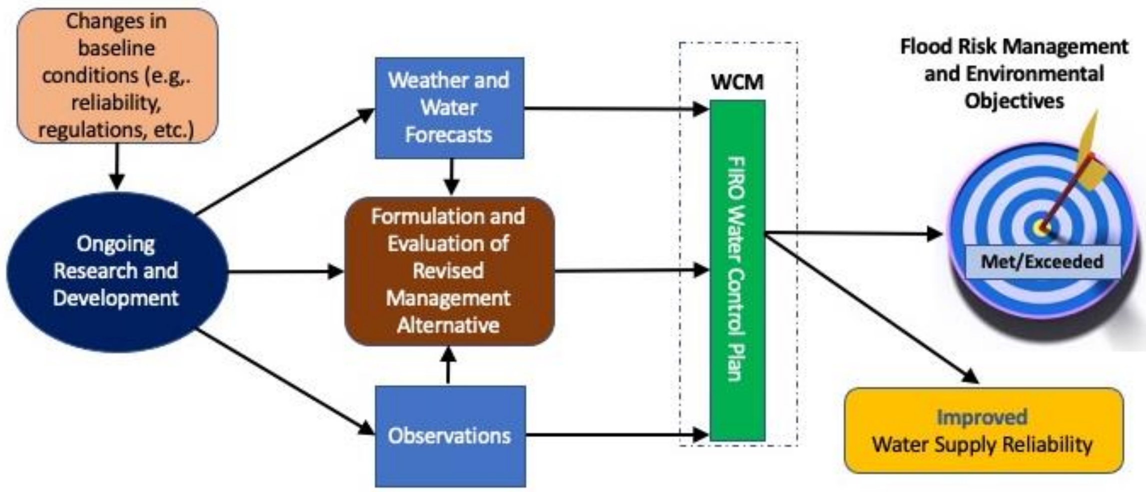

Figure 6.6. *Conceptual framework for a FIRO WCP that effectively adapts to (1) changes in baseline conditions, (2) weather and water forecast skill, (3) improved observations, and (4) improved reservoir management models.*

Given NEPA/CEQA compliance costs and other limitations, there may be a practical limit of the FIRO Space described in the WCM that the adaptation process cannot exceed without a formal update to the WCM. The movement process to FIRO 2.0 could be defined in the updated WCM, or it may require an update to the WCM. This movement (or update) could be triggered by an improvement in a defined set of objective forecast skill metrics that accurately reflect the required level of reservoir operator confidence. The development of these forecast skill metrics should be a collaborative effort among members of the Steering Committee and their staff with a special focus on and engagement of USACE San Francisco District reservoir operators.

6.3.4 Establishing Baseline Targets

The most important key to enabling change within the FIRO Space is to establish baseline targets for all primary and secondary reservoir management objectives. For Lake Mendocino, it is essential that any proposed changes in operations do not impair the ability of the project to deliver flood risk management objectives. It is also imperative that the proposed changes do not negatively impact the fisheries habitat downstream of the reservoir. As the analysis in Section 3 suggests improvements in baseline flood risk management and fisheries habitat can accompany improvements in water supply reliability when FIRO WCP alternatives are employed.

Nonetheless, the baseline objectives need to be strictly quantified, vetted, and documented. It is also important that the quantification of performance associated with a proposed shift in the FIRO Space not be prohibitively complicated or expensive to generate. For example, for Lake Mendocino, an evaluation of spill frequency, reservoir elevation, downstream flow frequency at key locations, and impacts on Lake Sonoma operations may be sufficient without engaging in a full HEC–Flood Impact Analysis or HEC–Flood Damage Assessment evaluation. Experience gained through Section 3 can be used to establish baseline objective targets which could be further refined in the process of updating the WCM.

6.3.5 Summary

From the beginning, FIRO was designed as a research effort with the overarching goal of using the best information and tools for reservoir operations. That research included demonstrating that the explicit use of existing forecasts could improve reservoir management outcomes, as well as efforts to improve forecast skill. Implementation of FIRO at Lake Mendocino is not a singular event. FIRO creates an environment where ongoing research investments in forecasts and their application yields ever-improving reservoir management outcomes. It is a commitment to research and research-to-operations. The analysis conducted as part of this demonstration project has shown that the investment in this research will result in high value benefits and effectively avoid expensive capital projects.

The research conducted and reported in Section 5 is emblematic of this commitment.

If continued improvements in flood risk management, water supply reliability, and ecosystems are to be realized, FIRO must define and develop the pathway for research and technology advancements to make their way into operational use. This is the intent and purpose of the FIRO Adaptive WCP Framework described here. And while significant progress has been made, additional work will be required to formally include this framework into the updated Lake Mendocino WCM.

6.4 Pathway for WCM Update

The WCM update will begin in the summer of 2020. The USACE San Francisco District is developing a project management plan for the technical tasks that need to be completed by USACE staff. The technical tasks include, but are not necessarily limited to, review of existing conditions, hydrologic analysis, reservoir simulation analysis, hydraulic analysis, environmental effects analyses, and public outreach. Research and development associated with the FVA will inform the WCP that is formulated during the WCM update. Anything associated with the WCM update is subject to USACE District, Division, and Headquarters review. It is currently estimated that the overall update may be completed in water year 2022.

Section 7. Recommendations

The Lake Mendocino Forecast Informed Operations (FIRO) effort, guided by the Steering Committee and the contributions of many individuals and agencies, has delivered a great deal of insight, understanding, and fundamental information that confirms the original project motivation identified in 2014. Key overarching findings and recommendations resulting from this Final Viability Assessment (FVA) are:

Key Findings:

1. FIRO at Lake Mendocino is viable using current forecast skill and will result in benefits to flood risk management, water supply, and ecosystems
2. FIRO benefits can increase even more with improved forecast skill (e.g., atmospheric rivers [ARs], precipitation, and streamflow)
3. Decision support, modeling tools, and enhanced observations are needed to facilitate the use of new FIRO strategies
4. The collaborative process employed for the Lake Mendocino FIRO project was essential in the success of the program by creating an understanding among partners and leading to robust results

Key Recommendations:

1. Initiate a formal update to the Water Control Manual (WCM) that potentially includes multiple phases of the Water Control Plan (WCP):
    a. An initial implementation of FIRO by developing a WCP that:
        i. Uses existing forecast information and forecast tools
        ii. Explicitly considers uncertainty
        iii. Meets Lake Mendocino FIRO objectives
        iv. Can currently be implemented given current forecast skill, operational constraints, U.S. Army Corps of Engineers (USACE) policy, and operator confidence
    b. A longer-term phased approach for implementation of FIRO that allows a growth path to achieve enhanced FIRO benefits (e.g., flood risk management, water supply, and ecosystems) by incorporating the FIRO Space concept (see Section 6.2) including:
        i. Phased growth path guided by increased forecast skill and operator confidence improvements
        ii. Methods to objectively determine when forecast skill improvements and reservoir operator confidence warrant phased increases
2. Pursue a five-year major deviation to enable FIRO benefits while the WCM update is in process
3. Support and continue development of FIRO decision support tools, models, and observations

4. Continue research investments to improve forecast skill and reservoir models that effectively leverage forecast skill and uncertainty. This includes the development and archival of relevant weather and water forecast metrics.
5. Continue Steering Committee function and role to assist in the process of updating the Lake Mendocino WCM.

7.1 Selection of Initial WCP

Modified Hybrid EFO

The Modified Hybrid EFO model is recommended for the initial WCP of the updated Lake Mendocino WCM. This FIRO alternative:

- Ranks favorably across all metrics compared to baseline and other WCP alternatives
- Can be feasibly implemented through either integration or adaptation to USACE standard decision tools and models, such as the Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim)
- Explicitly uses the uncertainty in streamflow forecasts
- Has a pathway for growth with improving forecast skill and model refinements

The details and rationale for the selection of the Modified Hybrid EFO model, based on the results of the evaluation described in Section 3, are provided in Section 6.2.

To allow for growth and development, the initial WCM should consider the FIRO Space concept as defined in Section 6.3. The notion of FIRO Space does not redefine the existing flood control pool nor its seasonal variation. The FIRO Space concept only defines a storage space where the release strategy can be informed by forecasts. It is recommended that the initial FIRO Space be consistent with the Modified Hybrid EFO model. Movement to Phase II and Phase III (Figure 6.4) could be defined in the updated WCM or it may require an update to the WCM. This movement should be objectively triggered by improvements in a defined set of forecast skill metrics that accurately reflect the required level of reservoir operator confidence. The development of these forecast skill metrics should be a collaborative effort among members of the Steering Committee and their staff with a special focus on and engagement of USACE San Francisco District reservoir operators.

7.2 Decision Support Tools, Models, and Observations

7.2.1 Decision Support

Decision support tools are an essential part of FIRO development and implementation. Current decision support tools are described in Section 4.2. As such, it is recommended that these continue to be supported as an integral part of FIRO in the future.

This includes the California Data Exchange Center (CDEC) based operations interface. In water year (WY) 2020, the California-Nevada River Forecast Center (CNRFC) recalibrated and refined their forecast model topology in the Russian River basin. Because of time limitations, the CDEC interface retained the WY 2019 model topology and the CNRFC made special accommodations. Work will be required before WY 2021 to reconfigure the ResSim model and the interface to reflect the CNRFC's model topology. The CDEC interface should also model the EFO Hybrid consistent with the proposed five-year major deviation.

The Major Deviation and Virtual Operations pages supported on the Center for Western Weather and Water Extremes (CW3E) website should continue to be offered. The alternative WCPs should include, at a minimum, the baseline, EFO Hybrid, and EFO Modified Hybrid models.

AR-centric web products and services available on the CW3E website should continue to be offered and should be developed and enhanced as the science and application permits. Development funded by other projects and programs directly benefit the Lake Mendocino FIRO effort (e.g., the AR Program funded by the California Department of Water Resources). Training on the appropriate interpretation of AR products should be offered to FIRO practitioners.

7.2.2 Models

To enable the USACE to more broadly adopt FIRO in the future, it is recommended that model development associated with the HEC toolset continue as described in Section 5.4. These enhancements will allow for the assessment of risk and uncertainty of FIRO WCPs that leverage ensemble streamflow forecasts. In addition, continued development of approaches to generate synthetic (artificial) forecasts that allow for WCP evaluation across the full probability space is recommended.

Continued development of the Sonoma Water EFO model as described and demonstrated in Section 5 is also recommended. Areas of development include, but are not limited to, optimization of the "risk curve" and multi-objective approaches. The Steering Committee also recommends that work continue to adapt and/or integrate the EFO methodology into accepted USACE tools such as HEC-ResSim.

7.2.3 Observations

The enhanced observation efforts in the Russian River watershed have and continue to facilitate research, as well as operational decision support. It is recommended that both onshore and offshore observation efforts be continued and supported (Section 5.2). Support and development of the Advanced Quantitative Precipitation Information System (AQPI) program is also recommended in support of both research and operational reservoir management decision making.

7.3 Future Research and Studies

Accurate and reliable forecasts are a fundamental underpinning of FIRO, and as such, FIRO creates an environment where ongoing research investments in forecasts and their application yields ever-improving reservoir management outcomes. Improving precipitation and streamflow forecasts at a range of lead times (from one-day to subseasonal) requires integration of observations, research, modeling, and forecast information into operational reservoir decisions. An enhanced observing network (RHONET) was deployed (Section 5.2) as part of the FIRO effort, and it is critical that this observation network be maintained and that FIRO integrates new observing networks such as the AQPI. These observations provide information about the current conditions and initialize and verify the models that create the forecasts to support FIRO. FIRO is a commitment to observations and research. The observations and research conducted and reported as part of this FVA, described in Section 2, are emblematic of this commitment and represent only the beginning. Below are recommendations for research beyond the FVA that will support forecast improvement and continue to enhance the application and benefits of FIRO.

7.3.1 Atmospheric River Reconnaissance

The Atmospheric River Reconnaissance (AR Recon) Research and Operations Partnership founded during FIRO Phase I demonstrated the value of the AR Recon to improved forecasts. The deep relationships with top international and national modeling centers working on this topic to benefit western weather and water forecasting have been and will be key to the success of the program. Within this partnership, scientists can focus on furthering the impact assessments that have already shown great benefit to forecast skill provided by these additional observations. In addition, scientists can continue research on utilizing novel observations such as GPS-RO, refining data assimilation strategies specifically for AR Recon observations, using observations to learn more and more about the fundamental physics and dynamics in ARs in order to improve model representations of these processes, and iteratively using all of this information to refine sampling strategies and become more impactful every year. To increase the impact of these data sets, the data need to be disseminated broadly, such as to the Global Telecommunications System, to improve the representation of the initial state of the atmosphere and improve the forecasts.

7.3.2 Atmospheric River Science

Continuing to build upon years of scientific advancements toward understanding AR dynamics and their relationship with extreme precipitation in California is fundamental to the long-term enhancement of FIRO. Important components of this research include establishing a framework for AR evolution that quantifies the role of AR moisture as an important modifier of large-scale circulation, and determining the limitations in the practical predictability of ARs by identifying physical sources of model uncertainty via ensemble weather prediction experiments. In addition, an essential component of AR Science in support of FIRO investigations is meteorological processes that explain precipitation variance beyond upslope moisture transport—including orographic convection, frontal precipitation, and precipitation microphysics—to determine how these processes influence hydrometeorological forecast skill during AR landfall. Importantly, the results from AR research need to be provided in a usable way to forecasters and stakeholders via open communication and decision support and situational awareness tools.

7.3.3 Regional Weather Forecasts

Dynamical weather forecast models are marvels of atmospheric and computer science. They encompass our current understanding of key physical processes driving the evolution of the atmosphere in space and time, as well as advanced numerical techniques and programming strategies. Regional weather forecast models, such as CW3E's West-WRF, an optimized version of the Weather Research and Forecasting Model for the Western U.S., target extreme precipitation prediction and can support FIRO by providing high-resolution model forecasts and testing novel modeling approaches to improve forecasts. A future area of research toward improving regional forecast model representation of ARs and orographic precipitation over the Western United States is the use of convection-permitting models (grid spacing less than 4 km) over the northern Pacific to better resolve mesoscale meteorological features that are important toward AR development. Additionally, further refinement of the model nests (West-WRF is currently at 3 km grid spacing; see Section 2.3) over California and the Western United States will allow for better representation of flow over complex terrain and associated orographic precipitation. Another area of research includes implementation of the variable grid resolution Model for Prediction Across Scales-Atmosphere (MPAS-A; Skamarock et al. 2012) into near real time operations, in both a deterministic and ensemble framework, to eliminate the dependence of lateral boundary forcing from operational models. The potential improvement in AR and precipitation forecast skill from MPAS simulations compared to WRF and operational global models remains to be comprehensively addressed. In addition, the development and application of verification metrics that are relevant to FIRO are an important component that enables assessment of forecast model skill to support FIRO objectives.

7.3.4 Subseasonal-to-Seasonal Forecasts

Skillful forecasts of ARs and precipitation at subseasonal-to-seasonal (S2S; two-week to at least two-month) timescales has the potential to provide valuable information for water management to prepare for wet or dry conditions. S2S forecasts have limited skill, however recent advancements in forecasting models and innovative data analysis techniques have increased the potential for improved long-range prediction of physical quantities affecting water resource management over the western United States. Future S2S research and experimental product development should focus on several key topics going forward, including exploring the use of machine learning methods to improve seasonal prediction of precipitation, investigating teleconnection patterns associated with climate variability impacts on forecasts of ridging and precipitation near California, and implementing hybrid statistical and dynamical methods to improve S2S prediction skill.

7.3.5 Machine Learning and Post-Processing

Postprocessing algorithms, which are machine learning methods, can build on the information provided by models and observations to further improve the model forecasts, both deterministic and probabilistic. More recently, machine learning has also been explored to analyze vast data sets to better understand physical processes, which led to the emergence of a new field called interpretable learning. Future research will focus on extending the current encouraging results for the prediction via machine learning of integrated water vapor transport to the prediction of precipitation, both at the regional and watershed level, as well as on the exploration of interpretable learning as it applies to FIRO.

7.3.6 Hydrology

Hydrologic models that make reliable streamflow forecasts are basic to FIRO's success. Building on the success of the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) distributed hydrologic model demonstrated in this report, future research should include a comprehensive testing strategy for distributed and operational models across multiple watersheds, and strong collaborations with meteorology colleagues to optimize weather forecast models for hydrological use. Additional efforts include assimilating data from RHONET, such as soil moisture, into hydrologic models and assessing the impacts of spatial variability and meteorological uncertainties on streamflow forecasts.

7.3.7 Environmental

This FVA has demonstrated that improved water supply reliability for Lake Mendocino translates into improved support for fisheries in terms of meeting both summer and fall instream flow requirements for rearing and spawning of threatened and endangered federal Ecological Society of America-listed salmonids. With greater levels of winter and spring reservoir storage, the "cold water pool" is also enhanced. This initiated a study on how water temperature conditions in the "cold water pool" in Lake Mendocino would influence the upper Russian River cold water tailrace (zone/reach) below the reservoir, and to what extent there would be impacts downstream (Section 5.5). The modeling results demonstrate benefits of higher reservoir storage levels to maintaining cooler water temperatures during the juvenile steelhead trout summer rearing season through the fall adult Chinook salmon migration period.

The National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) will continue its efforts to monitor stream temperature in the upper Russian River and water temperature at different depths in Lake Mendocino during summer through fall 2020. These new oncoming data will provide valuable information to improve the machine learning modeling approach.

Although the overall performance of the model is good, there are months in which the performance of the model needs to be improved. Therefore, NMFS will perform the additional analysis:

- Select the number of lag days for different months or seasons
- Perform additional training and validation process (e.g., cross-validation)
- Perform a sensitivity analysis to find the most relevant inputs of the model for different months or seasons

7.3.8 Development of Relevant Weather and Water Forecast Skill Metrics

Relevant weather and water forecast skill metrics are needed to guide research investments, measure progress, and safely trigger potential expansion within the FIRO Space concept described in Section 6.3. It is recommended that the Steering Committee coordinate a collaborative process to develop metrics for the Lake Mendocino FIRO application (with significant transferability potential) and establish a tracking and archival facility/function.

In addition, USACE water managers at San Francisco District and the CNRFC should continue to collaborate on forecast skill and lead time status and the potential to improve them over time with Hydrologic Ensemble Forecasting System enhancements, use of the Global Ensemble Forecast System version 12, and FIRO research outcomes.

7.4 Strategy for Moving Forward

7.4.1 Update the Lake Mendocino WCM

Fundamentally, FIRO is a research project. However, the goal of the research is to eventually lead to real operational changes in the way that Lake Mendocino is managed. The process for doing this involves updating the Lake Mendocino WCM. To the greatest extent possible, information and analysis from this FVA should be leveraged in the WCM update. While the WCM update is a USACE process, it is recommended that the Lake Mendocino FIRO Steering Committee remain intact and contribute to the effort and process. The pathway for an updated WCM is described in Section 6.4.

7.4.2 Request Five-Year Major Deviation of the Lake Mendocino WCM

From the past two years of operations under a major deviation and the results of the analysis described in Section 5, there are clear and immediate benefits associated with FIRO operations. The update of the Lake Mendocino WCM will take a number of years to complete, gain approval, and be implemented. In the meantime, it would be irresponsible to return to baseline WCM operations. As such, efforts are currently underway to request a five-year major deviation for the operation of Lake Mendocino. Additional details on the five-year major deviation are outlined in Section 6.1 and the full request to the USACE can be found in Appendix D.

7.4.3 Expand Research and Operations Partnership

During the tenure of the Lake Mendocino FIRO project, a great deal of effort has gone into research that will lead toward improved weather and streamflow forecast skill. The evaluations and engineering work conducted to demonstrate full viability in this report were based on existing forecast skill. A key element of FIRO involves this commitment to science and research and the integration of knowledge gained into future operations. This process requires an effective and robust Research and Operations Partnership (RAOP). Some of this will occur naturally ("if you build it, they will come"), but the greatest gains are available only through an intentional process. The Lake Mendocino FIRO Steering Committee recommends that additional emphasis and a more formal process for the FIRO RAOP be developed, supported, and utilized.

7.4.4 Pivot Efforts Toward Investigating FIRO for Lake Sonoma

The Lake Mendocino FIRO effort has created a model and a pathway for other reservoir systems to explore improved reservoir management through the explicit use of streamflow forecasts. As a pathfinder project, Lake Mendocino was a good choice because it carried a balance of uses and created a safe environment for interagency collaboration. The primary water supply reliability benefits for Sonoma Water associated with Lake Mendocino FIRO relate to maintaining higher instream minimums and providing elevated environmental flows. Lake Mendocino is not the primary water supply resource for Sonoma Water—that is Lake Sonoma.

With the Lake Mendocino FIRO project moving toward a WCM update, it now makes sense to pivot toward developing and implementing FIRO for Lake Sonoma. This will accomplish two things. First, this will provide a consistent reservoir management approach across the Russian River basin. Second, it has the potential to enhance the resiliency of Sonoma Water's delivery service for municipal, industrial, and environmental uses. As such, the Lake Mendocino Steering Committee recommends that Lake Sonoma be prioritized as a future FIRO project.

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