

# PRELIMINARY VIABILITY ASSESSMENT OF LAKE MENDOCINO FORECAST INFORMED RESERVOIR OPERATIONS

2017



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## Contributors

The preliminary viability assessment (PVA) of forecast informed reservoir operations (FIRO) of Lake Mendocino described in this document is the result of a collaborative and cooperative effort by a team of federal, state, and county agency representatives, academicians, and consultants. Their institutions and firms are listed in Table 1.

Table 1. Agencies, institutions, and consulting firms that contributed to the PVA

California Department of Water Resources (DWR)	USACE, Sacramento District USACE, San Francisco District
National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), California Nevada River Forecast Center (CNRFC)	US Bureau of Reclamation (USBR) US Geological Survey (USGS)
NOAA Earth System Research Laboratory (ESRL)	University of California San Diego (UCSD), Scripps Institution of Oceanography (SIO), Center for Western Weather and Water Extremes (CW3E)
NOAA Restoration Center	Sonoma County Water Agency (SCWA)
US Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC)	David Ford Consulting Engineers, Inc. <b>Arleen O'Donnell</b> , Eastern Research Group
USACE, Hydrologic Engineering Center (HEC)	

Activities of this study team were guided by a steering committee (SC), which was formed in 2014. SC members are shown in Table 2.

Table 2. Lake Mendocino FIRO SC members

Member (1)	Agency (2)
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F. Martin Ralph <sup>1</sup>	UCSD CW3E
Michael Anderson	DWR
Levi Brekke	USBR
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Patrick Rutten	NOAA Restoration Center
Cary Talbot	USACE ERDC
Robert Webb	NOAA ESRL

1. Co-chair of the steering committee.
2. Retired from NWS in September 2016; continued to participate as consultant.
3. Jones left USACE in June 2016 and moved to DWR. Forbis followed Jones as the USACE, Sacramento District representative.

Study findings and recommendations reported in this document were developed by members of the SC.

The analyses that support findings in the PVA and this PVA report, including the appendices, were reviewed by an independent panel. Members of that panel are shown in Table 3. Review does not imply endorsement by the panel members or their organization.

*Table 3. FIRO PVA independent reviewers*

Member (1)	Organization (2)
Dr. Dennis Lettenmaier	University of California Los Angeles (UCLA)
Dr. Roger Pulwarty	National Drought Information Service (NIDIS)
Mr. Mark Yuska	U.S. Army Corps of Engineers (USACE)

# Acronyms

For brevity, the following acronyms are used in this report:

Acronym (1)	Meaning (2)
AAD	average annual damage
ACE	annual chance exceedance
AEP	annual exceedance probability
AF	acre-feet
AR	atmospheric river
cfs	cubic feet per second
CNRFC	California Nevada River Forecast Center
CSI	critical success index
CW3E	Center for Western Weather and Water Extremes
D1610	Decision 1610
DSS	decision support system
DWR	California Department of Water Resources
EAD	expected annual damage
EFO	Ensemble Forecast Operations model
ERDC	Engineer Research and Development Center
ESRL	Earth System Research Laboratory
FAR	false alarm rate
FERC	Federal Energy Regulatory Commission
ft	feet
FIRO	forecast informed reservoir operations
FRA	flood risk analysis
FVA	Full Viability Assessment
GEFS	Global Ensemble Forecast System
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HEC	Hydrologic Engineering Center
HEC-HMS	HEC Hydrologic Modeling System
HEC-FIA	HEC Flood Impact Analysis
HEC-RAS	HEC River Analysis System
HEC-ResSim	HEC Reservoir System Simulation
HEC-WAT	HEC Watershed Analysis Tool
hr	hour
HRRR	High Resolution Rapid Refresh
in	inches
IVT	Integrated Vapor Transport
MAP	mean areal precipitation
MFW	mesoscale frontal waves

Acronym (1)	Meaning (2)
msl	mean sea level
NAVD	North American Vertical Datum
NBM	National Blend of Models
NGGPS	Next Generation Global Prediction System
NGVD	National Geodetic Vertical Datum
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PG&E	Pacific Gas and Electric Company
POD	probability of detection
POR	period of record
PVA	preliminary viability assessment
PVID	Potter Valley Irrigation District
PVP	Potter Valley Project
QPF	quantitative precipitation forecast
R <sup>2</sup>	coefficient of determination
R&D	research and development
RAP	Rapid Refresh
RMSE	root mean square error
RRFC	Mendocino County Russian River Flood Control & Water Conservation Improvement District
SC	steering committee
SCWA	Sonoma County Water Agency
SIO	Scripps Institution of Oceanography
SPD	South Pacific Division (USACE)
SWRCB	State Water Resources Control Board
UCSD	University of California San Diego
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USGS	US Geological Survey
WCM	water control manual
WIF	with imperfect forecast
WRDA	Water Resources Development Act
WSEL	water surface elevation

# 1 Executive summary

This report describes the preliminary viability assessment (PVA) of forecast informed reservoir operations (FIRO) for Lake Mendocino, which is located on the East Fork Russian River three miles east of Ukiah, California. The results described in this report represent the collective activities of the Lake Mendocino FIRO Steering Committee (SC) (SC members are named on the inside cover of the report). The SC consists of water managers and scientists from several federal, state, and local agencies, and universities who have teamed to evaluate whether current technology and scientific understanding can be utilized to improve reliability of meeting water management objectives of Lake Mendocino while not impairing flood protection. While the PVA provides an initial evaluation of the viability of FIRO as a concept, additional steps remain to complete the full viability assessment (FVA). Also, the PVA does not identify how FIRO strategies would be implemented. That effort would be the focus of the FVA, which builds off the analyses developed in the PVA.

This report summarizes current Lake Mendocino operation and a preliminary analysis of FIRO alternatives, including analysis methods, results, and recommendations. A set of accompanying reports describes the analysis in detail. These are referred to herein as the Sonoma County Water Agency (SCWA) report, the Hydrologic Engineering Center (HEC) report, and the Center for Western Weather and Water Extremes (CW3E) report (SCWA 2017, USACE 2017, and CW3E 2017, respectively).

## 1.1 How is Lake Mendocino operated?

Lake Mendocino has been operated cooperatively by SCWA and the US Army Corps of Engineers (USACE) for flood and water management and environmental protection since construction of the impounding structure—Coyote Valley Dam—in 1958. Operation is governed by rules established at the time of construction with best-available technology and knowledge of system hydrology and hydraulics at that time. The rules are published in the project water control manual (WCM), which was amended in 1986 and 2004 following its initial publication in 1959.

The original WCM rules allocate the 122,400 acre-feet (AF) of storage in Lake Mendocino to storage for flood management and storage for conservation purposes. The seasonally varying flood storage pool varies from a maximum of 54,000 AF in the winter rainy season to 11,400 AF in the drier summer season. Rules require the flood pool to be empty except briefly in periods of greatest inflow. Then flood runoff is stored and released at a rate that avoids or minimizes exceedance of downstream flow targets at Hopland (a key stream gage downstream from the reservoir), Healdsburg, Guerneville, and elsewhere.

The conservation storage, used for water management objectives and meeting minimum in-stream flow requirements (for fisheries and/or environmental purposes, herein referred to as environmental flows), is filled as water is available to do so. However, operation following the WCM rules strictly does not permit storage in the flood pool for conservation purposes. These rules apply even if inflow forecasts do not indicate an immediate need for empty space to manage flood water.

For example, in December 2012, a large storm associated with an atmospheric river (AR) filled space available in the conservation pool and encroached approximately 25,000 AF of the flood pool (i.e., consumed a large fraction of the 54,000 AF normal flood pool capacity). USACE dam operators followed the WCM rules and released this water from the flood pool, ensuring space was available to manage potential future floods, even though no storms or

flooding was forecasted in the near future. Storage in Lake Mendocino began to decline significantly through the late winter and early spring of 2013 because no additional storm events occurred. In order to preserve storage in Lake Mendocino and to prevent the reservoir storage dropping to unsafe levels by the fall of 2013, SCWA filed a Temporary Urgency Change Petition with the State Water Resources Control Board (SWRCB) to reduce environmental flows required by **SCWA's water rights permits**. Strictly following the WCM rules in this case resulted in the loss of water that SCWA could have used for greater environmental and recreational benefit, had the WCM rules allowed for some flexibility based on short-term (e.g. days) forecast information. (The environmental "storage" would be for the purpose of having adequate water in late summer for the early migration of Chinook salmon.) Furthermore, the winter of 2013 turned out to be the beginning of a severe and extended drought. If stored water could have been retained in Lake Mendocino from the December 2012 storm and AR event, drought impacts to the Upper Russian River could have been postponed and moderated.

## 1.2 What is FIRO, and how could it enhance operation?

State, federal, and local agencies, in cooperation with SCWA and the University of California San Diego (UCSD), Scripps Institution of Oceanography (SIO), initiated a research and development (R&D) project to enhance Lake Mendocino operation through more efficient use of the available storage. This project was guided by the Lake Mendocino FIRO SC. In 2015, the SC drafted a work plan, which provided a scope for the PVA. The SC shared a vision that operational efficiency would be improved by using forecasts to inform decisions about releasing or storing water. This strategy was identified as forecast informed reservoir operation, or FIRO. Because recent scientific advances had identified ARs as the cause of almost all flooding on the Russian River (Dettinger, et al. 2011), and ARs produce half of the annual precipitation, the SC also recognized the importance of incorporating research to evaluate and improve understanding and prediction of ARs.

FIRO, as viewed by the SC, includes expanding meteorological, watershed, channel condition, and environmental monitoring; advancing science to enhance meteorological, watershed, channel condition, and environmental forecasting; and integrating data collection, management, display, and analysis capabilities into decision support system (DSS) tools for Lake Mendocino operators. To make best use of these enhancements, technological components will be coupled with flexibility in operation rule interpretation (or with changes to the rules) for flood and water management and environmental protection.

With FIRO capabilities, operators could, for example, limit lost opportunities that arise in situations such as occurred in 2012. If improved forecasts had been available and used in 2012, and strong (AR-type) storms were not predicted to occur after the earlier storm, and if operation rules were more flexible, a decision could have been made to store water in the flood space needed to meet future demands, rather than to release that water. This could have made available up to 25,000 AF of additional water to meet beneficial uses right as the region entered into a severe and extended period of drought. Likewise, with FIRO capabilities, operators might mitigate flood risk when a storm is predicted to be intense and cause downstream damage. FIRO could result in a decision to release water from the **reservoir's** conservation pool to lower reservoir levels, providing additional storage for **"controlling" flood waters**.

### 1.3 What is the plan for implementation of FIRO?

The Lake Mendocino FIRO SC devised a multi-step strategy to assess the viability of FIRO and move to implementation of FIRO. This plan, published in late 2015, included first the PVA, to be conducted over two years, and the FVA, which would require substantial additional effort over roughly another three years. The PVA—results of which are reported herein—considered the following questions:

1. If FIRO is implemented, will operation improve reliability in meeting water management objectives and ability to meet environmental flow requirements, and to what extent?
2. If FIRO is implemented, will operation adversely affect flood risk management in the system? If so, where and to what extent can that be mitigated?
3. What meteorological and hydrological forecast skill is required to enable FIRO to be implemented? Is current forecast skill for landfalling ARs (and their associated heavy precipitation and runoff) and other extreme precipitation events adequate to support FIRO, and what improvements would be needed to enable full implementation of FIRO for Lake Mendocino?

**The SC's strategy for decision making was this:** If the PVA suggested FIRO would be viable, the project team would move forward with the FVA. Due to the preliminary nature of the analysis, the PVA relied on representations of FIRO system components, reasonable simulation of performance of those components, and anticipated flexibility in operation of Lake Mendocino under FIRO. In the subsequent FVA, candidate components of the Lake Mendocino FIRO system would be identified; the forecast parameters and associated forecast skill requirements would be quantified; research to improve forecast skill to meet those requirements would be conducted; alternative components formulated, assessed, and compared; and a plan for implementation developed. If necessary components do not exist, R&D programs would be identified in the FVA, and work initiated to develop the components. Finally, necessary changes to the operation rules and the process for modifying the rules would be identified in the FVA consistent with USACE procedures and protocols to support consideration of policy modifications by the USACE as it contemplates approaches to enhance reservoir operations.

If the PVA found FIRO implementation not viable, the project team would identify scientific and operational enhancements necessary to make FIRO viable. The team then would initiate an R&D effort to provide those enhancements. The enhancements might include state-of-the-art operational and emerging weather forecast systems such as the Rapid Refresh (RAP), High Resolution Rapid Refresh (HRRR), Next Generation Global Prediction System (NGGPS), the National Blend of Models (NBM), and other post-processing innovations. These enhancements may better forecast properties of AR storms. These storms are important drivers of inflow for which flood storage is needed in Lake Mendocino.

### 1.4 How was the PVA conducted?

The PVA was undertaken in three parts: analysis of the hydrometeorological forecast requirements and assessment of current forecast skill; a study to determine whether forecast informed operation could improve reliability of meeting water management objectives; and a parallel coordinated study to demonstrate whether forecast informed operation could improve reliability of meeting water management objectives while not increasing flood risk.

For the first part of the study, to support anticipated changes in operational decision making, SC members quantified forecast skill requirements. (5-7 days lead time is needed

on forecasts of 2 inches [in] of rain above Lake Mendocino in 24 hours [hr], which requires accurate prediction of AR landfall location, strength, and timing as well as runoff efficiency and timing). They also assessed current skill. (Prediction of AR landfall and streamflow have meaningful skill out several days, but improvements are needed in timing, location, strength and duration, while extended periods of dry weather were found to have greater predictability than the details of AR landfall and runoff).

For the second part of the PVA, SCWA analysts developed and used mathematical models to assess improvements to reliability of meeting water management objectives and ability to meet environmental flow requirements. For a range of meteorological and hydrologic conditions, they simulated Lake Mendocino operation with a variety of FIRO alternatives. The Perfect Forecast Operations alternative represents flexibility in operation rules and assumes perfect forecast skill (using the inflows that actually occurred as the forecasts), which establishes a theoretical maximum benefit. The Ensemble Forecast Operations alternative represents the same flexibility in operation rules but reflects current forecast skill and is thus more realistic. The Hybrid Operations alternative represents an initial or interim implementation of FIRO. The SCWA analysis **used a "risk-based" decision process to** determine releases, considering probability of future failures to satisfy targets. Performance metrics used for the SCWA analysis include:

- End of water year storage.
- Dry season environmental flows.
- Discharge at Hopland and Healdsburg.
- Uncontrolled spill from Lake Mendocino.

For the third part of the PVA, HEC analysts focused on flood risk impacts. To do so, they simulated Lake Mendocino flood operation for a wide range of meteorological and hydrologic conditions, accounting for flow requirements for water management objectives and environmental purposes. HEC analysts also considered a variety of FIRO alternatives. The Encroach alternative represents a simple FIRO alternative based on perfect precipitation forecasts. The Combined alternative represents a more complex FIRO alternative based on perfect forecasts of several types of data. The EncroachWIF [with imperfect forecast] alternative is the same as the Encroach alternative but is assessed using imperfect precipitation forecasts. Performance metrics used for the flood risk analysis include:

- End of water year storage.
- May 10 storage (when maximum conservation storage becomes available each year).
- Expected annual damage (EAD) and average annual damage (AAD) reduction.
- Discharge and stage frequency at Hopland, Healdsburg, Guerneville, and Lake Mendocino.
- Uncontrolled spill from Lake Mendocino.

## 1.5 What were the results of the PVA?

The analyses completed for the PVA demonstrated forecast informed operation, as simulated in the studies, improved reliability of meeting water management objectives without adversely affecting flood risk management in the basin.

The SCWA analysis with FIRO alternatives showed significant additional storage that resulted in improved reliability of meeting water management objectives. Compared with existing operation, additional water was stored and available for delivery for nearly all years

simulated. Table 4 shows the median end of water year storage for 1985-2010 for existing operation and each FIRO alternative. Increases attributable to FIRO as modeled range from 8,633 AF to 27,780 AF, or up to a 49% increase.

*Table 4. Potential improved reliability in meeting water management objectives achieved by FIRO alternatives in terms of increase in median end of water year storage based on simulation results for 1985-2010*

Alternative (1)	Median end of water year storage (AF) (2)	Increase from Existing Operations (AF) (3)	Percent increase (4)
Existing Operations	56,220	—	—
Perfect Forecast Operations	84,000	27,780	49%
Ensemble Forecast Operations	76,277	20,057	36%
Hybrid Operations	64,853	8,633	15%

The HEC analysis showed no significant loss of ability of the system to manage flood risk for the Russian River basin. HEC assessed risk in terms of AAD based on 1951-2010. Table 5 shows AAD for the existing condition and FIRO alternatives.

*Table 5. Russian River basin flood risk: FIRO alternatives do not measurably change flood risk based on analysis of 1951-2010 and statistical sampling.*

Alternative (1)	POR compute (60 years, 1951-2010)		FRA compute (5,000 events)	
	AAD (\$ million) (2)	Increase in AAD from existing <sup>1</sup> (\$ million) (3)	EAD (\$ million) (4)	Increase in EAD from existing <sup>2</sup> (\$ million) (5)
Existing Conditions	6.10	—	10.40	—
Combined (complex, perfect forecast)	6.10	0	10.40	0
Encroach (simple, perfect forecast)	6.10	0	10.50	0.10
EncroachWIF (simple, imperfect forecast)	6.10	0	10.50	0.10

As the PVA proceeded to answer the two operational questions, a question arose regarding the existence of or ability to develop forecasts of sufficient accuracy to support forecast informed operations. This question was addressed by researchers at CW3E. CW3E analyzed the reliability of the Global Ensemble Forecast System (GEFS) used by the California Nevada River Forecast Center (CNRFC) of the National Weather Service (NWS) for Lake Mendocino inflow forecasting (using procedures described in the CW3E report). CW3E computed R<sup>2</sup> (coefficient of determination) and root mean square error (RMSE), comparing GEFS 6-hr ensemble average mean areal precipitation (MAP) time series to observed data for the Lake Mendocino cool season (October to April) for 1985-2010 for forecast lead times of 1 to 16 days. They found RMSE increased with lead time, starting with 0.28 in of precipitation on

forecast day 1, increasing to 0.48 in by forecast day 16. They found  $R^2$  decreased with lead time from 0.64 on forecast day 1 to less than 0.01 at forecast day 16, remaining greater than 0.5 out to forecast day 3. CW3E also tested GEFS skill related to prediction of 1-in precipitation in 24 hr (a key metric for Lake Mendocino release decisions) and compared GEFS skill with CNRFC forecaster skill. Overall, CW3E found forecasts to support FIRO were available or could be produced with enhancements that will be available through additional research. Skill in precipitation forecasting was best during extended dry periods, and appears viable for use in FIRO; however, significant errors remain during stormy periods. Current and ongoing efforts seek to study (1) the predictive skill of transitions from extended dry periods into wet periods and (2) the predictive skill of ensemble-based forecasts of atmospheric water vapor flux during AR-type storm events. Individual cases of past events illustrate meaningful skill in (1) transitions out to 3 days lead time on average and up to 5 to 7 days leads for individual cases and (2) ensemble-based water vapor flux forecasts out to 5–6 days lead time on average and up to 9 days lead for individual cases.

Analysis of the river channel geometry and operating release rates showed that it would likely take roughly 2 days to release up to 10,000 AF without exceeding the established target flow rate and then 2 to 3 days for that release to move downstream past the flood-prone town of Guerneville. Thus, skill is required at 5-days lead time for prediction of landfalling ARs and their associated heavy precipitation and runoff.

The PVA reaffirms that ARs are the key to flooding on the Russian River, and errors in their prediction are the primary source of uncertainty in the prediction of major precipitation and runoff events affecting Lake Mendocino, its watershed, and the Russian River. The PVA demonstrates that errors in precipitation and streamflow forecast result partly from errors in the timing, duration, intensity, and location of landfalling ARs, mesoscale frontal waves (MFW, a disturbance that forms offshore and can change the locations and duration of AR landfall and associated heavy precipitation), and inaccuracies in the representation of clouds and precipitation.

An example of a landfalling AR associated with prediction uncertainty that caused flood stage to be reached at Guerneville occurred in December 2014 (Figure 1). Predictions of the stage at 1- to 3-day lead times varied by up to 10 feet (ft) (from roughly 4 ft below flood stage to 6 ft above), while the actual stage reached roughly 2 ft above flood stage. Analysis showed that this forecast uncertainty resulted from errors in the detailed characteristics of the landfalling AR. These errors originated partly from the relatively poor prediction of a MFW that modified the landfall of the AR and caused changes in precipitation and runoff. This event demonstrates that skillful forecasts are currently available but could be improved and refined through research investments associated with AR behavior.

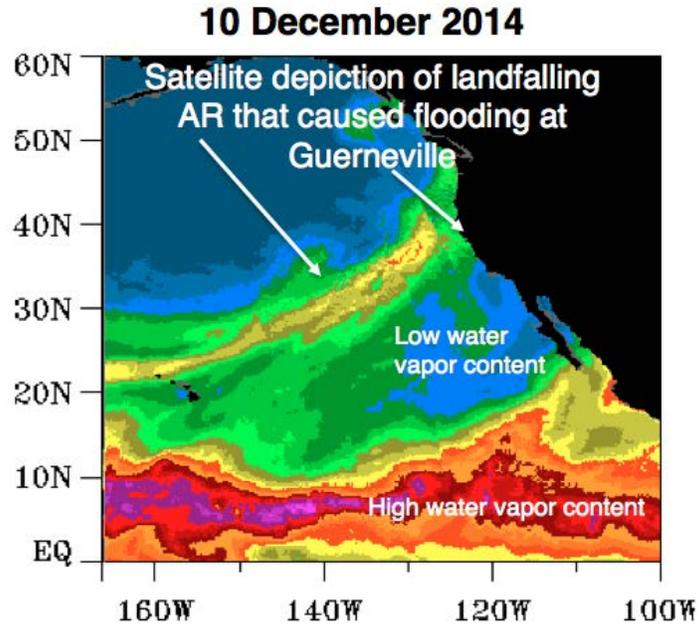


Figure 1: SSM/I imagery of a landfalling AR on 10 December 2014 (from the CW3E report)

The PVA identifies that additional efforts targeted at the development of weather prediction models tailored toward improving forecasts of precipitation and landfalling ARs over the **Russian River (such as the development of the “West-WRF” model being created at CW3E)**, additional unique performance and model evaluation metrics for precipitation and landfalling ARs that illustrate trends and improvements in forecast skill of existing models and derived decision support tools, and additional integration of existing and reconnaissance-based observational datasets (e.g., mesonets and aircraft data offshore, respectively) serve to improve the potential viability of FIRO at Lake Mendocino.

## 1.6 What are the findings of the PVA?

The PVA found:

- AR-type storms are, as found in previous research, the key drivers of both water supply and flood risk in this region, as these events produce heavy and sometimes prolonged precipitation and runoff.
- High-impact AR-type storms were observed at the coast in and near the Russian River watershed during record-setting water year 2017. These observations included some of the strongest IVT observations made on land and, occurring after the lengthy drought, illustrate the type of extremes that this watershed can experience on relatively short interannual time-scales.
- Predictive skill in the current forecast system, especially during extended dry periods, provides an opportunity to implement some elements of FIRO. However, significant uncertainty remains in the strength, timing, duration, and orientation of landfalling ARs and the associated precipitation and streamflow that can be reduced with further research.
- **In the cases considered in SCWA’s simulations, integrating forecasts of reservoir inflows and local flows downstream in release decision making would permit operators to more**

reliably meet water management objectives and environmental flows in the Russian River basin.

- **In the cases considered in HEC's simulations**, operating based on forecasts of reservoir inflows and local flows does not adversely affect flood risk management. (Results showed no significant increase in AAD or EAD.)
- The greatest improvements for reliability of meeting water management objectives and ability to meet environmental flow requirements come if WCM rules are modified to integrate FIRO, rather than relying on temporary deviations from the WCM rules.

## 1.7 Considering the preliminary results, what does the project team recommend as next actions for the FVA?

Considering results from the PVA, the SC recommends that the FVA of FIRO for Lake Mendocino proceed. The SC recommends:

(1) investigating viability in detail, considering and selecting components of the system and FIRO strategies that could be implemented in the near-term using current technology and scientific understanding (e.g., forecast of near-term dry conditions); and

(2) identifying and developing new science and technologies that can ensure FIRO implementation is safe and successful, and to enhance FIRO where possible.

(3) working with USACE and SCWA, the SC should develop a plan for utilizing deviations to the WCM for each of the next few years. Each deviation request by SCWA to USACE would be designed to explore the viability of implementing certain FIRO strategies using current forecast skill and technology with the appropriate constraints and limitations that meet USACE conditions for deviations per SPD (South Pacific Division) policy (*Engineering and Design Guidance on the Preparation of Deviations from Approved Water Control Plans*, 2014). **It is anticipated that each subsequent deviation request will build on the prior year's experience and will be modified as appropriate with the concurrence of USACE, SCWA and the SC.** The SC should also work with USACE and SCWA to determine what types of changes to reservoir operation rules are most effective to allow various levels and components of FIRO implementation, and what types of changes to reservoir operation rules will be acceptable to USACE (for example, rules that shift to accommodate forecasts of an extreme event). To implement FIRO, USACE approval will be required through updates of the WCM. USACE guidance on developing FIRO alternatives is needed.

The SC acknowledges the need for and recommends additional research be conducted by the contributing agencies and centers, including CW3E, SCWA, USACE ERDC, and others. The results of these additional studies should be included in the FVA to answer the following key questions that arose during the PVA:

- Although elements of the PVA considered the possibility of encroaching into the conservation pool prior to a predicted flood-producing storm, the PVA mostly emphasized consideration of retaining extra water to reduce drought impacts. A greater emphasis should be put on exploring how changes to the operating rules to permit pre-releases before a major landfalling AR could enhance flood-risk mitigation capacity of Lake Mendocino.
- What forecasting methods and technology (e.g., meteorological and watershed observations and models) must be enhanced to enable implementation of FIRO? While hydrometeorological forecasts of sufficient accuracy may be available for the Russian River watershed in many instances, important gaps remain in the details, even for

shorter lead times. In addition to better skill in the details of extreme event prediction at short lead times (up to 5 days), enhancements are also required for forecasting with longer lead times (5 days to several weeks) to realize fully the potential improved reliability in meeting water management objectives.

- Given the potential predictability of synoptic scale systems/circulation and ARs at these lead times, pursue the reliable and skillful outlooks at 6 to 10 days of the low risk for extreme precipitation events in the vicinity of the river basin that can provide guidance for operational decisions to hold additional water in the flood pool for another day rather than immediately evacuate water from flood.
- AR-specific forecast skill metrics should be developed. Skill should be considered as release decisions are made. Improvements to skill should be monitored.
- In addition to forecasting days to weeks ahead of ARs, enhancements that permit seasonal forecasting would provide even more opportunity for wise decision making about Lake Mendocino operation. Scientific inquiry is needed to support this.
- Evaluate the opportunities for significant improvements in forecast skill and reliability for extreme precipitation events and ARs using the state-of-the-art operational and emerging weather forecast systems such as RAP, HRRR, NGGPS, NBM, and other post-processing innovations.
- Evaluate emerging watershed and runoff forecast systems such as the National Oceanic and Atmospheric Administration's (NOAA's) **National Water Model (NWM)** and USACE's Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model run at temporal and spatial scales that directly support FIRO goals and objectives.
- In addition to forecasts, successful FIRO depends on, and can leverage for improvements, whatever knowledge is available regarding the current hydrologic state of the reservoirs, river (and tributaries), and watershed at the time of decisions. Scientific inquiry and plans to ensure that monitoring of the state of the system is adequate, or to improve monitoring, is needed.
- What is the full range of potential benefits that FIRO can provide? Additional assessments are needed to quantify costs and the socio-economic benefits of FIRO for agriculture, fisheries, recreation, water management reliability, flood risk management, and other societal and environmental needs.

## 2 What FIRO is and what it may accomplish at Lake Mendocino

Coyote Valley Dam, which impounds Lake Mendocino on the East Fork Russian River three miles east of the City of Ukiah, is operated cooperatively by SCWA and USACE for flood and water management and environmental protection. Operation is governed by WCM rules that allocate the 122,400 AF of storage to flood management and conservation purposes in a seasonally varying manner and specify how water may be stored in the flood pool and conservation pool. Additional information about the dam, reservoir, and river system, the demands, and the operation rules are provided in this section.

In the past decade, reliability of Lake Mendocino to meet water management objectives declined due to decreased inflow resulting from a reduction in diversions from the Potter Valley Project (PVP) upstream of the reservoir. The reduced storage in Lake Mendocino exacerbates the impacts of drier hydrologic conditions. The lack of flexibility in the WCM to adjust to these changed conditions created challenges for water managers. As described in this section, the risk-averse operation rules required release of water that could have been used later for water management objectives and to meet environmental flow requirements. (Environmental flows were reduced, which likely affected habitat, and the cold water pool was depleted.)

FIRO of Lake Mendocino is an alternative operation strategy that aims to match in an adaptive manner the available water with available storage, thus increasing reliability. As described in this section, FIRO would use available reservoir storage in an efficient manner by (1) better forecasting inflow (or lack of inflow) with enhanced technology, and (2) adapting operation in real time to meet the need for storage, rather than making storage **available “just in case” it is needed. For example, storage reserved for flood management** under current rules could be used for water management objectives unless and until a strong to severe AR lasting a day or longer is forecasted. In this example, if great inflow due to an AR is forecasted, space could be emptied to store and manage excessive flows and avoid uncontrolled release through the spillway. The envisioned FIRO strategy has the potential to simultaneously improve water supply reliability, flood protection, and ecosystem outcomes through a more efficient use of existing infrastructure while requiring minimal capital improvements in the physical structure of the dam.

### 2.1 Lake Mendocino history and description

Lake Mendocino is part of the Russian River Project. Figure 2 shows its location. The 1,485-square mile Russian River watershed is a narrow valley between 2 adjacent northern coastal mountain ranges. The watershed is about 100 miles long and varies from 12 to 32 miles in width. Table 6 provides an overview of Lake Mendocino and the watershed.

Figure 3 is a schematic of the Upper Russian River system—the system considered herein. Water from the Eel River is stored in Lake Pillsbury, which is part of Pacific Gas and Electric **Company’s** (PG&E) PVP. PG&E schedules releases from Lake Pillsbury 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 PVP Powerhouse. Eel River flows diverted through the PVP Powerhouse are released into the East Fork of the Russian River. A portion of the water released from the PVP is diverted by the Potter Valley Irrigation District (PVID) at two canals located just below the powerhouse. PVID has a contract with PG&E to divert up to 50 cubic feet per second (cfs). Additional water is diverted through the PVP Powerhouse to generate power and to maintain FERC-required minimum flows in the East Fork of the Russian River below the powerhouse.

As illustrated in Figure 3, water not diverted by PVID or other water rights holders flows into the East Fork of the Russian River into Lake Mendocino. Other inflows to Lake Mendocino are from runoff from an approximately 105-square mile drainage area. Water from Lake Mendocino flows generally south to Forks where it meets the West Fork Russian River. Flow continues south to Hopland, Cloverdale, and Healdsburg, where Dry Creek forms a confluence with the Russian River.

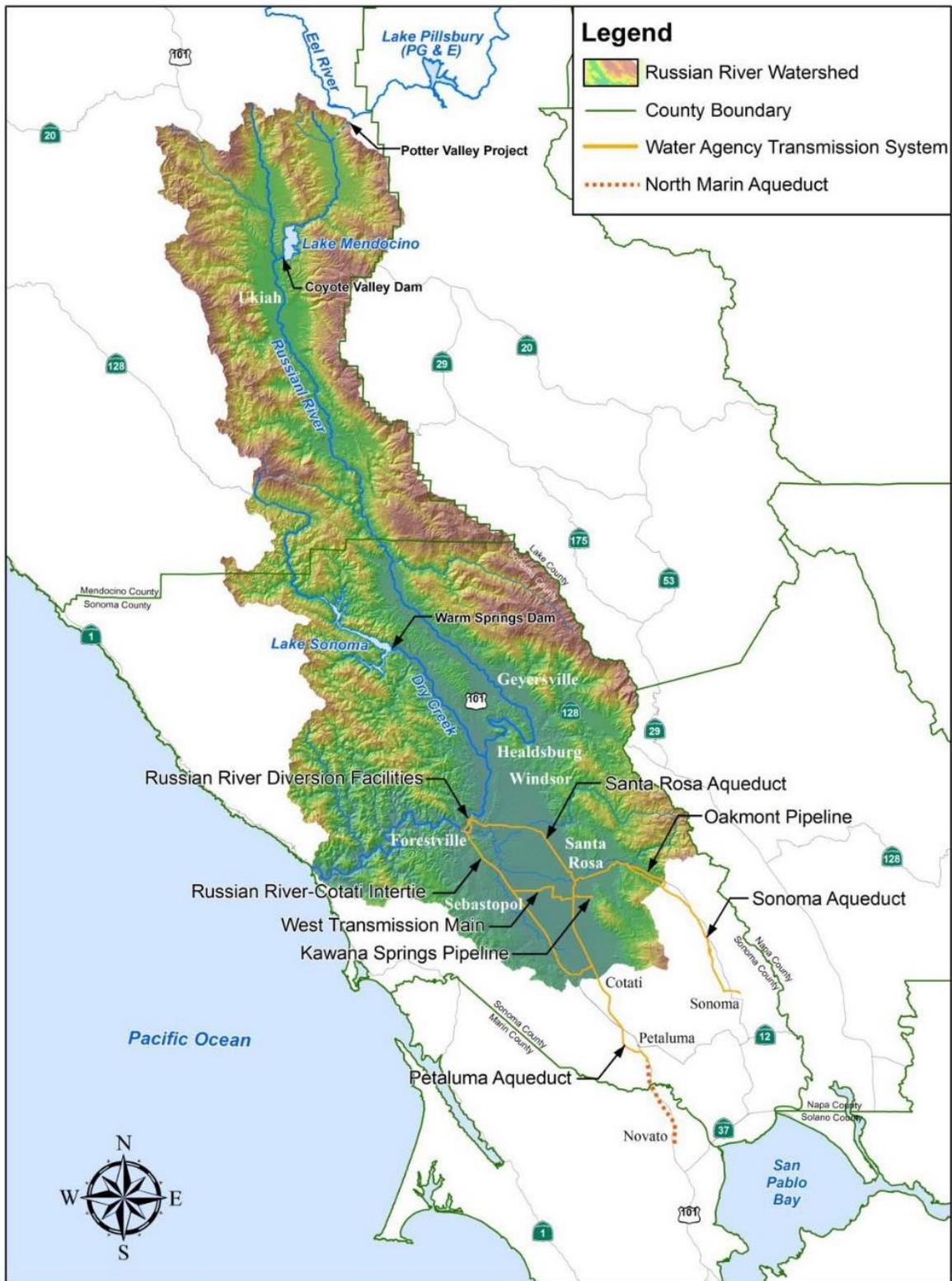


Figure 2. Map of Russian River watershed, including SCWA transmission system (FIRO Steering Committee 2015)

Table 6. Overview of Lake Mendocino and the Russian River watershed (summarized from the SCWA report)

Element (1)	Description (2)
Location	East Fork Russian River in Mendocino County, California
Watershed	Russian River watershed
Climate	Wet and dry seasons, with 93% of annual precipitation in October to May. A large percentage of the rainfall typically occurs during 3 or 4 major winter storms. These major storms often come in the form of an AR, which is a type of storm that transports large amounts of water vapor through the atmosphere along a narrow corridor. Although brief, ARs can produce 30-50% of the region's annual precipitation during a few days (e.g., Ralph et al. 20013). 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.
Flooding	Floods in the Russian River watershed are normally of short duration, lasting three to four days, developing within 24 to 48 hr after the beginning of a storm, but rapidly receding within 2 or 3 days (USACE 1984). Floods occur during the rainy season from November through April and larger storms can inundate the portions of the alluvial valleys (Ukiah, Hopland, and Alexander) adjacent to the river (USACE 2003). However, storms have occurred in October and May, which have caused minor or moderate flooding. Normally floods in the basin are flashy, since the times of concentration on tributaries are short and flows respond rapidly to variations in rainfall (USACE 1954).
Impoundment	Coyote Valley Dam, earth embankment dam approximately 160 ft high with a crest length of 3,500 ft
Dam construction	Completed in 1958
Project	Russian River Project, which also includes Lake Sonoma on Dry Creek
Dam owner	USACE
Operation objectives	Flood control, water supply, irrigation, hydropower, and recreation
Operator	USACE manages flows in the flood control pool of the reservoir
Operating partner	SCWA manages flows in the water supply pool of the reservoir
Water control manual	Lake Mendocino Water Control Manual, published in 1959, revised in 1986. Exhibit A of the manual was most recently revised in September 2003 to incorporate the most recent bathymetric survey information.
Storage at top of dam	153,700 AF
Storage at spillway crest	116,500 AF
Winter conservation pool capacity	68,400 AF
Spring/summer conservation pool capacity	111,000 AF
Reservoir inflows	From a 105-square mile drainage area and from PVP, which generates power and diverts water from the Eel River to the East Fork of the Russian River. Water is diverted for irrigation from the reach between PVP and Lake Mendocino.

Element (1)	Description (2)
Reservoir outflows	Reservoir 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.
Salmonid species	One endangered and two threatened species.
Downstream channel	Capacities range from 7,000 cfs near Ukiah to 35,000 cfs near Guerneville. During the rainy season (November through April), flow is mostly due to natural drainage instead of reservoir releases. During drier months (May through October) flow is largely from Lake Mendocino upstream of Dry Creek.
Flood history	<p>The City of Hopland and surrounding areas are some of the most flood prone regions along the Upper Russian River Reach. Flood stage at the US Geological Survey (USGS) gage near Hopland is 21 ft, which corresponds to a flow rate of approximately 15,000 cfs. Since 1959, the maximum flow rate recorded at the Hopland Gage is 33,700 cfs in December of 1964, and water levels have reached flood stage 16 times (22% of the years). Additionally, minor flooding begins occurring in Hopland when the stage exceeds the banks of the channel, which can cause flooding and closure of the Highway 175 bridge. According to the CNRFC, this occurs at a stage of 15 ft and a flow rate of approximately 8,140 cfs (NOAA n.d.). Since 1959, flows have exceeded 8,140 cfs 124 times (62% of the years).</p> <p>The City of Healdsburg is prone to flood during extreme rainfall events. Flood stage at the USGS gage near Healdsburg is 53,000 cfs (NOAA n.d.). Since 1959, the maximum flow rate recorded is 69,300 cfs, which occurred in January of 1995, and water levels have reached flood stage 4 times (7% of the years).</p> <p>The City of Guerneville is prone to flooding associated with heavy rainfall events. Flood stage at the Johnson Beach gage (USGS 11467002, Russian River at Guerneville) is 32 feet (NOAA n.d.). This gage is no longer rated as the official USGS flow records are collected upstream at Hacienda Bridge (USGS 11467000, Russian River near Guerneville). Stage at this location has reached flood stage in slightly more than 50% of years since 1940. The flood of record for this location was in December 1964 with a peak stage of 49.6 feet.</p> <p>USACE considers the 1955 and 1964 floods the two greatest floods of record. The December 1955 flood included a small peak followed by a second larger peak that caused substantial flood damage. The 1964 flood included 2 smaller peaks before the main flood peak and caused Coyote Valley Dam to spill for the first time since dam completion. The original Standard Project Flood for Coyote Valley Dam was based upon the January 1943 flood, but USACE later updated this to the December 1955 flood, even though the December 1964 storm produced a higher discharge.</p>

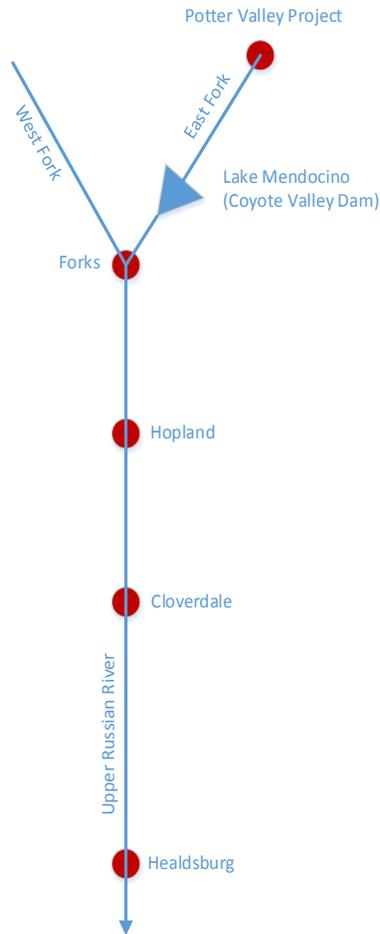


Figure 3. Schematic of the Upper Russian River (from the SCWA report)

## 2.2 Current reservoir operation

Operational decisions at Lake Mendocino are governed by rules in the Lake Mendocino WCM. Those rules allocate available storage to a flood control pool at the top of the reservoir and a conservation pool (water supply pool) below that. The storage allocation strikes a balance between the need to keep an empty reservoir for managing excess flood water and a full reservoir for meeting water management objectives and environmental flows.

Considering the seasonally varying need for flood storage in the Russian River watershed, the allocation of Lake Mendocino storage capacity is seasonal. In the winter, more storage space is allocated for the flood control pool with the bottom of the flood pool (top of the conservation pool) at 68,400 AF. In the spring, the amount of conservation storage space available increases, allowing the reservoir to refill for the summer. In the summer, the bottom of the flood pool (top of the conservation pool) is adjusted to 111,000 AF. In the fall, conservation pool storage again decreases to 68,400 AF. Figure 4 shows the rule curve (also called the guide curve) for Lake Mendocino, with its seasonally varying storage allocation.

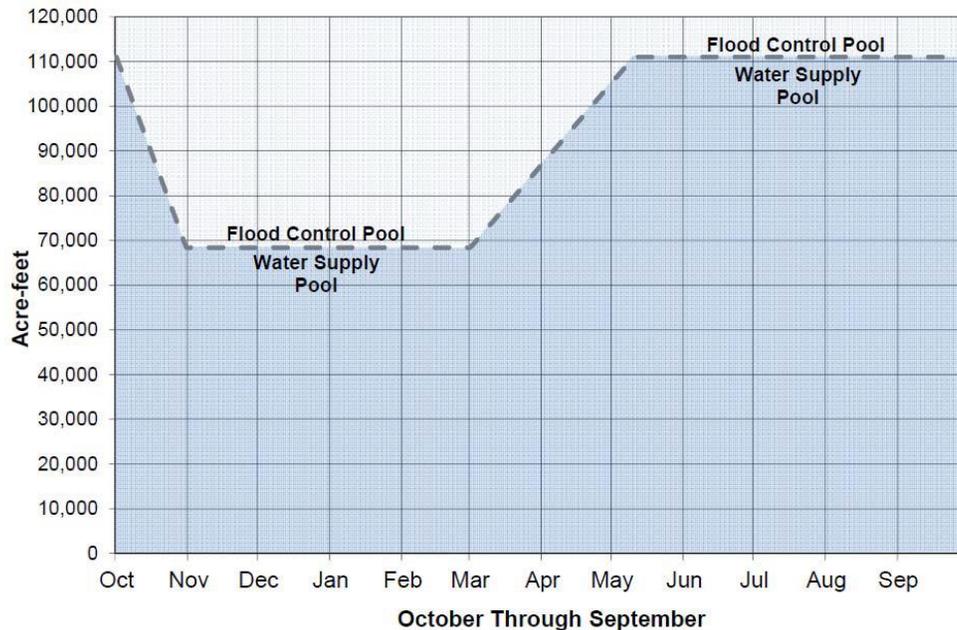


Figure 4. Simplified Lake Mendocino guide curve: water must be released from the lake between November 1 and March 1, when water levels are above 68,400 AF (FIRO Steering Committee 2015)

USACE developed the seasonal storage allocation represented with the guide curve when the WCM was published in 1959. USACE analysts based the allocation on data and technology available at the time. Streamflow records available since 1940 were analyzed, and the guide curve was developed considering weather patterns represented in that record. No provision was made in the rules for adjusting the allocation with information from short-term inflow forecasts of, for example, a large AR storm or due to a prolonged period of no inflow.

### 2.2.1 Flood management

The Russian River basin responds rapidly to variations in rainfall, resulting in rapid rises in river stage. In general, flood operation of Lake Mendocino is designed to store water during a flood event, then release soon thereafter to create storage space for another event. Rates of release called for in the WCM depend on pool level storage, properties of non-regulated flows in the Russian River, flood stages downstream of the dam, and current releases.

Major constraints specified by the WCM include:

- Limit flow to 8,000 cfs at Hopland. Current procedure is to limit flow to 8,000 cfs based on the assumption that local flooding at Hopland begins when flows exceed 8,000 cfs.
- Limit rate of change in releases to 1,000 cfs per hr. Sloughing is more likely to occur when channel flows decrease rapidly.

Operation also observes rate-of-change of release constraints to protect salmonid-occupied habitat. These were developed in consultation with the National Marine Fisheries Service (NMFS).

### 2.2.2 Water supply management

SCWA operates Lake Mendocino to (1) meet downstream demands of agricultural and residential water users and several public and municipal systems; and (2) maintain environmental flows in the upper river to its confluence with Dry Creek. Releases are made to meet environmental flow requirements from **SCWA's** water rights permits and provisions of SWRCB Decision 1610 (D1610), which was adopted on April 17, 1986. **SCWA's permits** authorize diversions to storage in Lake Mendocino, re-diversions of water released from storage, and direct diversions at points downstream. Their permits also establish environmental flow requirements for Dry Creek and the Lower Russian River. Operations are also subject to the Russian River Biological Opinion issued by NMFS on September 24, 2008.

The environmental flow requirements are based on hydrologic year type, an index of watershed wetness specified **in SCWA's** water rights permits. The hydrologic year type for the Russian River system is based on cumulative inflow into Lake Pillsbury on the upper Eel River. As discussed before, Lake Pillsbury is outside the Russian River basin and is part of PG&E's **PVP**. Thus, **Lake Mendocino's** operation to meet water management objectives and environmental flow requirements **is highly dependent on operation of PG&E's PVP**. Hydrologic year types for 1985 to 2010 are shown in Figure 5.

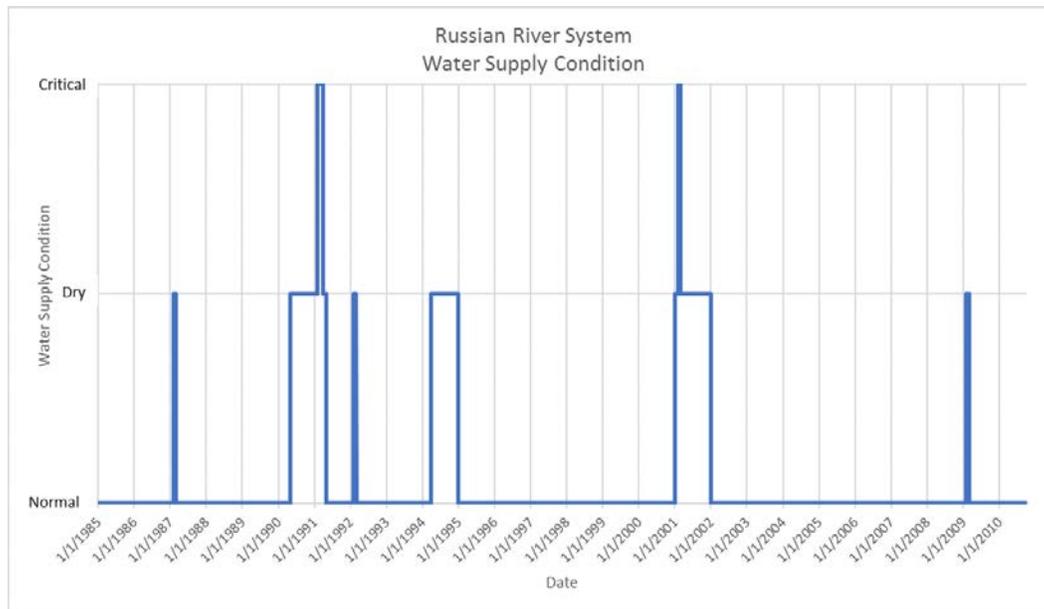


Figure 5. Lake Mendocino hydrologic year types for 1985 to 2010

### 2.2.3 Operation challenges

SCWA with approval from USACE must operate the reservoir to meet multiple objectives, which can at times present challenges in terms of competing goals of water management reliability and flood management.

Operation for water management objectives has become more difficult because of changes **in operation of the PVP. These changes are due to amendments to PG&E’s license to operate** the hydropower facilities of the PVP. The amendments significantly constrain PVP operations during the spring, yielding decreases in inter-basin transfer. While the PVP historically provided approximately 160,000 AF annually to the Russian River Watershed, since 2006 the diversion has been reduced to an average of 72,000 AF annually. (The average water year natural inflows into Lake Mendocino excluding PVP imports is approximately 107,000 AF per year as calculated from the unimpaired flows prepared by the CNRFC from water year 1959 to 2010.) This has resulted in an overall reduction of water supply in Lake Mendocino.

Observed and anticipated shifts in climate have created challenges in operation. For example, the prolonged drought in California stretched the capability of Lake Mendocino to meet summer requirements. An analysis by SCWA for the 2015 *Lake Mendocino Water Supply Reliability Report* found supply from Lake Mendocino will become increasingly unreliable in a variety of climate change and population growth scenarios.

In the future, increasing demands for water will create more stress on the ability of Lake Mendocino to meet water management objectives reliably for the region, especially with more variable hydrologic conditions predicted. The WCM rules when developed relied on 1950s estimates of seasonal flood potential to allocate flood storage and to establish release requirements to keep flood storage empty in anticipation of future flood events. As noted above, this means in some years operation to evacuate storage to manage floods anticipated with the 1950s estimates releases water that otherwise could be used for water management objectives.

For example, following an AR-type storm in December 2012, water was released to create flood space according to the WCM, dropping reservoir levels by more than 35%. Calendar year 2013 was the driest year on record, resulting in little inflow to refill the reservoir. By December 2013, lake levels were extremely low and remained low through 2014. Ideally, water from the December 2012 event could have been retained based on daily updates of short-term (e.g. 5-day) precipitation forecasts, lessening the impact of drought for the first few months. Making such a decision considering the likelihood of future flood inflows is a challenge for Lake Mendocino operators.

Changes in the variability and intensity of extreme precipitation events and ARs provide additional reservoir management challenges in a non-stationary climate. While not evaluated as part of the PVA, more effective use of the best-available data and forecast information under the auspices of FIRO could enhance flood protection in the watershed through the release of additional **water from the reservoir's** conservation pool to lower reservoir levels, providing **additional storage for "controlling" flood waters prior to heavy** rainfall events.

## 2.3 Opportunities for improved operation

Lake Mendocino operation for flood and water management and environmental protection can be improved and challenges overcome with use of advanced technology and with changes to operation rules.

### 2.3.1 Advanced technology

Currently available and developing technology can provide better information to operators to make release and storage decisions for Lake Mendocino. That technology includes, but is not limited to:

- Instrumentation for enhanced observation of weather conditions that influence precipitation in the Russian River watershed. This is particularly important, as studies have found approximately 50% of the precipitation and 80% of the floods are due to AR events that are detectable offshore.
- Instrumentation for enhanced observation of watershed conditions that influence runoff in the Russian River watershed. This instrumentation includes, for example, probes that measure soil moisture, a key modulator of runoff in the watershed.
- Enhanced weather prediction models, including models that better forecast timing and intensity of AR events and describe the uncertainty about the forecast. These include improvements in forecast skill and reliability for extreme precipitation events and AR events using the state-of-the-art operational and emerging weather forecast systems such as RAP, HRRR, NNGPS, NBM, and other post-processing innovations.
- Improvements in AR characterization offshore through airborne reconnaissance and innovative remote sensing satellite measurements targeting the detailed position and structure of ARs offshore 1-to-3 days prior to AR landfall.
- Enhanced watershed runoff models that better represent high-frequency physical processes, including surface-groundwater interaction, and effectively integrate uncertainty associated with observations, model states and formulation, and future (meteorological) forcings. Examples of emerging technologies include **NOAA's NWM** and the **USACE's GSSHA**.
- Enhanced data management systems that permit SCWA, USACE, and others to organize, store, retrieve, and share weather and water data and information.

- Enhanced visualization software applications with which operators and stakeholders can produce charts, graphs, maps, and other displays of observed and forecasted states of the watershed, reservoir, and river system, and uncertainty about those states.
- Advanced river models that simulate behavior of the Russian River under differing flow conditions and describe uncertainty about that behavior.
- Advanced reservoir models that simulate reservoir operation following specified rules.
- Decision support systems that integrate data management functions, visualization tools, and simulation models for ease of use by operators.

### 2.3.2 Opportunities for deviations in and improvements to operation rules

While the operation rules included in the Lake Mendocino WCM are firm rules, USACE provides a process for modifications to improve operation. These WCM modifications can be categorized as:

- Significant permanent changes that require an update to the WCM. This would include, for example, permanent change in the allocation of storage to flood management and conservation pools. The Lake Mendocino WCM has been updated twice since 1959 to incorporate permanent changes. WCM changes are subject to review and approval by USACE water management policy makers.
- Temporary deviations from the existing WCM rules. On December 18, 2014, USACE SPD issued *Engineering and Design Guidance on the Preparation of Deviations from Approved Water Control Plans*. This described the policy for granting and procedures for requesting changes for emergency, unplanned, and planned (minor and major) deviations to WCMs. A planned minor deviation is short-term operational change *...limited by 1) flood control pool elevation will not vary more than 2 feet from what would have been the water surface elevation under the approved Water Control Plan or ii) storage difference from approved Water Control Manual will not exceed 5% of the total storage. Minor deviations should not last more than 10 days. Longer minor deviation must be coordinated with the SPD Senior H&H/Water Control Engineer*. Operational changes outside these limits are categorized as major deviations. For those, USACE requires analysis of risk changes attributable to the deviation, along with assessment of the impact of uncertainty about the risk drivers.

Anticipating difficulties in meeting demands due to drought conditions, the Mendocino County Russian River Flood Control & Water Conservation Improvement District (RRFC) requested and the USACE approved a deviation from the normal water control plan in February 2014 to store up to an additional 5,825 AF, or 5% of total storage at Lake Mendocino. However, storage never exceeded the conservation pool capacity in 2015, so the deviation was not exercised that year. The deviation was used for the winter of **2015/2016 and resulted in the USACE temporarily retaining inflow in Lake Mendocino's** flood pool for a series of storms in February 2016. The additional water stored under this deviation provided improved reliability in meeting water management objectives for SCWA and water users in the Upper Russian River reach for the remainder of the 2016 water year. A similar deviation request in 2017 permits similar operation.

### 2.3.3 FIRO

FIRO for Lake Mendocino combines advanced technology with changes to operation rules so release and storage decisions can take advantage of additional or more accurate information available through use of the technology. The goal at Lake Mendocino is to make modest incremental adjustments to the WCM flood management guidelines to improve reliability in meeting water management objectives and ability to meet environmental flow requirements without diminishing (or actually enhancing) flood protection or dam safety. To achieve this,

operation would be informed by enhanced technology, with specific components identified in the FVA should the PVA described herein demonstrate a potential for achieving the goal.

Examples where Lake Mendocino FIRO could provide benefits include:

- Drought mitigation scenario—When recent storms have caused moderate-to-high reservoir levels, but no major precipitation is forecasted for several days, water could be stored in the flood pool, at higher levels than currently allowed (unless a new storm appears before spring refill). This action may provide additional water during the summer dry period.
- Flood mitigation scenario—When a storm is predicted to be intense enough to cause **inundation, water could be released from the reservoir's** conservation pool to lower reservoir levels (if confidence is high the storm will at least refill the reservoir to the level of the standard conservation pool). This action may provide additional storage for **"controlling" flood waters.**
- Ecosystem benefits—Increased flexibility in reservoir storage can improve the timing and volume of releases to improve water quality conditions and provide reliable flow for endangered salmonids. For example, greater spring reservoir storage volumes lead to **wetter "year type" classifications which result in higher minimum in-stream flow requirements** during the summer period.

Operation informed by forecasts have been proposed and implemented successfully elsewhere in California. Forecast informed operation has been proposed for operation of Folsom Lake (located about 25 mi northeast of Sacramento, California) by the Water Resources Development Act (WRDA) of 1999. Assessments have shown that forecast informed operation **would allow the reservoir to pass the  $p=0.005$  ("200-year") flood event** without exceeding target releases, an improvement from other alternatives that do not include forecast informed operation. This is due to forecast informed operation providing reservoir operators the flexibility to drawdown the reservoir early based on forecasts of inflows. Improved reliability in meeting water management objectives is also anticipated as forecast informed operation would permit operators to hold more water when storms are not forecasted. Forecast-coordinated operations for the Yuba-Feather River system in northern California also illustrate the potential benefits of forecast informed operation. In this case, reservoirs in parallel (Lake Oroville on the Feather River and New Bullards Bar Reservoir on the Yuba River) are operated for target flows at a common downstream location below the Yuba-Feather River confluence. By using forecasts and models of reservoir operation integrated into a DSS, water managers from different agencies can assess potential release schedules and ensure coordinated operation so that flow is not exceeded at the downstream control point.

## 2.4 FIRO and the Lake Mendocino collaboration

To explore methods for better balancing flood management and reliability of meeting water management objectives with FIRO in the Russian River watershed, the Lake Mendocino FIRO SC was formed. The committee, led by CW3E and SCWA, includes USACE and other federal and state agencies. (Members of the SC are listed in Table 2.) The SC collaboratively developed a work plan to assess the viability of FIRO for Lake Mendocino. Figure 6 illustrates the viability assessment process envisioned. This is described in greater detail in *A Comprehensive Plan to Evaluate the Viability of Forecast Informed Reservoir Operations (FIRO) for Lake Mendocino* (FIRO Steering Committee 2015).

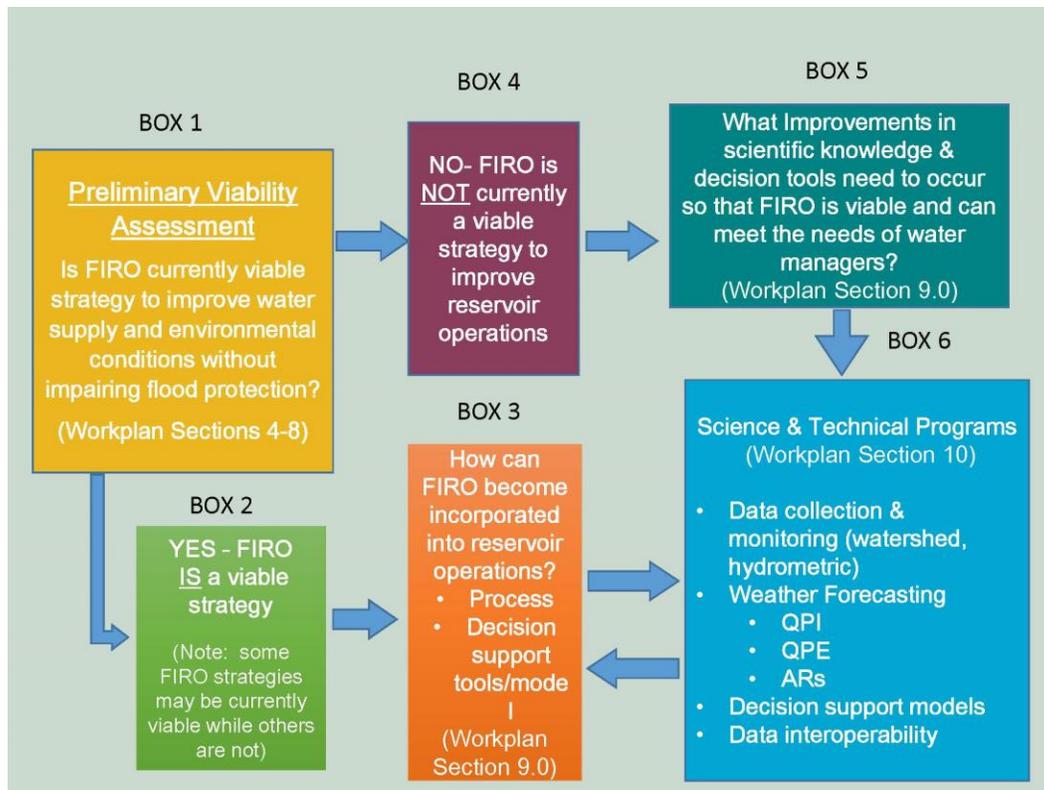


Figure 6. Flow diagram depicting the FIRO viability assessment process (FIRO Steering Committee 2015)

The study reported herein is the PVA of FIRO, with additional studies to follow, as illustrated. The PVA was undertaken in 2 parts, each of which is described in Section 3 of this report:

1. An independent study to consider if forecast informed operation could improve reliability in meeting water management objectives and to what extent improvements are achieved.
2. An independent but coordinated study to consider impacts forecast informed operation would have on flood risk management in the system, and if the capability of the system is diminished, if that can be mitigated.

For the PVA, specific technical components and operational rule changes were not identified. Instead the studies included components consistent with those that may be included. The studies also simulate performance of enhanced forecasting systems. If the PVA finds benefit attributable to FIRO, the subsequent FVA will include (1) identification of alternative technology and operational changes that would be included in FIRO; (2) evaluation and comparison of the flood management, water management reliability, and ecosystem benefits of those alternatives; (3) selection of components of the system for implementation; and (4) a detailed evaluation of benefits of the selected system.

## 3 How we assessed the viability of FIRO

The Lake Mendocino FIRO SC collaboratively developed a multi-year work plan to assess the viability of FIRO for Lake Mendocino. The initial task in that plan was the *preliminary* assessment of the viability, PVA, of forecast informed operation—an assessment intended to **inform the SC's decision (1) to take steps to deploy FIRO components with existing technology; (2) to delay FIRO implementation until enhancements to the technology are available; (3) to take an incremental approach, implementing FIRO with available technology, then refining Lake Mendocino operation as enhanced technology becomes available; or (4) to seek a different solution.**

### 3.1 Questions we sought to answer in the PVA

For the PVA, the study team developed FIRO alternatives for Lake Mendocino and—using models of the reservoir operation to simulate forecast informed operation—answered the following questions to inform decision making about how best to proceed:

1. If FIRO is implemented, will operation improve reliability in meeting water management objectives and ability to meet environmental flow requirements, and to what extent?
2. If FIRO is implemented, will operation adversely affect flood risk management in the system? If so, where and to what extent can that be mitigated?

SCWA analysts focused on the first question, assessing improved reliability in meeting water management objectives attributable to FIRO. HEC analysts focused on the second question, assessing changes in flood risk attributable to FIRO. The SCWA model seeks releases that meet a selected level of risk tolerance. The HEC models follow a defined operation rule set, then report risk.

In addition, to assess forecast accuracy, CW3E focused on the following question for the PVA:

3. What meteorological and hydrological forecast skill is required to enable FIRO to be implemented? Is current forecast skill for landfalling ARs (and their associated heavy precipitation and runoff) and other extreme precipitation events adequate to support FIRO, and what improvements would be needed to enable full implementation of FIRO for Lake Mendocino?

The SCWA, HEC, and CW3E accompanying reports describe the analyses in detail. This section of the report provides an overview of the methods used. Results of the analyses are included in the accompanying reports and are summarized in Section 4 of this report.

The body of work completed by SCWA, HEC, and CW3E were conducted to efficiently address the questions identified by the SC and to inform decisions associated with how and if to pursue the FIRO strategy.

### 3.2 Overview of how SCWA answered the water management reliability related question

#### 3.2.1 Water management reliability assessment method

SCWA analysts developed a numerical model using MATLAB software to simulate Lake Mendocino operation. This model computes reservoir storage levels, releases, and flow conditions in the Russian River from the reservoir to the USGS Russian River at the Healdsburg stream flow gaging station approximately 65 miles downstream of Lake

Mendocino. The SCWA model simulates operation to meet both water management and flood control objectives, with and without-FIRO. The model simulates operation for 1985-2010, the period for which information about historical flows and forecasts is available.

**Recognizing forecast uncertainty, SCWA's model uses a "risk-based"** release decision process that makes available maximum storage for water management objectives without strict adherence to a rule curve. That process relies on an ensemble forecast of runoff from precipitation throughout the Russian River watershed, including inflow volumes to Lake Mendocino. This ensemble, an example of which is shown in Figure 7, is provided by the CNRFC. Each hydrograph shown in the figure represents runoff from a possible future precipitation and temperature condition, and each is considered equally likely.

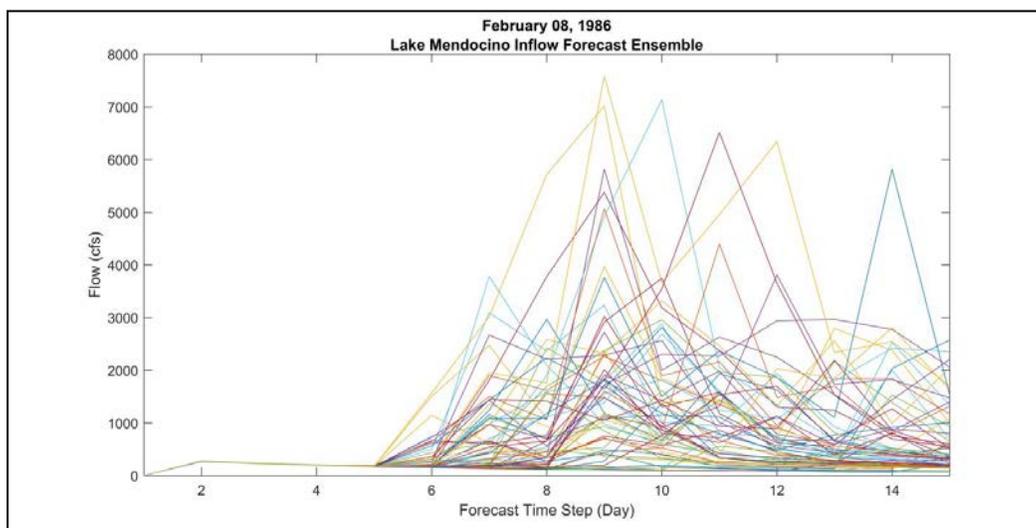


Figure 7. Lake Mendocino ensemble forecast example (from the SCWA report)

To generate the ensemble forecasts used in this study, the CNRFC leveraged the Hydrologic Ensemble Prediction System (HEFS). HEFS utilizes the identical CNRFC hydrologic modeling framework used to generate routine single-value short-term forecasts. This includes mean areal processors for precipitation and temperature, a rain-snow operation, a snow model (mostly inactive in the Russian), the Sacramento Soil Moisture Accounting Model (SAC-SMA), a simple reservoir model, a variable lag&k routing model, and a host of arithmetic operations. Components of the Russian River model were calibrated by CNRFC hydrologists over the period of record of gage observations (1958-present), with emphasis on the more recent data (e.g. last 15 years). HEFS begins each of its ensemble member runs with the current model state and projects an equally likely outcome of streamflow over time for each ensemble member of future weather (temperature and precipitation).

Future ensembles of precipitation and temperature are generated by the Meteorological Ensemble Preprocessor (MEFP). The MEFP calibrates the relationship between a set of historical predictions (e.g. model predicted precipitation for a specific grid) and historical observations (e.g. mean areal precipitation for a watershed near or within the same model grid). Fundamentally, the MEFP transforms a single-value forecast (e.g. GEFS ensemble mean of precipitation) into an unbiased set of  $n$  ensemble members that accurately represent the uncertainty through the spread exhibited in the ensemble members. Uncertainty and bias are allowed to vary throughout the year and are assessed for all lead-times of the available historical forecasts. The MEFP also contains a feature that allows for

temporal aggregation that leverages the skill in multi-period (e.g. more than 6-hour) forecasts. If the historical forecasts have perfect skill (correlation=1.0), then the resulting ensembles will be de-biased and will all be identical (no spread). If the historical forecasts have no skill (correlation=0.0), the resulting ensembles will reflect observed climatology. In practice, something in between happens that accounts for skill that varies with lead time and aggregation periods. The number of ensemble members generated by the MEFP is a function of the number of years of mean areal precipitation (MAP) and mean areal temperature (MAT) available. The details of this process are described by Demarge, et.al. 2014.

For this study, the CNRFC calibrated the MEFP using the 25-year (1985-2010) reforecast of the GEFS v10 generated by Hamill(2013) against a subset (1985-2010) of the 1949-2010 calibration MAP and MAT time series for each watershed of the Russian River from the inflow to Lake Mendocino down to Guerneville. The MEFP was then used to generate a 61-member ensemble reforecast for each day from 1985 through 2010 given the GEFS v10 reforecast of ensemble-mean temperature and ensemble-mean precipitation for that day.

Initial hydrologic model states for each day (1985-2010) were generated **by the CNRFC's** operation model through continuous simulation using the calibration MAPs and MATs. Using these initial model states (one for each day) and the MEFP reforecast 61-member ensembles of precipitation and temperature, the CNRFC hydrologic model was used to generate the 61-member ensemble reforecasts of streamflow used in the SCWA study. **The term "reforecast" and "hindcast" used elsewhere in this report are** synonymous.

Because the GEFS v10 reforecast is limited to 1985-2010, the HEFS reforecasts are also limited to this period. While this period does include three major runoff events (1986, 1997, and 2005/6), it does not include the flood of record (1964) or a robust sample of extreme events. This is a limitation that warrants consideration and may necessitate further work. Further, since the initial watershed states were generated through simulation **without the "benefit" of forecaster interaction, the reforecasts** likely represent a slightly less skillful approximation of the current operational hydrologic forecasting process.

**SCWA's approach** uses selected inflow ensemble members to model and forecast Lake Mendocino storage conditions with a candidate release strategy. An example of the computed storage is shown in Figure 8 for the February 8, 1986 inflow hindcast, just days before the large flood event of 1986. As shown, the storage forecast includes a broad array of potential outcomes: Operation with some inflow ensemble members and the candidate release yields storage elevations below the spillway crest storage level of 116,500 AF while operation with others yields elevations that reach or exceed the spillway crest or top of the dam.

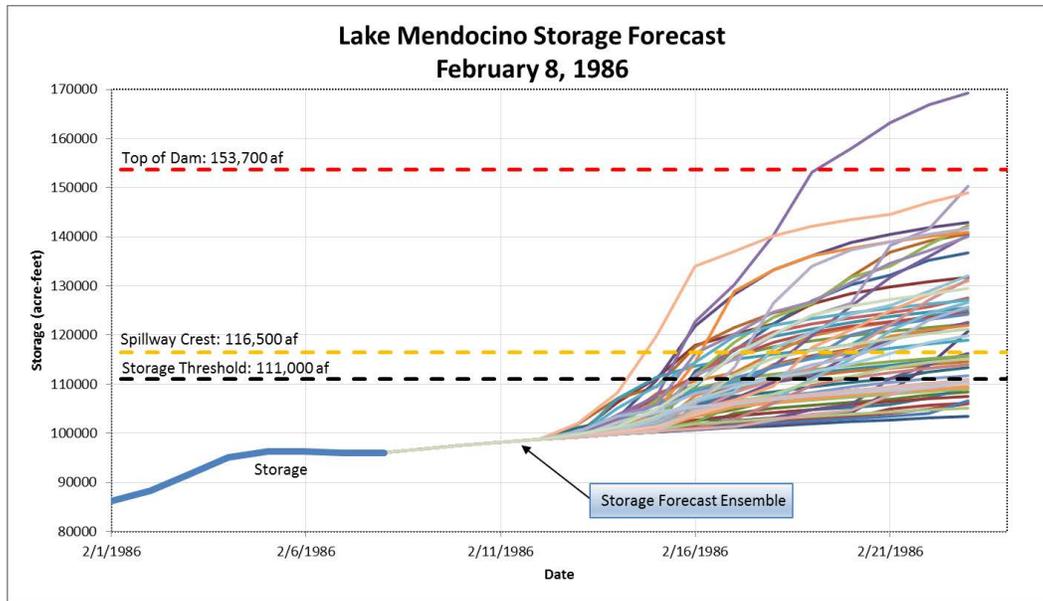


Figure 8. Example of SCWA model storage forecast ensemble, using CNRFC flow forecast ensembles for February 8, 1986 with candidate release schedule (from the SCWA report)

From the storage forecast ensemble, the SCWA model estimates the likelihood of exceeding a specified storage level with a candidate release schedule as the frequency of exceedance. Then if the likelihood exceeds a tolerable risk level, the SCWA model adjusts the candidate release until the exceedance frequency is tolerable.

The storage level threshold used for this analysis is 111,000 AF (761.8 ft mean sea level [msl]). This is the maximum storage level for conservation water in Lake Mendocino. The tolerable risk (frequency of exceedance of the threshold) varies with forecast lead time, as illustrated with the example risk tolerance curve shown as

Figure 9. The frequency is determined by the number of storage ensembles that exceed the threshold divided by the total number of storage ensembles. For shorter forecast lead times, when forecasts are typically more reliable, risk tolerance is zero (no members are allowed to exceed the threshold). For longer forecast lead times from 7 to 15 days, the risk tolerance levels increase each day, to a level of 30% on day 15. The risk curve used in the SCWA study was tuned by trial and error to achieve desired reservoir management **outcomes (water supply and flood control)**. **Research and development into an “optimized” risk curve may lead to improved performance of the technique.** **The selection of “zero risk” through the first 6 days of the forecast period likely addresses situations where very large storms could create an infeasible situation where there is insufficient time to evacuate adequate flood storage.**

Reservoir releases are determined in the SCWA model by identifying the release that reduces forecasted exceedance frequency below tolerance for all lead times through 15 days. This process is illustrated in Figure 10 and Figure 11. The top panel of Figure 10 shows forecasted storage hydrographs; the storage threshold of 111,000 AF is indicated with a black dashed line. Many of the storage hydrographs exceed the storage threshold. Forecasted risk, computed as the exceedance frequency for each day, is shown as the red solid line in the bottom panel of Figure 10. The risk tolerance is shown as the dashed blue line. Here, forecasted risk exceeds the risk tolerance curve from day 6 of the forecast to day 15.

Through a ranking analysis in the SCWA model, storage ensemble members are selected, and required releases are calculated to bring the selected ensemble members storage outcomes below the storage threshold. This is illustrated in Figure 11, where the top panel shows the storage hydrographs after releases are adjusted. The release for the current time step is selected as the release that will satisfy the risk tolerance levels for all future forecast time steps. For this example, the release was 1,936 cfs. With this release, storages are recomputed and exceedance recomputed. The bottom panel shows the exceedance frequency for all time steps now falling below the tolerable risk level.

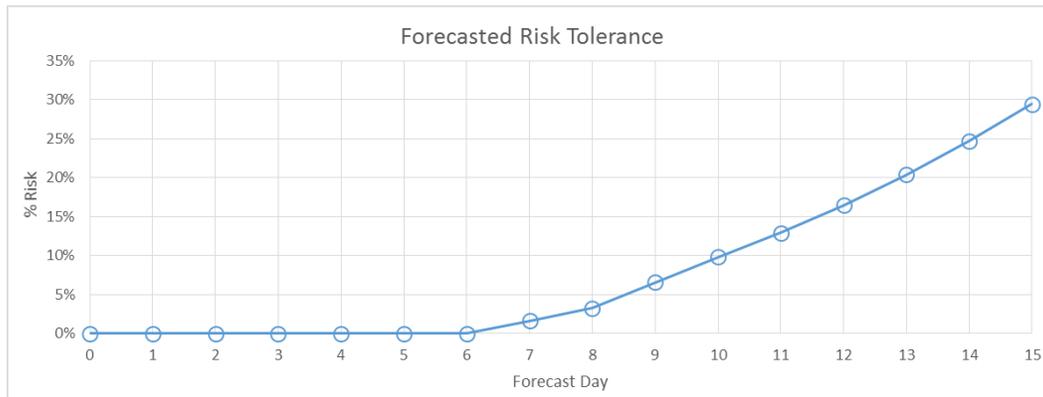


Figure 9. Risk tolerance example from SCWA model (from the SCWA report)

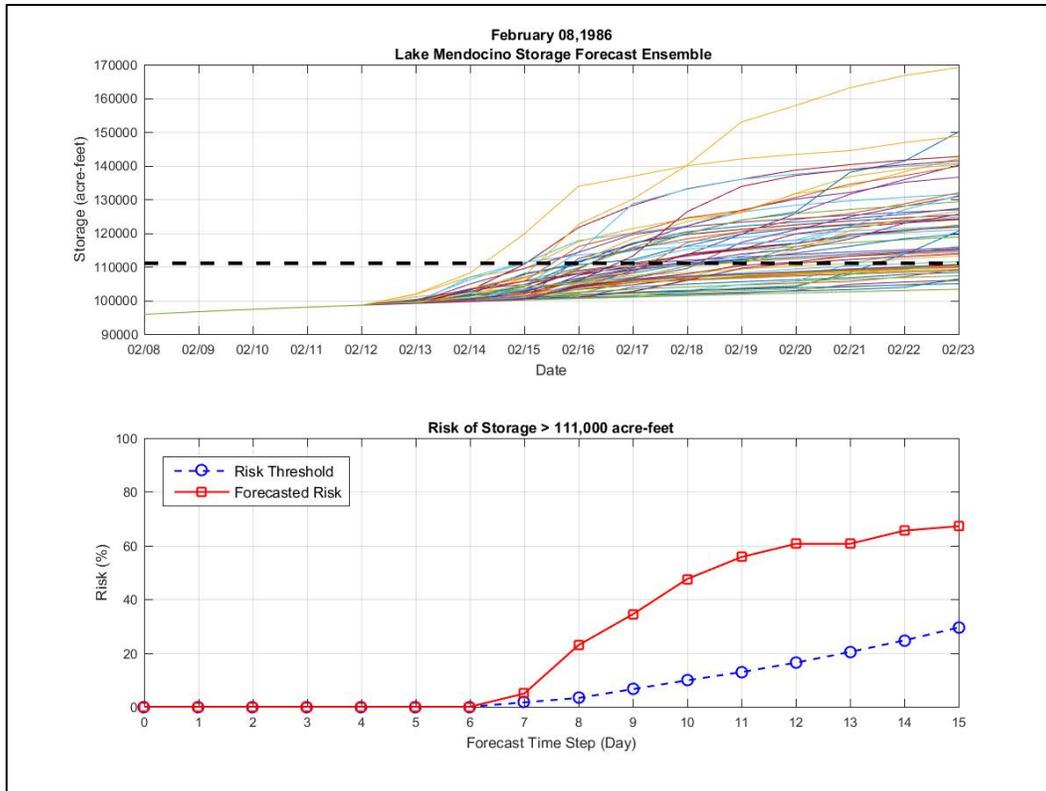


Figure 10. Forecasted storage ensemble and risk with initial candidate release for February 8, 1986 ensemble (from the SCWA report)

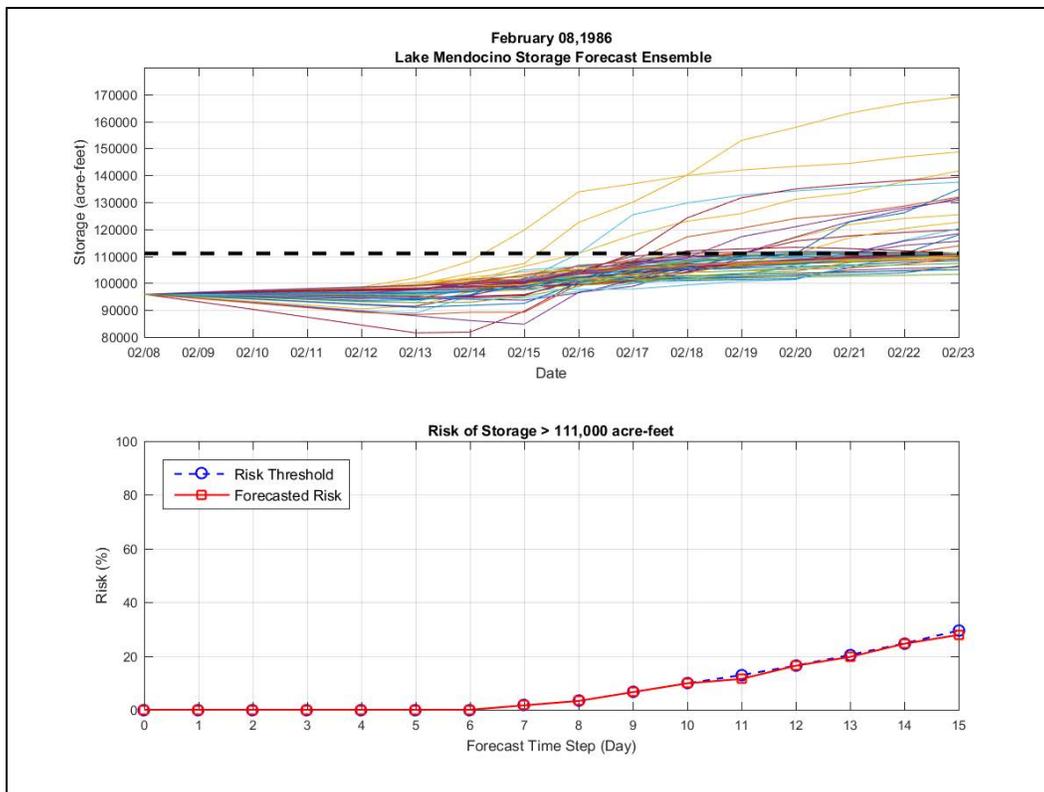


Figure 11. Forecasted storage ensemble and risk with adjusted release for February 8, 1986 ensemble (from the SCWA report)

This process is repeated for the analysis period, with candidate releases adjusted each day to yield risk within tolerable limits. More detail of the computation methods and algorithms is presented in the SCWA report.

### 3.2.2 Water management reliability assessment alternatives

As noted above, SCWA analyzed Lake Mendocino operation with a variety of FIRO alternatives. The Perfect Forecast Operations alternative represents flexibility in operation rules and assumes perfect forecast skill (using the inflows that actually occurred as the forecasts), which establishes a theoretical maximum benefit. The Ensemble Forecast Operations alternative represents the same flexibility in operation rules but reflects current forecast skill and is thus more realistic. The Hybrid Operations alternative represents an initial or interim implementation of FIRO.

Table 7 describes the water supply assessment FIRO alternatives. All FIRO alternatives were modeled with the same assumptions for the following boundary conditions:

- Hopland maximum flow constraint: simulated flood releases are limited to prevent downstream flows at the Hopland junction from exceeding 8,000 cfs.
- Increasing and decreasing rate of change release constraints (ramping rates): Ramping rates only apply to compliance and flood control releases made through the controlled outlet and do not apply to uncontrolled spillway releases or emergency releases. Increasing rate of change constraints are consistent with the WCM. The decreasing rate of change constraints were defined in a 2016 letter to the USACE from NMFS.

- Water management operations: are consistent with current management conducted by SCWA to comply with the SWRCB D1610 and the 2008 Biological Opinion issued by NMFS.
- Since the operation of the PVP changed in 2006, a synthetic historical time series of PVP diversions into the Russian River basin was generated to provide consistency with current operations and delivery rates.

*Table 7. Water supply assessment FIRO alternatives*

Alternative (1)	Description (2)
Existing Operations	Existing operation without FIRO. Operation is computed based on rules in the Coyote Valley Dam WCM (USACE 2003) (approved deviations are not considered). This includes use of the existing guide curve and Hopland downstream flow constraints.
Ensemble Forecast Operations	<p>The Ensemble Forecast Operations alternative simulates flood control operations according to the risk-based approach described above. This is a non-guide curve approach to flood control operations, where flood control releases are determined with the risk-based approach for the entire reservoir conservation pool and flood control pool. This alternative incorporates a risk storage threshold of 111,000 AF and the risk tolerance curve shown in Figure 9.</p> <p>As described above, CNRFC ensemble flow forecasts are used as input to the model. In this case, hindcasts were developed for 1985-2010.</p>
Hybrid Operations	<p>The Hybrid Operations alternative is designed to incorporate both the risk-based approach used in the Ensemble Forecast Operations alternative and guide curve operations similar to Existing Operations. The Hybrid Operations alternative incorporates a modified flood control guide curve (modified guide curve) with the November 1 to March 1 storage level increased by 10% of the total pool storage (116,500 AF).</p> <p>As shown in Figure 12, this increases the November 1 to March 1 storage level from 68,400 AF to 80,050 AF. When simulated storage levels exceed the level of the modified guide curve, this alternative calculates flood control releases using guide curve operations. For releases calculated according to the modified guide curve, maximum downstream flow constraints at the Hopland junction are accounted for.</p> <p>The modified guide curve developed for this scenario is just an example to demonstrate how a possible Hybrid Operations alternative could work and might serve as an initial or incremental step in the implementation of FIRO for Lake Mendocino.</p> <p>Additionally, similar to the Ensemble Forecast Operations alternative, the Hybrid Operations alternative also calculates flood control releases with the risk-based approach any time storage levels are within the conservation pool or the flood control pool. This alternative also incorporates the risk storage threshold of 111,000 AF and the risk tolerance curve shown in Figure 9. For any simulation time step where both Ensemble Forecast Operation and guide curve operation flood control releases have been calculated because storage levels are above the level of the modified guide curve, the flood control release applied for the time step is the maximum of the two.</p>

Alternative (1)	Description (2)
Perfect Forecast Operations	<p>The Perfect Forecast Operations alternative simulates flood control releases similar to the Ensemble Forecast Operations alternative, but in place of using the flow ensemble hindcast, this scenario uses the actual unimpaired flows for 15 days ahead of each simulation time step. The perfect forecast is a single member ensemble. Therefore, the risk tolerance is set at 0% for all forecast time steps. The Perfect Forecast Operations alternative incorporates the risk storage threshold of 111,000 AF.</p> <p>This alternative is designed to simulate operations that incorporate a perfect forecast (zero forecast error or uncertainty) and reasonably represent the maximum that can be achieved both for water management and flood protection using this method</p>

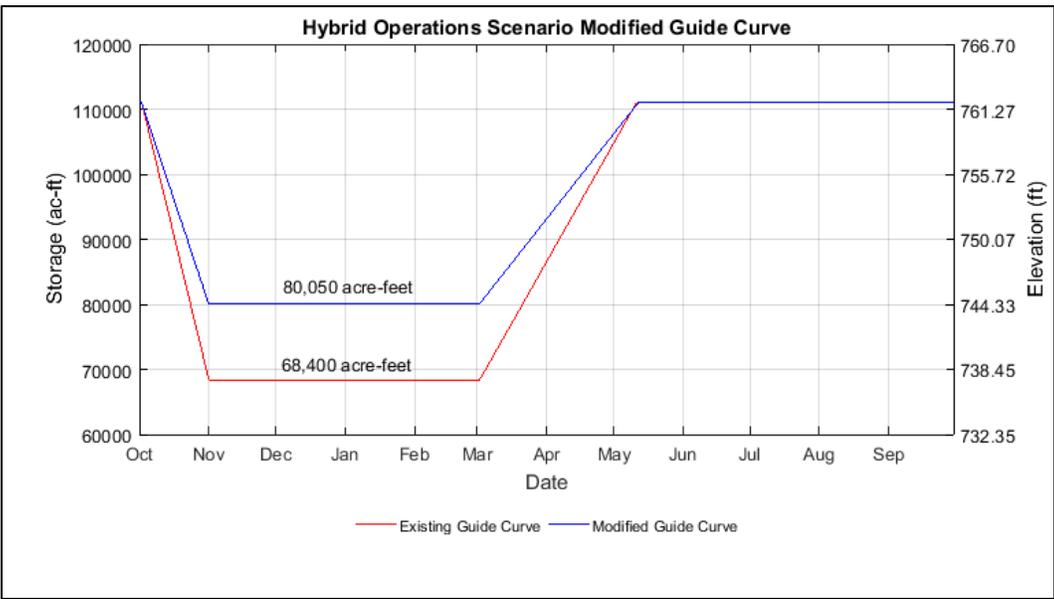


Figure 12. Lake Mendocino modified guide curve for hybrid operations (from the SCWA report)

3.2.3 Water management reliability assessment metrics

SCWA assessed water management reliability over 1985-2010 in terms of end of water year storage. SCWA also assessed flood metrics, including discharge at Hopland and Healdsburg and uncontrolled spill from Lake Mendocino. These results are shown in Section 4 of this report and described in greater detail in the SCWA report.

3.3 Overview of how HEC answered the flood risk related question

HEC addressed the impact of FIRO on flood management capability of Lake Mendocino, simulating behavior of the system following alternative reservoir operating rules, then assessing the risk associated with that operation, and comparing risk with FIRO to that without. A goal of the analysis was to determine if forecast informed operation—as simulated in this PVA—would adversely affect the ability of Lake Mendocino to reduce flood risk in the Russian River floodplain.

### 3.3.1 Flood risk assessment method

The assessment by HEC defined and computed flood risk as likelihood of adverse consequences from flooding. To determine flood risk and changes to risk attributable to FIRO, HEC accounted for (1) flood hazard, which is the frequency and magnitude of flood flows; (2) performance of flood risk reduction measures, particularly the ability of Lake Mendocino to alter the frequency and magnitude of flood flows; and (3) consequence of excessive flows, which can be measured in terms of economic damage, loss of life, environmental impact, or other specified measure of flood risk. The hazard, performance, and consequence analysis was completed with an integrated modeling system that included:

- A watershed runoff and routing model, HEC-HMS. This application assesses hydrologic hazard by simulating hydrologic processes in the Russian River basin, including runoff from rainfall, overland flow, and channel flow.
- A reservoir and river system model, HEC-ResSim. This application assesses changes to hydrologic hazard by simulating reservoir operation under a specified deterministic operation rule set, with reservoir inflows and unregulated downstream system flows provided. For the reservoir release selection, HEC-ResSim considers inflows and unregulated downstream flows in the future, simulating actual operation.
- A fluvial process model, HEC-RAS. For the PVA, this application simulates the movement of releases and unregulated flows throughout the Russian River system, accounting for the impact of flow obstructions, channel geometry changes, vegetation, and so on. The results include stages throughout the channel network and in the adjacent floodplain.
- A consequence-assessment application, HEC-FIA. To complete the risk analysis, this application estimates the impact of hydrologic hazard, considering the exposure and vulnerability of floodplain assets.

For the PVA, HEC used HEC-HMS with either historical or statistically derived rainfall sequences to compute system inflow hydrographs, thus simulating both “observations” and forecasts with a FIRO system. Historical observations of inflow and streamflow were not used because they could not be manipulated to evaluate the management strategies tested. As such, the error associated with HEC-HMS simulation is assumed to be zero. Modification of those hydrographs with flood storage available in Lake Mendocino was then simulated with HEC-ResSim, yielding release hydrographs and regulated flows in the system. The simulation with HEC-ResSim used, in this case, perfect forecasts of future flows. Using HEC-RAS, HEC analysts then computed water surface elevations (WSELs) in the channels and—in cases of channel capacity exceedance—WSELs in adjacent floodplains. The consequences of floodplain inundation were then estimated with HEC-FIA. HEC analysts used their HEC-WAT application to integrate the individual software applications, execute them in an efficient manner, and manage and post-process the results from the simulations.

To more appropriately reflect current operations of the PVP, the HEC analysis also utilized a synthetic historical record that reflects present-day operations.

### 3.3.2 Flood risk metrics

HEC assessed flood risk impacts of FIRO using average annual damage, or AAD. This is a consequence metric computed for index points on channels within the system. Each index point is associated with a distinct floodplain area for which inundation depths and resulting inundation consequence is computed. For each operational alternative, HEC-HMS and HEC-ResSim are executed to create a time series of flow at the index points. Depths are computed with HEC-RAS, and the damage associated with the annual maximum depth for each year of the analysis period is computed with HEC-FIA. The annual damage values are averaged to compute AAD.

HEC assessed flood risk in the Russian River basin, first simulating existing operations at Lake Mendocino for 1950 to 2010, then with FIRO alternatives at Lake Mendocino for the same period. (This period includes the flood of record—December 1964—and drought of record—1976-77). HEC compared the values to determine whether flood risk increased with the FIRO alternatives.

In addition to AAD, HEC analysts computed and compared expected annual damage, or EAD. Whereas the AAD calculation is limited by the range and types of hydrologic events included from 1950 to 2010, EAD is not. For the EAD calculations, HEC analysts identified from the historical record relevant properties of the statistical distribution of rainfall. Then HEC analysts used sampling to create longer records with the same statistical properties but varying sequences of rainfall over the watershed. With these hypothetical, but likely sequences, HEC repeated the process of computing runoff, simulating reservoir operation, determining channel and floodplain stages, and estimating consequences. This is described in detail in the HEC report.

HEC also evaluated and compared operational alternatives using as metrics the WSEL and flow at Lake Mendocino, Hopland, Healdsburg, and Guerneville. This included development of flow- and stage-frequency curves and determination of the 1% chance annual **exceedance (“100-year”) WSEL** at each location for each alternative. HEC also assessed the frequency with which WSEL at Lake Mendocino exceeded the spillway crest elevation.

Incidental to the flood risk analysis, HEC assessed storage available for conservation based on the alternatives developed. HEC quantified refill success by comparing the storage computed for May 10 each year, which corresponds to the date that the existing guide curve reaches the summer pool level. HEC also assessed September 30 (end of water year) storage. Storage on September 30 represents the storage available to support autumn flows for fishery management, and aligns with long-standing reporting practices of SCWA.

### 3.3.3 Flood risk assessment alternatives

HEC assessed flood risk for the current WCM rules for Lake Mendocino and a variety of FIRO alternatives. The Encroach alternative represents a simple FIRO alternative based on perfect precipitation forecasts. The Combined alternative represents a more complex FIRO alternative based on perfect forecasts of several types of data. The EncroachWIF [with imperfect forecast] alternative is the same as the Encroach alternative but is assessed using imperfect precipitation forecasts. Table 8 describes the alternatives. HEC did not formulate **or recommend an “optimal” FIRO rule set. However, analysis of alternatives using perfect forecasts and these FIRO alternatives was found by HEC analysts to establish reasonable bounds on performance of forecast informed operation of Lake Mendocino.**

Table 8. Flood risk assessment FIRO alternatives

Alternative (1)	Description (2)
Existing operations	<p>Existing operation without-FIRO (with boundary condition assumptions). Operation is computed based on the existing guide curve. Reservoir levels above the guide curve trigger flood control operations, with the objective of releasing water in order to evacuate storage and get back to the rule curve level. The outflows are subject to constraints, which typically results in reducing project releases and storing water in the flood zone until local flows downstream begin to recede. Coyote Valley Dam flood operations are subject to rate-of-change limitations and include a rule against reservoir releases that result in flows over 8,000 cfs at the Hopland gage. The release constraints become less of a consideration for very large events that threaten to exceed <b>the dam’s storage capacity</b> due to high inflows and high incremental flows downstream. Most of the time, Lake Mendocino levels are at or below the rule curve, and the dam operates in <b>“generating mode” with releases that meet</b> downstream demands and generate incidental hydropower.</p>
Encroach - Perfect Forecast Operations	<p>The Encroach alternative with perfect forecast is a simple FIRO-based approach, adding a single rule to the existing operations during winter/spring that permits the reservoir to store additional water in the flood pool in the absence of significant precipitation forecast during the next 5 days. If at least 3 in of total precipitation is forecast during the next 5 days, as much water as possible is released to get the reservoir pool back to guide curve levels, within the existing condition physical and operational constraints. (The threshold for significant precipitation was determined using a trial-and-error process that balanced the amount of storage captured against added flood risk because resulting operations increase downstream peak stages, or lead to substantially more spillway flow, or result in a net increase of violations of the Hopland 8,000 cfs rule.)</p> <p>The amount of flood pool encroachment is capped at 761.8 ft NGVD (the guide curve target for summer pool level). The rule is in effect from January 15 through May 31.</p> <p>A key assumption for this alternative is that the forecast is correct or <b>“perfect,” so the forecasted event that operation is based on is equivalent to</b> the observed event.</p>
Combined -Hybrid Operations	<p>The Combined alternative with perfect forecast demonstrates other potential forecast informed operations. This alternative includes:</p> <ul style="list-style-type: none"> <li>• A pre-release rule considering 1-, 2-, 3-, and 5-day volumes of forecasted reservoir inflow.</li> <li>• A capacity rule that uses forecasts of unregulated flow at Hopland to release the most from Lake Mendocino without violating the 8,000 cfs rule.</li> <li>• A change in the guide curve, illustrated in Figure 13.             <ul style="list-style-type: none"> <li>• Change summer shoulder from May 10 to March 10.</li> <li>• Change winter shoulder from Oct 31 to Nov 30.</li> <li>• Change filling time from March 01 to Feb 01.</li> </ul> </li> </ul> <p>Again, a key assumption here is that the forecast is perfect.</p>

Alternative (1)	Description (2)
EncroachWIF	The Encroach with imperfect forecast alternative demonstrates the possible impact of forecast error. Here, the Encroach alternative is simulated using an imperfect forecast of 5-day total precipitation instead of observed. The forecast was made imperfect by randomly sampling a value from a normal distribution that centers on the correct 5-day total precipitation value, with a standard deviation equal to some percentage of the correct value, such as 15%. This was calculated separately for each day, allowing greater uncertainty for forecasts farther in the future.

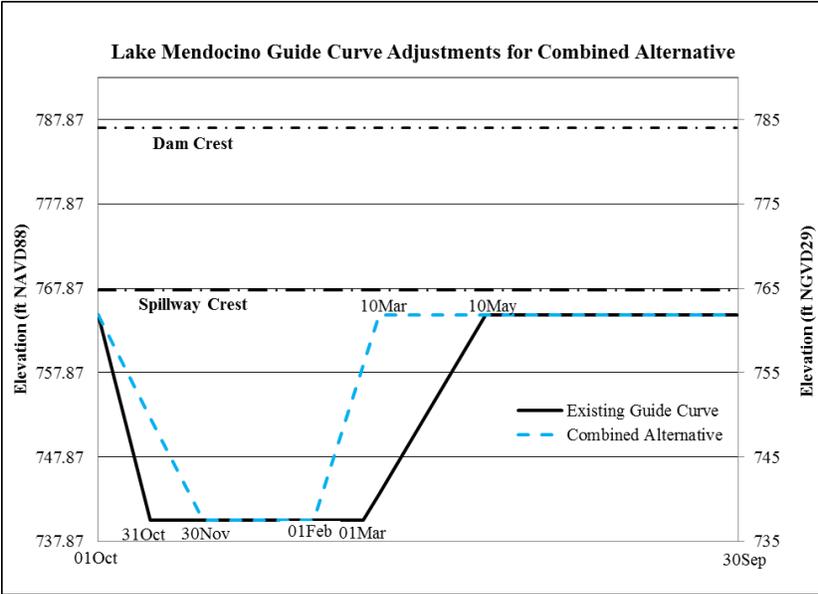


Figure 13. Lake Mendocino guide curve adjustments for Combined alternative (from the HEC report)

### 3.4 Overview of how CW3E assessed forecast accuracy

What can be achieved with forecast informed operation at Lake Mendocino depends on the quality of the forecasts available. For the preliminary viability assessments by SCWA and HEC, analysts made assumptions about the quality and form of the forecast. HEC considered a perfect forecast of precipitation which was then processed through an HEC-HMS model to derive streamflow, while SCWA considered a streamflow forecast consistent with that currently provided by CNRFC operations. These conditions were judged by the SC to be adequate for the PVA.

Beyond the PVA, the FVA will seek to enhance the accuracy of forecasts through enhancements to science and technology as feasible and as needed. Accordingly, as a component of the PVA, researchers at CW3E addressed a set of questions related to the forecasts, the answers to which will inform and guide research and development actions in the FVA. Those questions, and methods used to answer them, include the following:

1. What is the required forecast lead time? **Using SCWA’s streamflow routing model,** CW3E analysts determined the travel time of Lake Mendocino releases, which are flow-dependent, to downstream critical locations. With this information, analysts estimated

the lead time reservoir operators need to make a forecast informed release to avoid downstream target exceedance (in cases for which exceedance can be avoided).

2. What are the forecast requirements for extreme rainfall events? The current Lake Mendocino WCM includes rainfall rates of 0.5 in/6 hr and 1.0 in/24 hr as thresholds to alert operators of potential flooding. These rates were assigned originally, considering they would lead to critical flow rates in the system. CW3E analysts revisited this, considering MAP that would lead to inflows equal or greater than 2,500 cfs, a critical rate for the reservoir. To answer the question, CW3E analysts examined observed inflows, comparing those to MAP values to identify MAP rates for which flow exceeded 2,500 cfs. They also compared inflow to rainfall rates observed at Willits Howard Ranger Station, a key gage used by the CNRFC.
3. What is the current forecast skill level for rainfall that has an impact on Lake Mendocino operation? To answer this question, CW3E analysts applied statistical tests of accuracy and skill to 5-day 6-hr quantitative precipitation forecasts (QPFs) made by the CNRFC. Each 6-hr forecast was compared to the 6-hr observed MAP for 2000 to the present;  $R^2$  and RMSE were computed. In addition, CW3E analysts considered skill in forecasting threshold rainfall rates of 0.5 in/6 hr and 1.0 in/24 hr. By comparing forecasted rates with observed MAP, the analysts computed 3 common indices of skill: probability of detection (POD), false alarm rate (FAR), and critical success index (CSI).
4. What is the current skill in forecasting no significant rainfall (AR landfall)? The CW3E report notes that from a water management standpoint, forecast of lack of significant rainfall is critical to operational decision making, as it may permit a decision to be taken to store water in the flood pool at least temporarily during the rainy season. Accordingly, CW3E analysts considered current skill in forecasting MAP of 1 inch or less 1-5 days into the future. They computed again the indices of skill identified above, using 16 years of archived forecasts and observations.
5. Will current streamflow forecasts support FIRO for Lake Mendocino? To answer this question, CW3E analysts computed RMSE and CSI with historical observations and forecasts for January 2006 to May 2016. Forecast lead times of 1 to 5 days were analyzed.
6. Are the ensemble precipitation forecasts suitable for testing and evaluating FIRO strategies as SCWA did? CW3E analyzed the 1985-2010 GEFS Version 10 reforecasts of precipitation (used by the CNRFC to generate streamflow hindcasts) to assess the skill at lead times relevant to FIRO. These were also compared with the 5-day precipitation forecasts issued directly by the CNRFC.
7. How important are extreme rainfall events to annual precipitation in the Russian River watershed? CW3E has characterized the need for forecast enhancements and reviewed the literature focused on historical rainfall events and flooding. From this review, the frequency and intensity of ARs as the cause of flooding was identified and highlighted the importance of accurately forecasting ARs in the context of FIRO.
8. What is the relationship of upslope water vapor flux and rainfall for land-falling ARs? The CW3E contribution to the PVA considered and refined the scientific definition of an AR, using 6 years of additional data to refine the role of storm-total upslope water vapor flux in controlling storm-total rainfall. CW3E analysts also used and fine-tuned the GEFS AR Landfall tool from Jason Cordeira to assess probability of AR conditions (Cordeira, et al. 2017).
9. What is the impact of frontal waves along ARs on flood forecasting in the Russian River Basin? The CW3E report notes that mesoscale frontal waves, or MFWs,

slow down the forward movement of ARs, affecting the timing and location of the heaviest rainfall. As a component of the PVA, analysts considered how the MFWs affected AR properties and identified research needed.

The CW3E report provides more detail on the analyses.

## 4 What the assessment studies found

As described in previous sections of this report, the PVA study considered the following questions:

1. If FIRO is implemented, will operation improve reliability in meeting water management objectives and ability to meet environmental flow requirements, and to what extent?
2. If FIRO is implemented, will operation adversely affect flood risk management in the system? If so, where and to what extent can that be mitigated?

Detailed results of the analyses that addressed these questions are included in the SCWA and HEC reports. Results, which are summarized in this section, show forecast informed operation (as simulated) improves reliability in meeting water management objectives and ability to meet environmental flow requirements without adversely affecting flood risk.

In addition to the assessments of FIRO impacts on meeting operational objectives, analysts addressed questions related to accuracy of current forecasts and future forecast needs to inform operation. Findings from that work are summarized in this section and provided in the CW3E report.

### 4.1 Water management reliability assessment results

SCWA analysts assessed potential improved reliability in meeting water management objectives attributable to these forecast informed operation alternatives:

- Perfect Forecast Operations.
- Ensemble Forecast Operations.
- Hybrid Operations.

To do so, they simulated operation, computed measures of performance, and compared those with existing operation outputs, as described in Section 3 of this report.

These alternatives were assessed through simulation of reservoir operation with 1985-2010 streamflow hindcasts and historical flows. SCWA quantified water management reliability benefits with storage metrics and examined also occurrence of uncontrolled spillway flow at Lake Mendocino and exceedance of key flow levels downstream at Hopland and Healdsburg to assess flood management impacts.

The SCWA report provides a complete description of the analysis, which also includes examination of constraint on environmental flow compliance and flood management releases due to ramping rate rules.

#### 4.1.1 Storage at Lake Mendocino

The FIRO alternatives increase storage at Lake Mendocino for almost all years simulated. This is illustrated in Figure 14, which is a hydrograph of simulated daily storage levels. Wet years 1998, 2003, 2006, and 2010 do not show increased storage. These years were all characterized by high, late-season rainfall after March 1, which allowed the reservoir to fill to the level of the existing rule curve without forecast informed operation.

Simulation of operation for 1997, 2002, and 2007 to 2009 shows a decline in minimum annual storage for the Hybrid Operations alternative compared to existing operations, even though the winter peak storage is greater for the Hybrid Operations alternative. A similar result is found for 2009 for the Ensemble Forecast Operations alternative. Operation with the Ensemble Forecast Operations and Hybrid Operations alternatives make more water available for all years of the simulation. This wetter condition results in higher environmental flow requirements downstream of Lake Mendocino. Therefore, water

management releases are higher, which causes storage levels for the Hybrid and Ensemble Forecast Operations alternative to fall below the Existing Operations scenario for certain years.

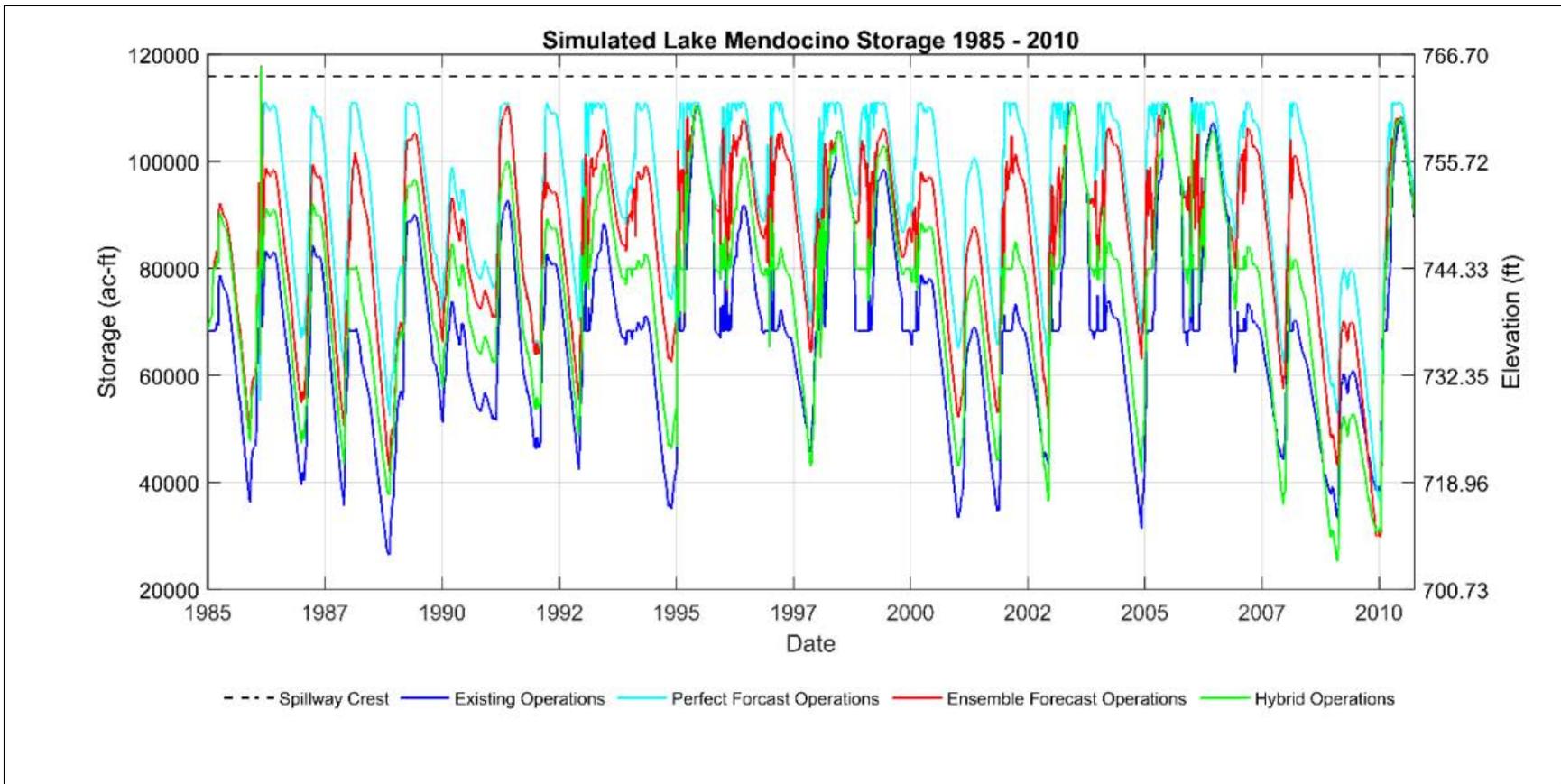


Figure 14. Lake Mendocino simulated storage levels for the FIRO alternatives and existing operation from 1985 to 2010: The FIRO alternatives increase storage at Lake Mendocino for almost all years simulated (from the SCWA report)

Figure 15 shows a plot of Lake Mendocino end of water year storage exceedance probability (shown as % chance exceedance), and Table 9 provides a summary of results. The Perfect Forecast Operations alternative yields the largest increases in end of water year storage for most exceedance levels, with an increase in median end of year storage of approximately 27,780 AF compared to Existing Operations.

The Ensemble Forecast Operations alternative also demonstrates significant storage gains throughout the range of exceedance, with an increase in median end of water year storage of approximately 20,057 AF over Existing Operations.

The Hybrid Operations alternative demonstrates modest storage gains throughout the range of exceedance, with an increase in median end of water year storage of approximately 8,633 AF over Existing Operations.

Figure 15 also shows that all FIRO alternatives result in a decrease in spread of end of water year storage throughout the range of exceedance values compared to the Existing Operations scenario. The Perfect Forecast Operations alternative yields the smallest difference between the 4% and the 96% exceedance storage levels, demonstrating less uncertainty about the end of year storage if operation follows this FIRO strategy.

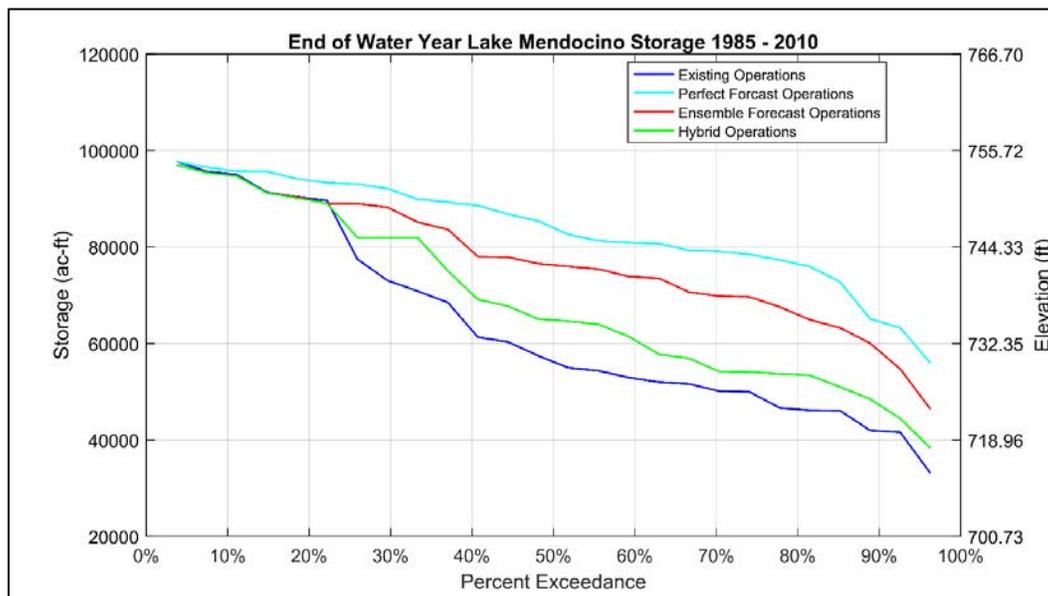


Figure 15. Lake Mendocino simulated end of water year storage percent exceedance of all scenarios for 1985-2010 (from the SCWA report)

Improved reliability in meeting water management objectives attributable to forecast informed operation yields a benefit to habitat conditions downstream of Lake Mendocino. Results demonstrate that the increase in available water decreases the occurrence of *dry* hydrologic conditions, resulting in higher environmental flow requirements preferred by rearing salmonids. Although not assessed specifically, increased storage levels in the fall would retain a greater cold water pool in Lake Mendocino and provide lower release temperatures relative to Existing Operations. This benefit is important, considering releases have been observed to reach temperatures that are detrimental to salmonids when storage is drawn down to low levels in the fall during drought years.

Table 9. Summary of end of water year assessment results

Alternative (1)	Median end of water year storage (AF) (2)	Increase from Existing Operations (AF) (3)	Percent increase (4)
Existing Operations	56,220	—	—
Perfect Forecast Operations	84,000	27,780	49%
Ensemble Forecast Operations	76,277	20,057	36%
Hybrid Operations	64,853	8,633	15%

4.1.2 Example operation: Water year 1988

Water year 1988 is an example of the benefits of forecast informed operation in a challenging water management year. In water year 1988, the Ukiah gage measured 29.8 in of rain, which is approximately 81% of the 30-year average for this station. Most rainfall (82%) occurred before the end of January, with very little rainfall occurring after February. Figure 16 shows a hydrograph of simulated Lake Mendocino storage for the year. Following existing WCM rules, Lake Mendocino would not store conservation water during the wet season (November through February) beyond the 68,400 AF threshold. Because very little rainfall occurred after March 1, storage levels peaked at approximately 68,900 AF in early March and declined for the remainder of the water year.

In contrast, because operation is not constrained by the existing rule curve, the Perfect Forecast and Ensemble Forecast Operations alternatives yield storage of more water in the wet season. The Perfect Forecast alternative reached 111,000 AF (top of conservation pool), and the Ensemble Forecast Operations alternative reached a peak storage of 101,700 AF.

Like Existing Operations, the Hybrid Operations alternative is limited by the modified rule curve developed for this alternative, which has a November 1 to March 1 storage level of 80,050 AF. Because the rule curve storage level is increased for the wet season, the Hybrid Operations alternative storage reaches a higher peak storage (80,500 AF) than with existing operations.

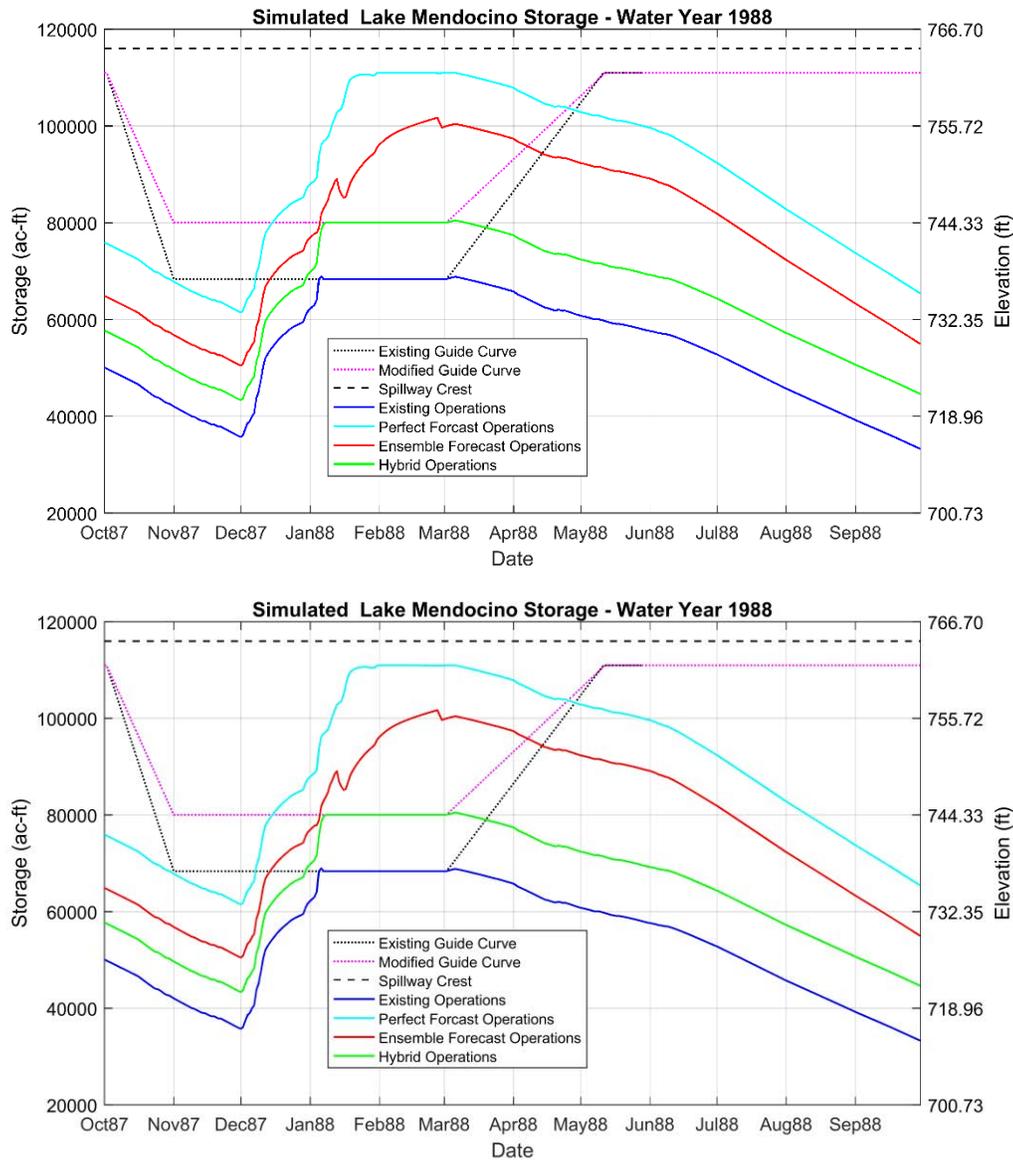


Figure 16. Lake Mendocino simulated storage of all scenarios for water year 1988 (from the SCWA report)

End of water year 1988 storage is 33,100 AF with existing operations. However, with Hybrid Operations, the end of water year storage level was about 11,300 AF higher, which is approximately the level to which the rule curve was raised for the wet season (116,500 AF). End of water year storage levels for the Perfect Forecast and Ensemble Forecast Operations alternatives were approximately 65,100 AF and 54,700 AF respectively, an improvement over existing operations storage.

The rate of storage decline in the dry season (June through September) for the Perfect Forecast and Ensemble Forecast Operations alternatives is greater than for the Existing and Hybrid Operations alternatives. Due to higher storage levels on May 31 for the Perfect Forecast and Ensemble Forecast Operations alternatives, the hydrologic condition is classified *normal* from June through December—a classification that results in greater environmental flow requirements (125 cfs) than those for the Existing Operations and Hybrid Operations alternative; with those operations, classification transitions to a *normal*-

*dry spring 2* condition, with a lower minimum in-stream flow requirement (75 cfs) (the SCWA report describes hydrologic condition classifications). The higher flows for the Perfect Forecast and Ensemble Forecast Operations alternatives provide improved downstream flow conditions for rearing salmonids from June 1 to September 30.

#### 4.1.3 Uncontrolled spillway releases

Simulation of operation for 1985-2010 with forecast informed operation shows no significant increase in occurrence of uncontrolled spillway releases. This is illustrated in Figure 14, where the spillway crest elevation is shown with a gray dashed line. (The simulation shows uncontrolled spillway releases for the February 1986 event with 3 scenarios [Existing Operations, Ensemble Forecast Operations, and Hybrid Operations]. While uncontrolled spillway releases were not historically observed during this event, these results do not indicate an error. Instead, the difference between observation and simulation is due to difference in representation of the physical properties of the reservoir. The simulation model includes storage information developed from a 2001 bathymetric survey, with storage less than was available in 1986. This leads to computed outflows that may exceed those observed.)

#### 4.1.4 Example operation: Water year 1986

Figure 17 shows a hydrograph of simulated daily Lake Mendocino storage levels for water year 1986. Additionally, Figure 18 provides a focused illustration of conditions for the February 1986 flood event. As shown in the top panel of Figure 18, the FIRO alternatives operate with storage levels well above existing operations in the beginning of February. Due to forecasted high inflows for mid-February, the FIRO alternatives show an increase in releases to draw down storage in advance of the event to reduce the likelihood of exceeding the 111,000 AF threshold. The Perfect Forecast Operations alternative draws down storage the most, with storage levels dropping well below the existing rule curve in advance of the event. The Ensemble Forecast and Hybrid Operations alternatives draw down storage to about the level of the existing rule curve.

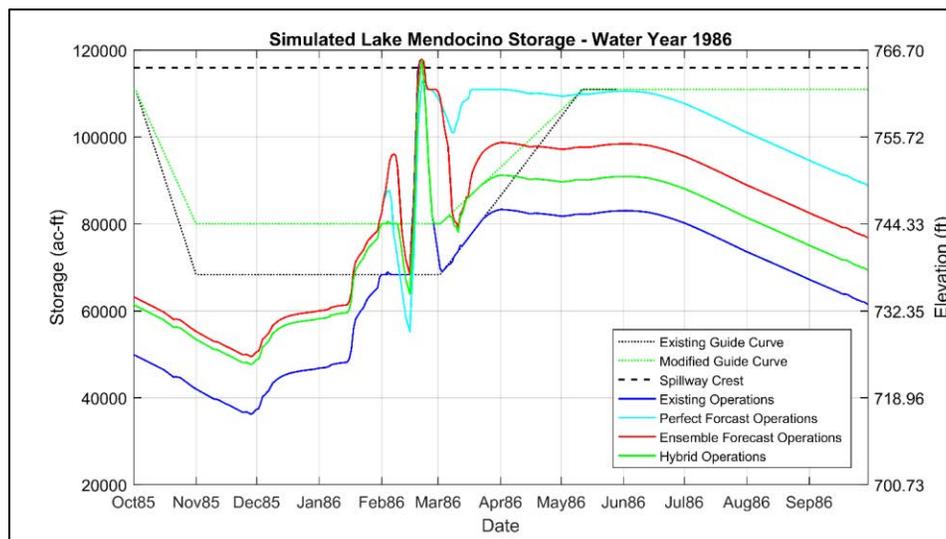


Figure 17. Lake Mendocino simulated storage of all scenarios for water year 1986 (from the SCWA report)

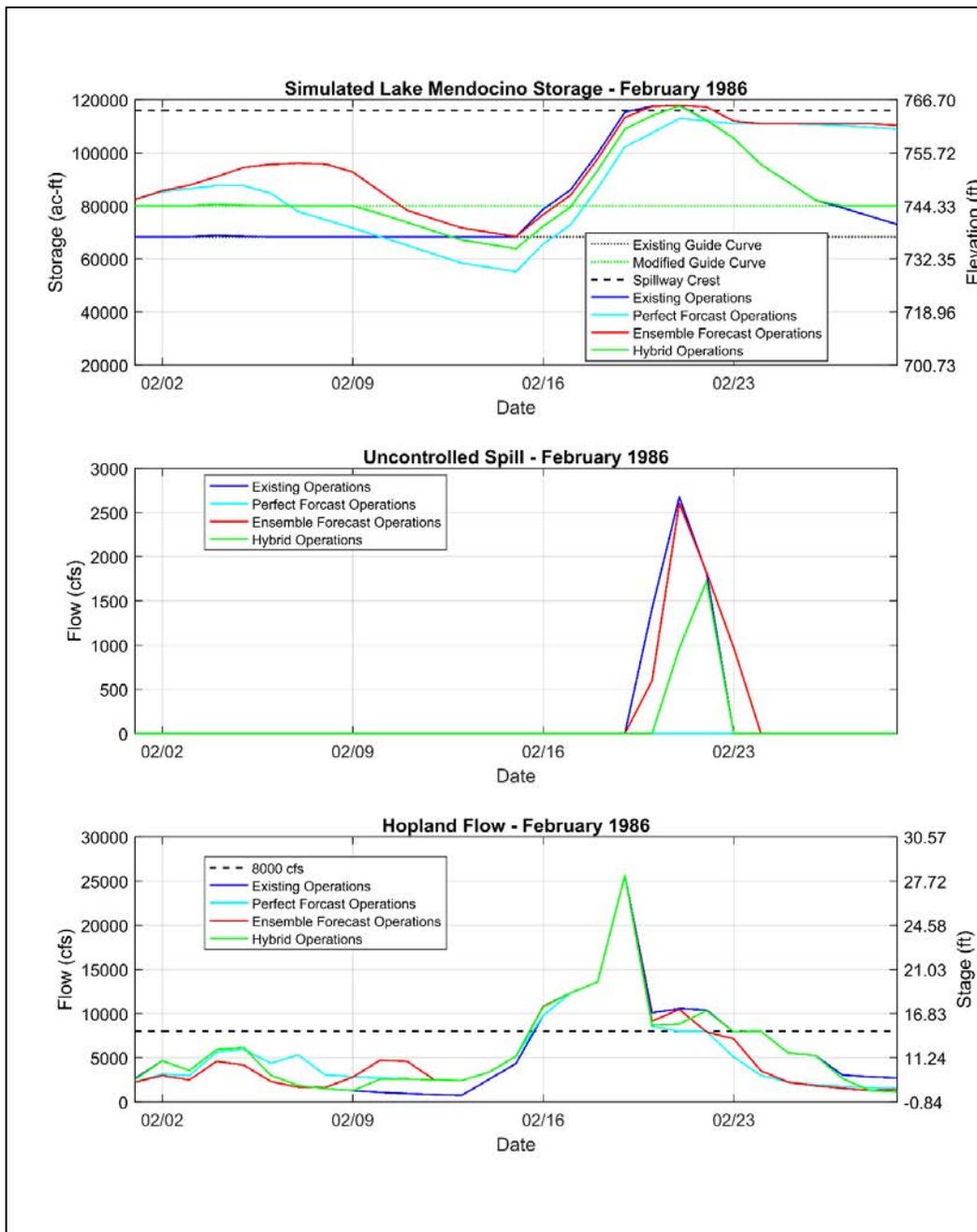


Figure 18. Lake Mendocino simulated storage, uncontrolled spillway release, and Hopland flow of all scenarios for the storm in February 1986 (from the SCWA report)

Because flows exceeded 8,000 cfs at the Hopland gage, minimal releases are made from Lake Mendocino from February 16 to 21 for all alternatives. As shown in the top panel of Figure 18, this results in storage levels rapidly rising. Except for the Perfect Forecast alternative, all other scenarios simulate storage levels rising above the crest of the uncontrolled spillway, resulting in uncontrolled releases. A hydrograph of the uncontrolled spillway releases is shown in the middle panel of Figure 18. The uncontrolled spillway releases reach a peak release of 2,677 cfs for existing operations, 2,605 cfs for Ensemble Forecast Operations, and 1,723 cfs for Hybrid Operations. The Ensemble Forecast Operations alternative results in uncontrolled releases for a total of 4 days, 1 day longer

than with existing operations and 2 days longer than with Hybrid Operations. The total volume of the uncontrolled spillway release is 11,720 AF for existing operations, 11,900 AF for Ensemble Forecast Operations, and 5,333 AF for Hybrid Operations. Although the duration of the uncontrolled spillway release is 1 day longer for Ensemble Forecast Operations compared with existing operations, the peak spill release and total volume release is close for the two alternatives.

None of the alternatives result in an increase in downstream flows at Hopland over existing operations. This is illustrated in the bottom panel of Figure 18, which shows a hydrograph of flows at Hopland. All of the alternatives reach a peak flow of 25,636 cfs on February 18.

As illustrated in Figure 17, peak spring season (post March 1) storage levels are greatest for the Perfect Forecast Operations alternative with a storage level close to 111,000 AF. This alternative represents the upper bound for potential storage of water for this year. The Ensemble Forecast and Hybrid Operations alternatives reach peak spring season storage levels of approximately 98,500 AF and 91,000 AF, respectively. Both alternatives show gains in water capture for water management purposes relative to Existing Operations, which reaches a peak spring season storage level of approximately 83,100 AF.

#### 4.1.5 Downstream flow conditions

Operations were also compared in terms of downstream flow conditions. Downstream flows for the FIRO alternatives match closely the Existing Operations scenario. Plots of percent chance exceedance of daily flows for Hopland, Cloverdale, and Healdsburg are shown in Figure 19, Figure 20, and Figure 21, respectively. Flows for the FIRO alternatives are above the Existing Operations scenario from the 75% to 93% exceedance range (dry season conditions) for each location. This increase is due to greater compliance releases to maintain higher environmental flow because of greater water availability in Lake Mendocino for these scenarios. This is an improvement over the Existing Operations scenario through maintaining higher flows for fishery needs and other beneficial uses.

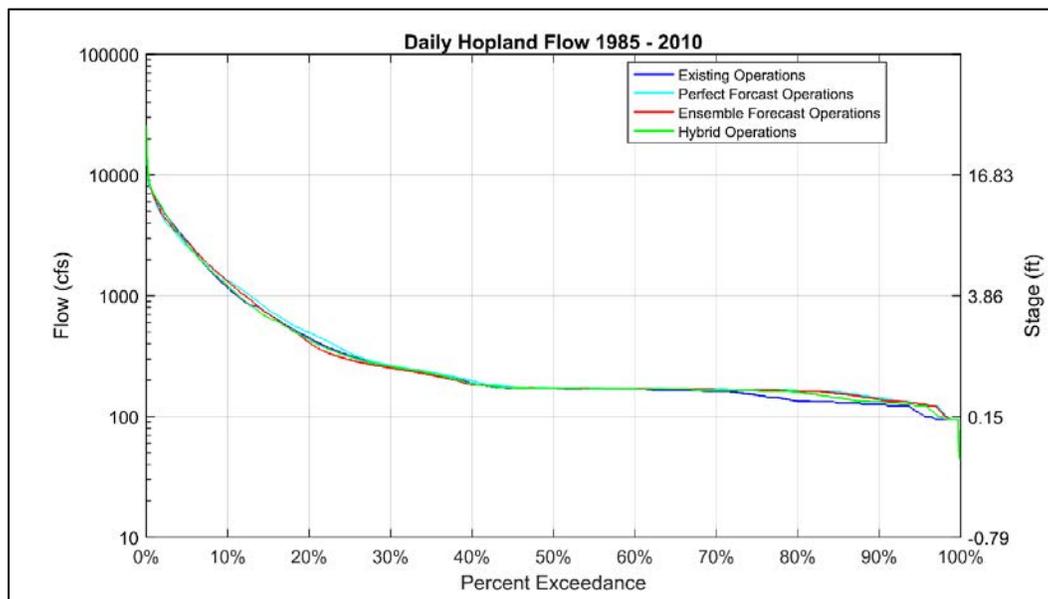


Figure 19. Hopland simulated flows percent exceedance of all alternatives for 1985-2010 (from the SCWA report)

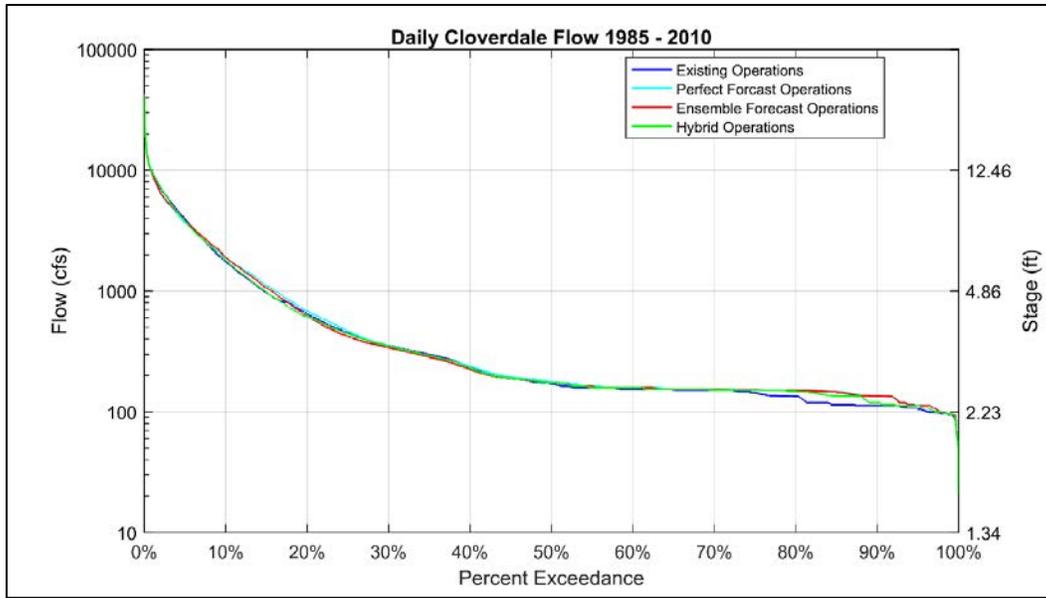


Figure 20. Cloverdale simulated flows percent exceedance of all alternatives for 1985-2010 (from the SCWA report)

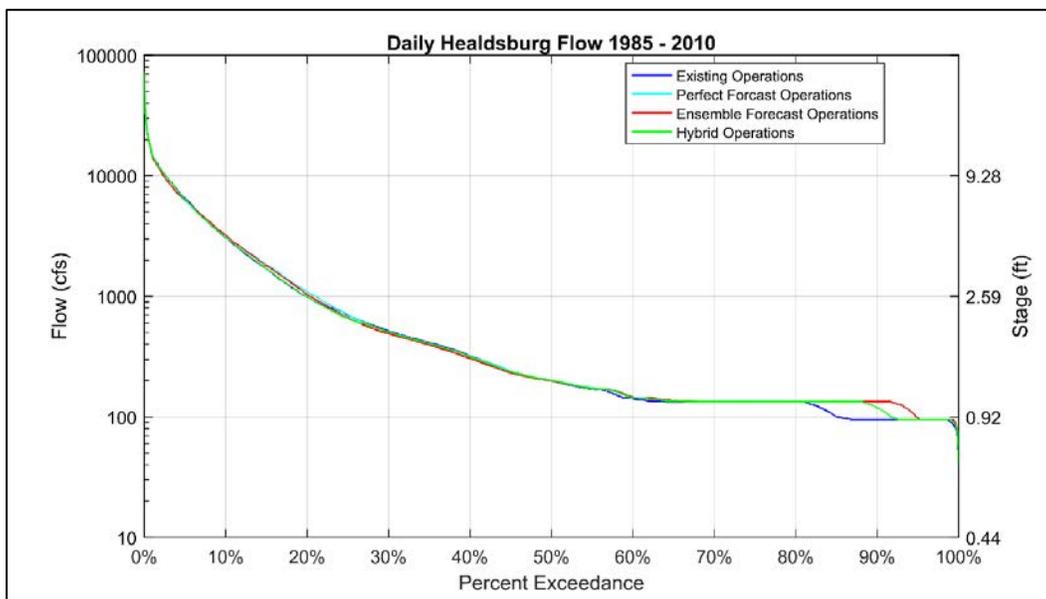


Figure 21. Healdsburg simulated flows percent exceedance of all scenarios for 1985-2010 (from the SCWA report)

SCWA also assessed whether the FIRO alternatives created cases in which flows were increased relative to the Existing Operations scenario during high flow periods for Hopland and Healdsburg. While there are instances of increased (and decreased) flow, simulation results show no increase in frequency of exceeding flood stage in the analyzed period with all FIRO alternatives. (This study evaluated operation with a historical period that does not include the greatest event of record, which occurred in December 1964. Additionally, the daily simulation time step used in the SCWA model does not capture precisely instantaneous peak reservoir storage or peak flows downstream.)

## 4.2 Flood risk assessment results

HEC analysts assessed the potential for FIRO to increase flood risk by simulating 3 FIRO alternatives and comparing performance measures to existing operation, as described in Section 3. Alternatives are identified by HEC as:

- Combined (complex, perfect forecast).
- Encroach (simple, perfect forecast).
- EncroachWIF (simple, imperfect forecast).

These alternatives were assessed through simulating operation with simulated flows for 1951 to 2010 and for series generated with sampling techniques, as explained in the HEC report. HEC assessed flood management performance of the alternatives in terms of EAD for the synthetic series and AAD for the historical series. HEC also assessed discharge and stage frequency at Hopland, Healdsburg, Guerneville, and Lake Mendocino, and uncontrolled spill from Lake Mendocino. Incidental to the flood impact analysis, HEC assessed end of water year storage and May 10 storage (when maximum conservation storage becomes available each year). The HEC report provides a complete description of the analysis.

### 4.2.1 Flood damage

As described in Section 3, HEC assessed flood risk in the Russian River Basin in terms of frequency and magnitude of damage to structures and contents. To facilitate the assessment, HEC used a suite of models, integrated using the Watershed Analysis Tool (HEC-WAT). HEC assessed flood risk based on 1951-2010 (referred to as *POR compute in HEC's documentation*), yielding AAD. HEC also generated with statistical methods a sample of 5,000 synthetic precipitation events, computed runoff and simulated reservoir operation with those, and computed EAD (this is referred to as an *FRA compute in HEC's documentation*). Table 10 provides a summary of the results for each alternative. This shows the FIRO alternatives simulated by HEC do not significantly increase flood risk. This is not surprising since the operational configurations (ResSim rule sets) were designed to store as much water as possible without increasing flood damages. The difference between the AAD and EAD results emphasize the need to look beyond the historical record and consider a full range of potential events.

Table 10. Summary of flood risk assessment results

Alternative (1)	POR compute (60 years, 1951-2010)		FRA compute (5,000 events)	
	AAD (\$ million) (2)	Increase in AAD from existing <sup>1</sup> (\$ million) (3)	EAD (\$ million) (4)	Increase in EAD from existing <sup>2</sup> (\$ million) (5)
Existing Conditions	6.10	—	10.40	—
Combined (complex, perfect forecast)	6.10	0	10.40	0
Encroach (simple, perfect forecast)	6.10	0	10.50	0.10
EncroachWIF (simple, imperfect forecast)	6.10	0	10.50	0.10

1. Increase = FIRO alternative - Existing Condition.

HEC analysts found Lake Mendocino flood operations affect downstream flood risk through 3 mechanisms:

- Delay of reducing outflow. If releases in advance of a storm continue too long, then a portion of the volume may still be present when the event impacts downstream locations, resulting in higher flood peaks and damage. The decreasing rate of change of release rule can exacerbate this effect and result in greater damage. Page B-3 of the 1959 WCM states: **“In addition, care must be exercised that releases from the reservoir do not unnecessarily increase the effective reduction of subsequent flood peaks due to residual flow in damage reaches in the downstream portion of the river.”**
- Potentially more frequent spillway flow. Whether less depleted at the beginning of flood season or more aggressive in filling at the end of flood season, higher levels of Lake Mendocino also mean it is closer to the spillway when storms approach. The 8,000 cfs rule for Hopland limits the ability of advance releases to mitigate the risk. Figure 23 illustrates an example of this.
- Spillway flow potentially increasing downstream flood peaks for large events. If flow over the Coyote Valley Dam spillway starts early, it can increase downstream flows during the peak of the event. This potential risk was observed in simulation of very large events during the FRA compute, but HEC analysts found it did not lead to significant difference in the EAD.

#### 4.2.2 Flood frequency at Lake Mendocino

Flood risk considerations for Lake Mendocino include potential for additional loading on the dam and spillway (uncontrolled flow). The FIRO alternatives developed for this assessment were formulated with a tolerance for minor increases in peak stages and spillway activation.

The FIRO alternatives simulated by HEC all result in higher stage-frequency relationships for the Lake Mendocino pool, as shown in Figure 22. These differences are expected because more of the conservation storage pool above the existing rule curve is available during flood season, resulting in higher pool elevations. (The Encroach alternative is not sensitive to errors in the forecast, so the red line representing the Encroach alternative, and the orange line representing the Encroach with imperfect forecast alternative almost coincide.)

Early in the flood season, the Existing Condition pool levels simulated are often substantially below the rule curve, providing extra flood storage. This reflects summer depletions and the frequent inability to fill the reservoir during the previous spring. The greater ability of the FIRO alternatives to fill the reservoir results in the FRA compute sampling starting levels close to the rule curve (bottom of flood control pool) for early season storms, providing incidental extra flood storage.

Late in the flood season, operation with the FIRO alternatives results in higher lake levels than operation with existing rules. The FIRO alternatives store runoff from storms smaller than the 5% annual chance exceedance (ACE) event, as evidenced by the flat portion of the FIRO plan frequency curves corresponding to the summer pool level of 761.8 ft NGVD. Large events late in the season sometimes result in higher lake levels under the FIRO alternatives due to the encroachment or early fill operations.

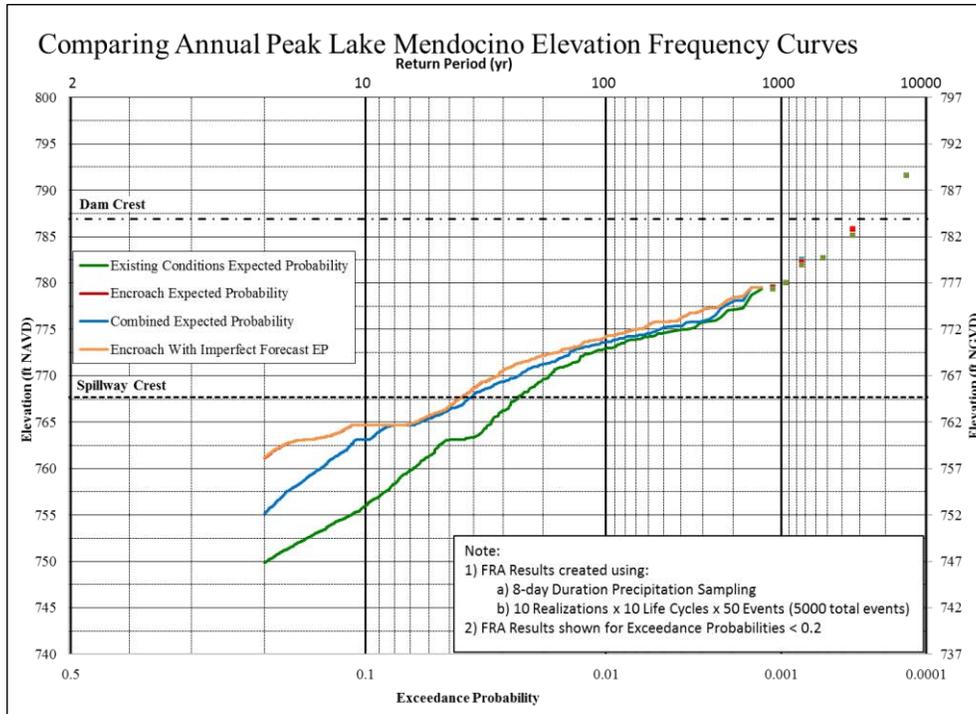


Figure 22. Comparison of Lake Mendocino annual peak frequency (from the HEC report)

Table 11 summarizes key flood risk metrics for Lake Mendocino for the alternatives simulated. The FIRO alternatives increase the 100-year (1% ACE) lake level by about a foot and increase the chance of spillway flow in any given year by about 2%. However, the additional pool elevation and flow and duration over the spillway do not translate into additional flood risk in the consequence areas below the dam, since it seldom occurs early enough in a flood event to affect downstream peaks.

Table 11. Comparison of Lake Mendocino frequencies at key elevations

Alternative (1)	Event with 1% ACE			AEP <sup>1</sup> of spillway flow (NAVD 767.7 ft/ NGVD 764.8 ft) (5)
	WSEL (NAVD ft) (2)	WSEL (NGVD ft) (3)	Storage (AF) (4)	
Existing Conditions	772.99	770.12	126,400	0.026
Combined (complex, perfect forecast)	773.67	770.80	127,700	0.041
Encroach (simple, perfect forecast)	774.32	771.45	128,900	0.045
EncroachWIF (simple, imperfect forecast)	774.32	771.45	128,900	0.044

1. AEP is annual exceedance probability.

Table 12 displays additional summary statistics from the 1951-2010 analysis. Substantial spillway flow occurs for simulations of the 1964, 1986, 1995, and 2006 events for the FIRO alternatives. The spillway crest elevation is 764.8 ft NGVD. The alternatives using the encroachment approach experience substantially longer spillway flow and reach higher pool levels. Also, a storm in May 2005 causes the Encroach alternative to use the spillway briefly. (HEC analysts recommend evaluating in more detail these differences in subsequent

analyses to determine the nature and magnitude of spillway flow to minimize structure and downstream impacts.)

Table 12. Comparison of spillway flow durations for 1951-2010 simulations

Alternative (1)	Total hours of spillway flow (2)	Maximum level (NAVD ft) (3)	Maximum level (NGVD ft) (4)
Existing Conditions	204	771.79	768.92
Combined (complex, perfect forecast)	180	771.74	768.87
Encroach (simple, perfect forecast)	324	773.85	770.98
EncroachWIF (simple, imperfect forecast)	324	774.00	771.13

Figure 23, a plot showing reservoir elevations for the 1964 event helps illustrate typical performance of the alternatives for events large enough to activate the spillway. All three alternatives enter the event at levels below the 737.5 ft NGVD rule curve, although the Encroach alternative is much higher than the others due to more success in filling the reservoir during the previous spring. The inflow from the 1964 event quickly fills available flood storage and drives the pool more than 5 ft above the spillway crest. Pool elevation does not recede below the spillway until 4 days later. The spillway flow does occur late enough to avoid significantly increasing downstream flood peaks. The Existing Condition simulation only reaches the spillway for 36 hours, demonstrating the benefit of incidental extra flood storage due to its failure to fill the pool earlier in the year. With the Combined alternative, operation as simulated makes advance releases to avoid reaching the spillway.

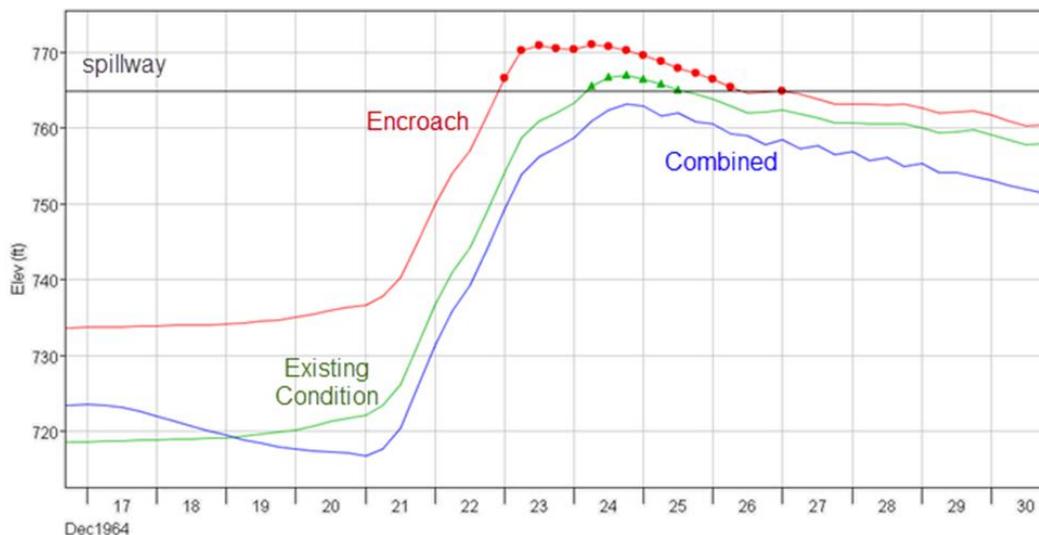


Figure 23. Comparison of Lake Mendocino levels (ft NGVD) simulated for the 1964 event (from the HEC report)

#### 4.2.3 Flood frequency at downstream locations

Table 13, Table 14, and Table 15 show key flood frequency statistics from the FRA compute results at the primary gages along the Russian River. None of the FIRO-based alternatives result in a significant increase at these locations for the 100-year flow or stage. The alternatives also do not increase the annual probability of reaching flood stage. Results at

other locations below Coyote Valley Dam are consistent with these results, demonstrating that the FIRO alternatives do not transfer flood risk between communities along the Russian River. (The AEP of flood stage is not shown in Table 15 because flood stage is not defined for the Russian River near Guerneville [USGS 11467000, drainage area 1,338 square miles]. The official NWS flood forecast point is several miles downstream at Guerneville [USGS 11467002, drainage area 1,353 square miles, stage only, no longer rated]. Given the proximity of these two locations and the insignificant shift in the 1% ACE discharges among the alternatives, no difference should be expected in the AEP of flood stage at the official flood forecast location downstream.)

Small differences are seen among the results for the alternatives due to timing effects if advance releases or spillway flow add or subtract to flood peaks downstream.

Table 13. Comparison of key frequencies at Russian River near Hopland gage - USGS 11462500/NWS HOPC1/RM 84.78

Alternative (1)	Event with 1% ACE			AEP of flood stage (Gage 21.00/ NAVD 521.46 ft) (5)
	Discharge (cfs) (2)	WSEL (NAVD ft) (3)	Gage height (ft) (4)	
Existing Conditions	66,200	531.74	31.28	0.509
Combined (complex, perfect forecast)	66,300	531.75	31.29	0.509
Encroach (simple, perfect forecast)	66,300	531.75	31.29	0.506
EncroachWIF (simple, imperfect forecast)	66,300	531.75	31.29	0.509

Table 14. Comparison of key frequencies at Russian River near Healdsburg gage - USGS 11464000/NWS HEAC1/RM 35.42

Alternative (1)	Event with 1% ACE			AEP of flood stage (Gage 23.00/ NAVD 102.87 ft) (5)
	Discharge (cfs) (2)	WSEL (NAVD ft) (3)	Gage height (ft) (4)	
Existing Conditions	118,600	108.18	28.31	0.052
Combined (complex, perfect forecast)	118,600	108.18	28.31	0.052
Encroach (simple, perfect forecast)	118,600	108.18	28.31	0.052
EncroachWIF (simple, imperfect forecast)	118,600	108.18	28.31	0.052

Table 15. Comparison of key frequencies at Russian River near Guerneville (Hacienda) gage - USGS 11467000/NWS RIOCI/RM 21.29

Alternative (1)	Event with 1% ACE			AEP of action stage (Gage 31.00/ NAVD 54.02) (5)
	Discharge (cfs) (2)	WSEL (NAVD ft) (3)	Gage height (ft) (4)	
Existing Conditions	120,100	72.76	49.74	-
Combined (complex, perfect forecast)	120,000	72.76	49.74	-
Encroach (simple, perfect forecast)	120,500	72.78	49.76	-
EncroachWIF (simple, imperfect forecast)	120,500	72.78	49.76	-

#### 4.2.4 Hopland flow rule

Formulation of the FIRO alternatives also considered performance in observing the rule that calls for releases to avoid causing flows greater than 8,000 cfs at the Hopland gage. (This threshold is typically exceeded several times per year by unregulated flows, and causes no

direct flood damage.) Table 16 summarizes results from the 1951-2010 simulations demonstrating the FIRO plans can improve frequency of meeting this regulation rule.

*Table 16. Hopland rule compliance comparison*

Alternative (1)	Hours with flow greater than 8,000 cfs (60-year simulation, 1951-2010) (2)
Existing Conditions	3,828
Encroach (simple, perfect forecast)	3,438
Combined (complex, perfect forecast)	3,552
EncroachWIF (simple, imperfect forecast)	3,522

#### 4.2.5 Storage available

The FIRO alternatives considered by HEC analyst were designed to store the most water possible without significant increase in flood damage. HEC used the 1951-2010 simulation of reservoir filling and depletion under each alternative to determine the potential storage gain under a perfect forecast scenario.

The schedule of the existing rule curve calls for Lake Mendocino to reach its full summer pool of 761.8 ft NGVD by May 10 of each year. In practice, the reservoir usually does not attain this level. A measure of the success of a FIRO alternative is the increased likelihood of refilling to the full summer pool level. Figure 24 compares the frequency of storages simulated on May 10 for the alternatives. The FIRO-based alternatives typically capture about 20,000-29,000 AF more than operation with the Existing Condition scenario. HEC analysts suggest the median gain of 29,000 AF is a reasonable estimate of the maximum additional storage possible without increasing flood risk because these alternatives used aggressive operations leveraging perfect knowledge of future conditions.

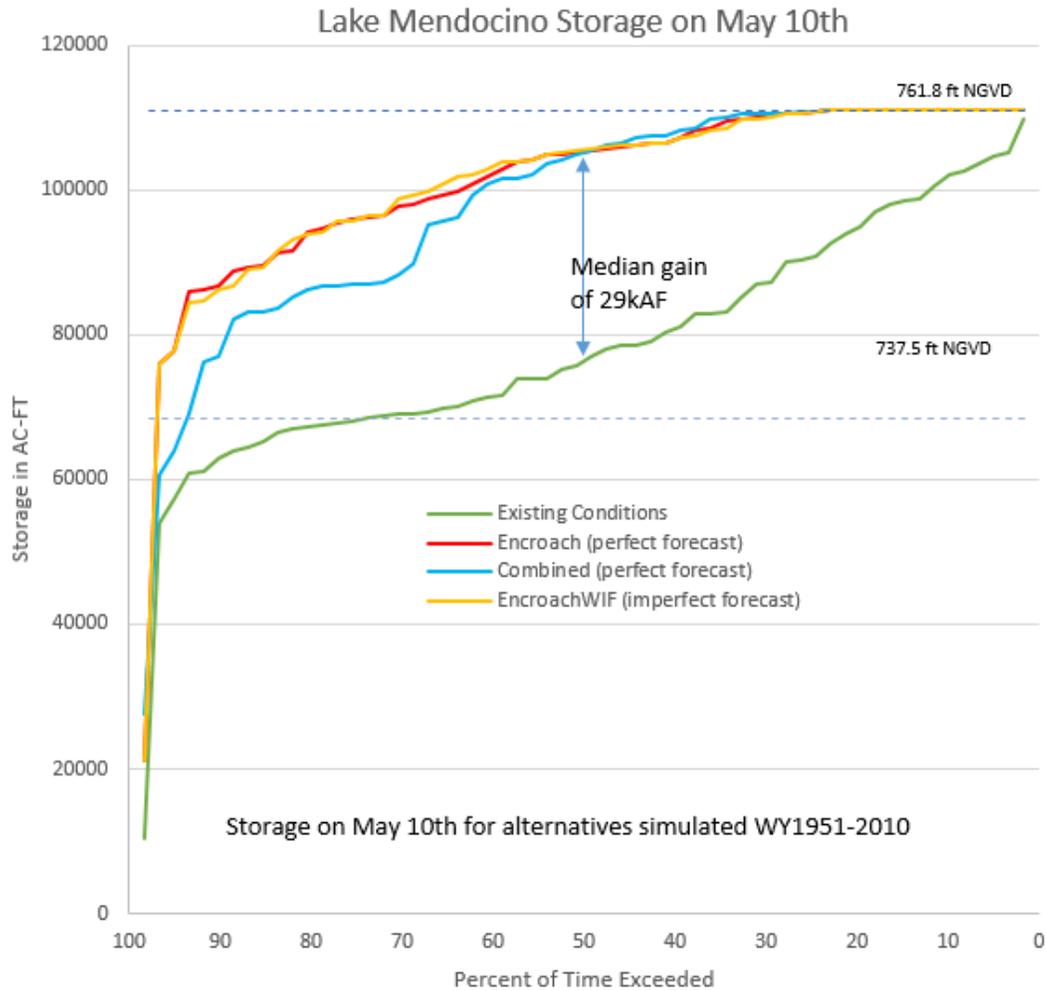


Figure 24. Distributions of Lake Mendocino May 10 storage (from the HEC report)

The storage available after summer depletions is highly correlated with the storage available at the beginning of the summer. Figure 25 illustrates this, showing how forecast informed operation results in similar amounts of additional storage remaining, which would be available for downstream flow objectives during autumn.

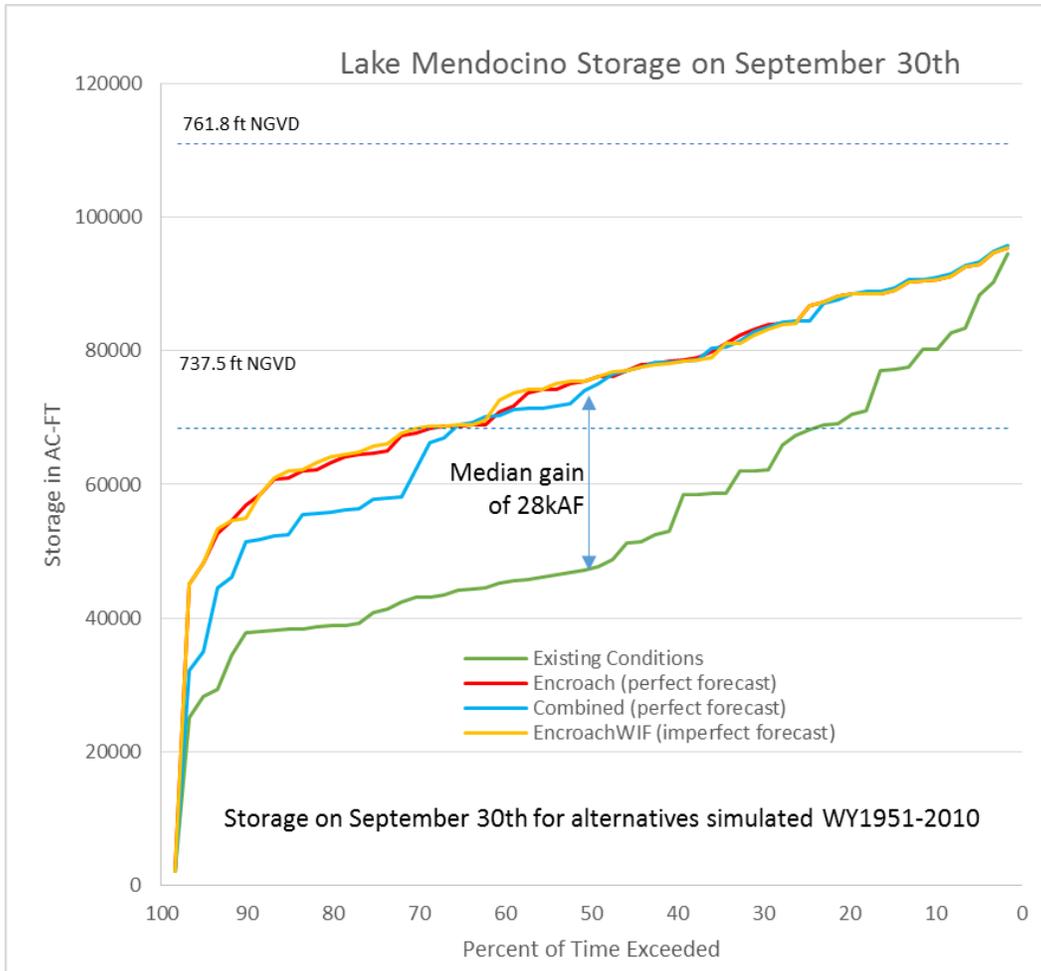


Figure 25. Distributions of Lake Mendocino September 30 storage (from the HEC report)

### 4.3 Forecast accuracy assessment results

The studies completed by CW3E identified needs for forecasting within FIRO of Lake Mendocino, assessed current skill in forecasting, and identified research and development needed to enhance forecasts considering the importance of AR events to conditions in the watershed. Findings of the analysis include the following:

1. Forecast lead time. CW3E analysts found forecast lead time of approximately 5 days is required if an additional 10,000 AF for water management is stored in the flood pool under a FIRO scheme. With such lead time in advance of an AR event, system modeling indicates that the stored water could be released without adverse impacts downstream, emptying the flood space so the reservoir can be used to manage flood risk.

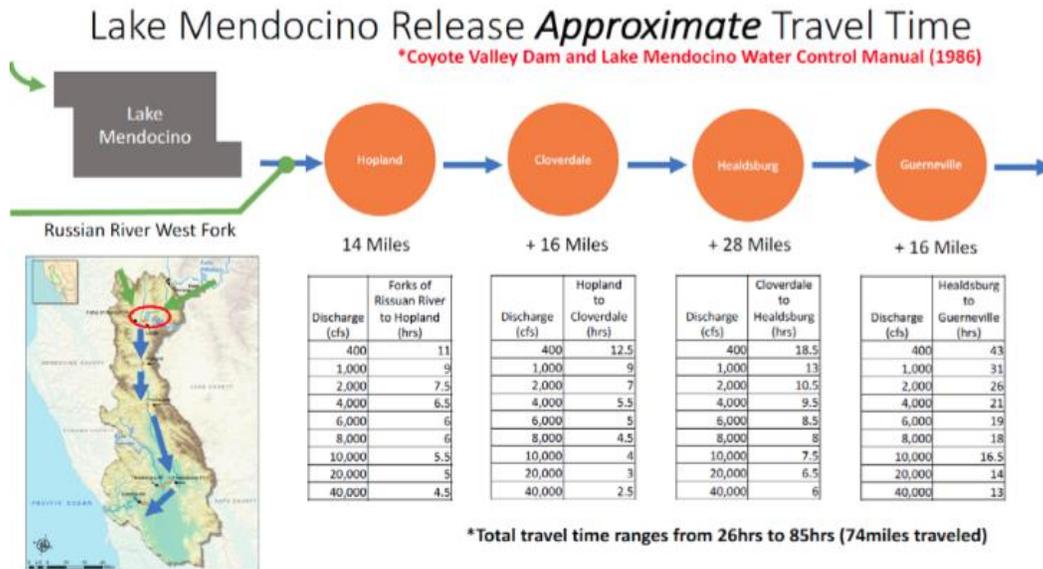


Figure 26. Conceptual graphic of the forecast lead time required to pre-release a volume of 10,000 ac-ft and have it pass out of harm's way prior to a significant AR landfall (from the CW3E report).

- Forecast requirements for extreme rainfall events. CW3E's analysis found that a precipitation forecast of 2 in/24 hr is a key indicator of high inflows once soils in the basin have been wetted significantly and corresponds to conditions that raise flooding potential in the Russian River watershed. CW3E recommends that this be further evaluated as a threshold in determining potential changes in releases from Lake Mendocino.

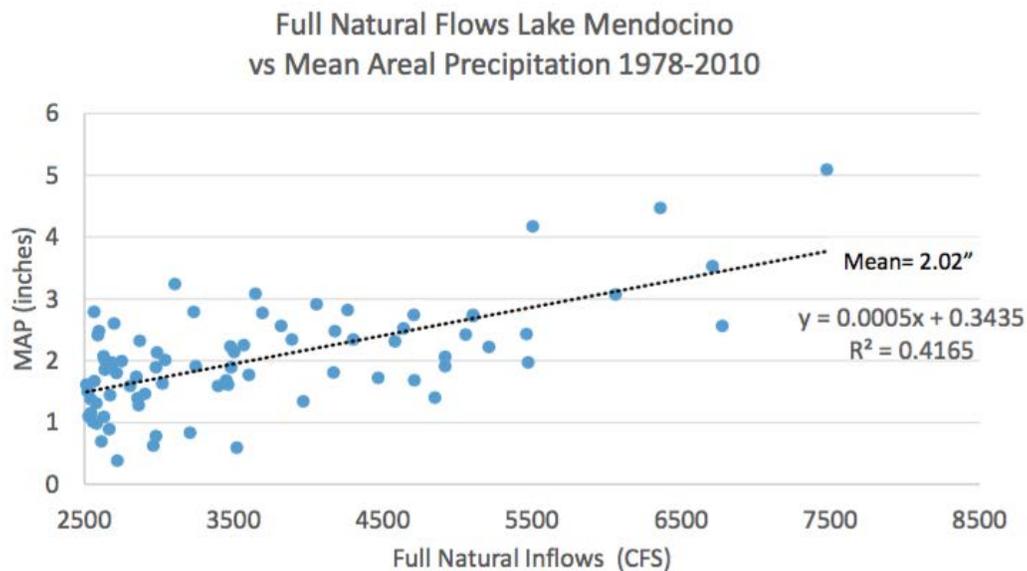


Figure 27. Full natural inflows to Lake Mendocino versus MAP (from the CW3E report)

3. Current forecast skill level for rainfall that has an impact on Lake Mendocino operation. CW3E analysts found CSI values for CNRFC rainfall forecasts for the Russian River watershed greater than values reported for the continental US for the cool season. Further, CSI values for forecasts of 2 in/24 hr with lead times of 1 and 2 days in the Russian River watershed exceed values for the entire CNRFC forecast domain. CW3E analysts reported the higher skill levels are due to the strong orographic nature of the precipitation. They concluded from this that reservoir operation along this region of the west coast is well suited for a forecast informed strategy, as cool season QPFs have at or near the highest skill in the continental US. CW3E analysts recommended future research focus on improving forecasts of timing and intensity of AR landfalls; this will improve the short-term forecasts that are critical for Lake Mendocino operation decision making. (The current Lake Mendocino WCM includes rainfall rates of 0.5 in/6 hr and 1.0 in/24 hr as thresholds to alert operators of potential flooding.)
4. CNRFC 5-day deterministic QPF has more skill than the GEFS ensemble mean used to force the Ensemble Forecast Operations model (EFO). Therefore, consideration should be given to using the deterministic forecasts for days 1-5 as input to the Meteorological Ensemble Forecast Processor that outputs the ensemble streamflows used by the EFO.
5. Current skill in forecasting no significant rainfall (AR landfall). A key finding of **CW3E's analysis was POD and CSI are large and FAR small** for CNRFC forecasts of MAP less than or equal 1 inch in 24 hours. Few forecasts of under 1 in per 24 hr observe greater than 1 in per 24 hr in a 5-day forecast. Thus, operational decisions formulated with the expectation of little rainfall are unlikely to compromise flood risk management or dam safety due to an unpredicted significant inflow event. This analysis result supports a preliminary conclusion that FIRO can enhance water management operation of Lake Mendocino without jeopardizing the flood protection provided.
6. Ability of current streamflow forecasts to support FIRO for Lake Mendocino. CW3E found the following from analysis of CNRFC streamflow forecasts:
  - RMSE increases as forecast lead time increases for 24-hr and 72-hr volume forecasts.
  - The 90<sup>th</sup> percentile value for 24-hr and 72-hr volumes *...shows good CSI values for all forecast periods*. CSI values for 24-hr volumes range from 0.73 for day 1 to 0.56 for day 5, and CSI values for 72-hr volumes range from 0.66 for day 1 to 0.62 for day 3.
  - The 95<sup>th</sup> percentile value for 24-hr volume forecasts shows good skill to forecast day 3. After that, the CSI value drops below 0.50. The 95<sup>th</sup> percentile values for 72-hr forecasts show good (>0.50) values for day 1 and 2.
  - The CSI values for 24-hr volumes at the 99<sup>th</sup> percentile value decrease rapidly beyond day 1 of the forecast. The values for 72-hr volume forecasts are greater than 0.4 for days 1 and 2.

In summary, the CW3E analysis of skill concluded ***...the CNRFC streamflow forecast archive shows skillful forecasts for the 90<sup>th</sup> percentile forecast events for all lead times...99<sup>th</sup> percentile volumes, which represent some of the most extreme events...show skill for day 1...but drops off substantially after that.*** Accordingly, CW3E recommends research to improve forecasting of the most extreme streamflow events of the region.

7. Suitability of ensemble precipitation forecasts for FIRO. As described in Section 7 of the CW3E report, the analysis found through statistical tests of accuracy and skill that the GEFS ensemble mean MAP is suitable for testing and evaluating FIRO based

strategies. This finding confirms the appropriateness of the SCWA risk-based modeling, which relies on the ensemble forecast to estimate the probability of threshold exceedance with alternative releases.

8. Importance of extreme rainfall events to annual precipitation in the Russian River watershed. CW3E analysts reported AR events cause a “disproportionate number” of the wettest days in California. In the Russian River, over 80% of the year-to-year variability in total water year precipitation is caused by the wettest days. This implies that fewer extreme events can lead to drought. So while a FIRO strategy for Lake Mendocino may focus on event-by-event operations, CW3E analysts note management of the largest events also relate directly to management of drought risks.

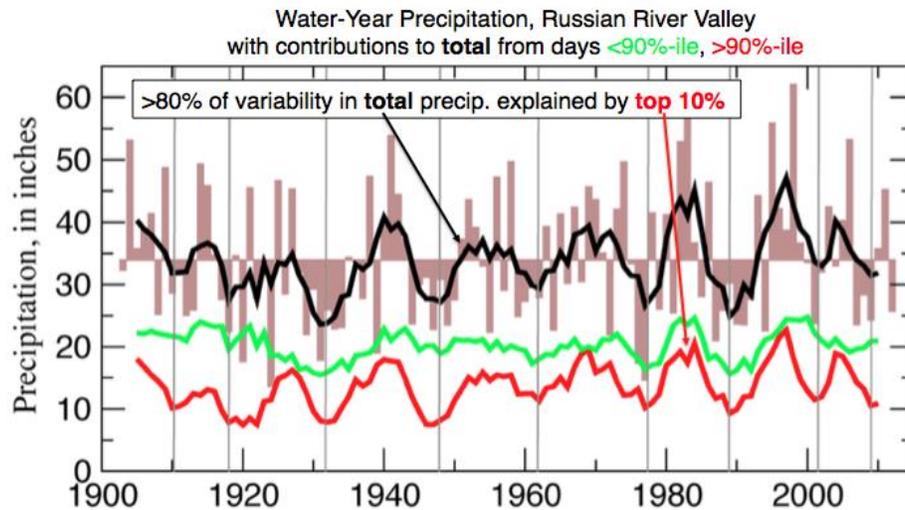


Figure 28. Water-year precipitation over Russian River Valley with contributions to total from days with “top 10%” precipitation (from the CW3E report)

9. Relationship of upslope water vapor flux and rainfall for land-falling ARs. CW3E analysts sought to improve capability to forecast landfalling ARs by incorporating 6 years of additional data on upslope water vapor. While this addition did not increase the correlation, it did confirm (a) the relative strength of an AR can be determined with upslope water vapor flux information, and (b) other atmospheric conditions play a large role in AR forecasting. CW3E recommended continuation of research to better understand these factors.
10. Impact of frontal waves along ARs on flood forecasting in the Russian River Basin. Through analysis of December and February 2014 events, CW3E analysts demonstrated the effect frontal waves can have on orographic precipitation. This meteorological impact, in turn, influences forecast skill. CW3E analysts showed a poorly predicted frontal wave modified precipitation during a strong landfalling AR, which caused flood stage to be reached at Guerneville. The analysts further showed 10-ft variations in the forecasts of river stage, even at 2-3 day lead times (flood stage is at 32 ft). CW3E identified research to define better how frontal waves affect AR duration and the location of heaviest precipitation as a critical need to ensure viability of FIRO.

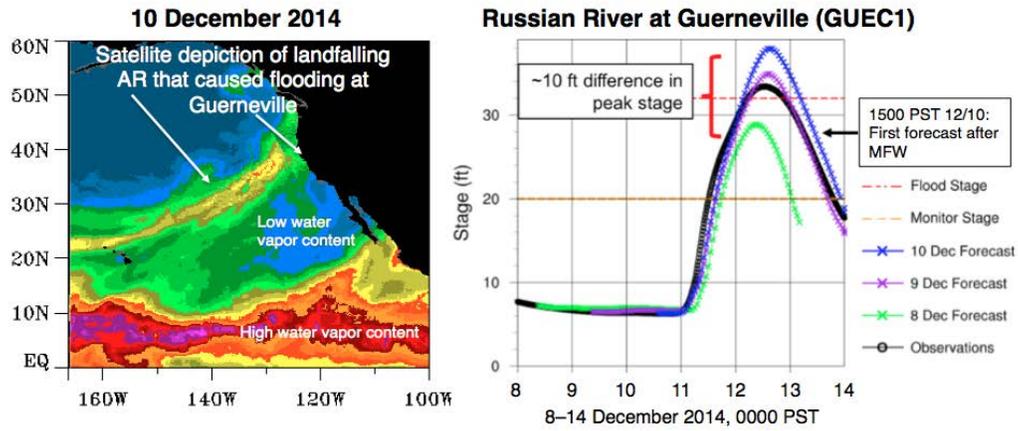


Figure 29. Satellite analysis of a landfalling AR that contained a MFW that resulted in forecast uncertainty of river stage at Guerneville (from the CW3E report)

The CW3E report provides more detail on the results and recommendations.

## 5 What we conclude about the viability of FIRO

The studies described herein found:

- In the cases considered in SCWA's simulations, integrating forecasts of reservoir inflows and local flows in release decision making allow operators to improve reliability of meeting water management objectives in the Upper Russian River.
- In the cases considered in HEC's simulations, integrating forecasts of reservoir inflows and local flows in release decision making does not adversely affect flood risk management.
- The greatest operational improvements for reliability in meeting water management objectives and maintaining environmental flows are realized if WCM rules are modified to provide flexibility for FIRO.
- Overall, CW3E found that existing forecast skill is adequate to support FIRO implementation strategies related to most forecast scenarios. Forecast skill for low-frequency, high-intensity atmospheric storm events is lower and requires continued research to improve understanding of landfall location, intensity, and duration of these events. Skill in precipitation forecasting was best when forecasting extended dry periods and appears viable for use in FIRO. Significant errors can occur during heavy precipitation associated with landfalling ARs and should be accounted for when deciding how much water to pre-release ahead of an AR event.

Based on these study findings—and consistent with the FIRO SC's **decision**- making process illustrated in Figure below—the SC's **opinion** is:

1. Elements of FIRO are currently viable, and can improve reliability in meeting water management objectives and ecosystem conditions without impairing flood protection.
2. Major deviation requests should be developed and submitted to USACE for consideration for winter 2017/18 and beyond.
3. Additional improvements in forecast skill have the potential to further enhance reservoir operations.
4. Research into integrated hydrometeorological modeling and monitoring with incorporation into decision support systems is required to realize the full potential of FIRO including for enhanced reliability in meeting water management objectives, flood mitigation, and ecosystem services.

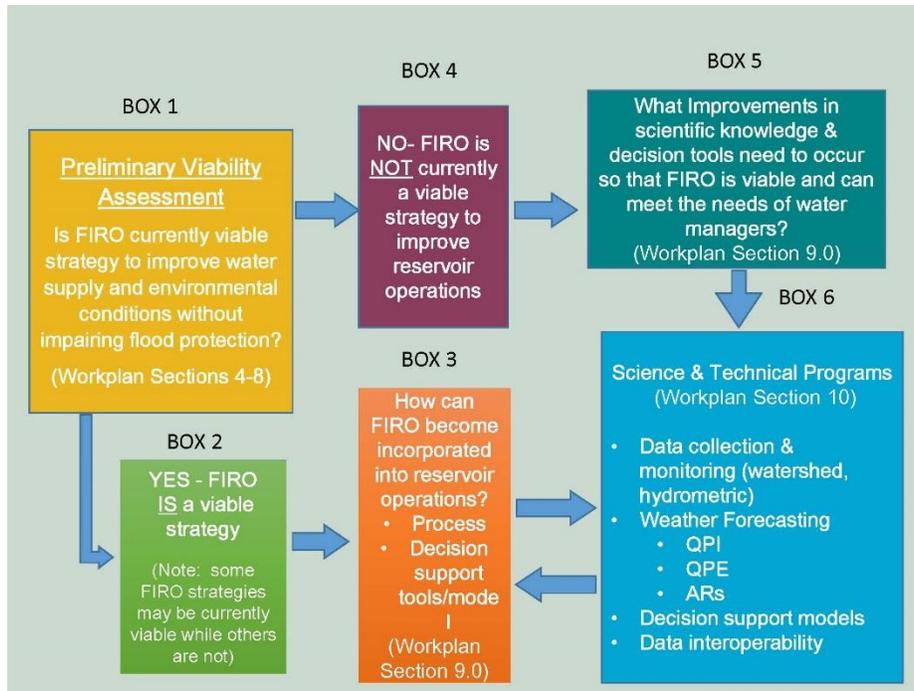


Figure 30. Flow diagram depicting the FIRO viability assessment process (FIRO Steering Committee 2015)

The SC recognizes and acknowledges the viability assessment studies completed by SCWA and HEC are preliminary. In both studies, the FIRO process and DSS tools and models are simulated. As illustrated by box 3 in the figure above, the actual components of the FIRO DSS will be identified in subsequent work, as the FVA proceeds. Furthermore, the studies did not include a comprehensive assessment of uncertainty associated with performance of various elements of FIRO, as those elements have not yet been selected and, in some cases, are not yet available. For example, both studies considered uncertainty associated with inflow forecasts made with currently available data collection and monitoring, weather forecasting, decision support models, and data operability. But neither study could consider the uncertainty reduction attributable to scientific advances, enhanced data collection, and technical programs that will be completed as the FVA proceeds (as illustrated by box 6 in the workflow diagram.) Nevertheless, the SC finds the results of the SCWA and HEC studies convincing and sufficient to recommend proceeding, with uncertainty analysis included as a component of the FVA.

## 6 What we recommend as the next actions

Based on findings of the PVA, the SC recommends the following:

- The FVA should proceed as proposed.
- The FVA should identify candidate components of the FIRO system, investigate viability of those alternative components to improve meeting water management and flood management objectives, and select components of the system, integrating new technology if necessary. The alternatives should be tested in an operational setting. In planning alternatives, the FVA should also consider and assess dam safety.
- Implementation of FIRO should be incremental, with FIRO system elements presently functional implemented in the near-term, while other elements continue to be developed or refined as part of research and development programs.
- Science and technical programs should proceed as proposed to develop new methods for data collection and monitoring, weather forecasting, decision support models, and data operability.
- Policy adjustments needed to implement FIRO effectively should be identified and coordinated with USACE water management policy makers to ensure continued safe operation of Lake Mendocino.
- The analysis performed in support of the PVA clearly identified that both objective flows for Hopland and rate of change limits for Coyote Valley Dam limit the project's ability to discharge excess stored water when conditions warrant. Initial field evaluations of the 8,000 cfs target flow for Hopland may be slightly lower than necessary, and it is not clear if the local impacts are associated with releases, local runoff, or some combination of both. Rate of change criteria are not contingent upon background magnitude, rising or falling, or recent events. Further investigation is needed to clearly identify the appropriate controlling factors for Coyote Valley Dam releases both in terms of rate of change and appropriate efforts to reduce nuisance flooding in the vicinity of Hopland.
- 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 SC recommends the FVA include studies to answer the following questions about FIRO:

- What are the consequences throughout the watershed of release decisions, and how should those be incorporated into FIRO for high water conditions?
- What probability of storage exceeding capacity can be tolerated in the context of the EFO tool?
- Which changes to reservoir operation rules are most effective for FIRO implementation? For example, is it more effective to change fixed flood control space to variable space or to specify reservoir drawdown release amounts based on forecasted inflow? The PVA studies did not address this, but the FVA should.
- What changes to reservoir operation rules will be acceptable to USACE within and beyond the Lake Mendocino system? To implement FIRO, USACE approval will be required for deviations from the current WCM or for changes to the WCM. USACE guidance, collaboration, and cooperation is needed for developing FIRO rules that comply with current policy or for changing policy.

- Which components of inflow forecasting technology must be enhanced to accommodate FIRO, including detailed forecasts of AR landfall characteristics (timing, location, duration, intensity, orientation)? While hydrometeorological forecasts of sufficient accuracy may be available for the Russian River watershed for shorter lead times in most cases, enhancements are required for forecasting details of AR conditions at landfall, forecasting in potential flood situations, and forecasting with longer lead times to realize fully the potential water management reliability benefit. Furthermore, in addition to forecasting days to weeks ahead of a storm, enhancements that permit seasonal forecasting would provide even more opportunity for wise decision making about Lake Mendocino operation. Scientific inquiry is needed to support this.
- What benefits can FIRO provide for environmental purposes and others? Additional assessments are needed to quantify FIRO benefits for other societal and environmental purposes.
- What are the benefits of additional water, and how do those compare with the cost of the research?
- What should be the operational targets in the system? For example, current WCM rules aim to constrain flows to 8,000 cfs at Hopland. This threshold was established by USACE as the project was constructed. PVA studies and recent observations raised doubts about the appropriateness of the threshold. Modeling studies and field investigations should be completed to confirm current channel conditions and vulnerability of people and property in the floodplain.
- What observational enhancements are needed? Observational enhancements that have the best potential to improve hydrologic forecasting that will be a primary input to FIRO include improved precipitation estimates, improved stream gaging above Lake Mendocino and of currently ungauged inflows to the Russian River below it, and soil-moisture conditions throughout the basin. Furthermore, the science of forecasting ARs advances primarily on the basis of new and evolving research observations including measurements of the atmospheric conditions within the AR storms that dominate the Russian River basin; such measurements include vertical profiling of temperatures, water vapor, winds, aerosols, cloud microphysics, isotopic compositions of water and water vapor, and more. A critical step in advancing measurements and monitoring in the basin is identification of the most advantageous locations, densities, and kinds of observations for support of FIRO; an evaluation of observational needs and opportunities in support of FIRO will be an important step in the FVA.

## 7 References

The main body of this report draws from the SCWA, HEC, and CW3E reports. Additional sources of information are listed in those reports.

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