PRELIMINARY VIABILITY ASSESSMENT OF LAKE MENDOCINO FORECAST INFORMED RESERVOIR OPERATIONS

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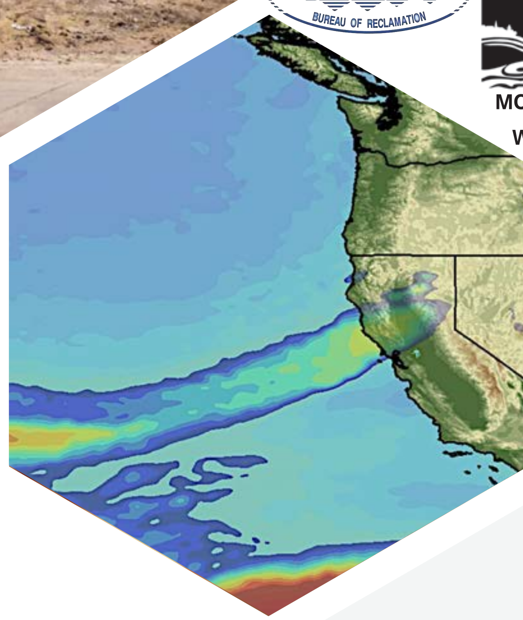


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Forecast Informed Reservoir Operations Steering Committee. (2017). Preliminary viability assessment of Lake Mendocino. Available from: http://escholarship.org/uc/item/66m803p2

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 1 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 1. 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 2 shows AAD for the existing condition and FIRO alternatives.

Table 2. Russian River basin flood risk: FIRO alternatives do not measurably change flood risk based on analysis of 1951-2010 and statistical sampling.

	POR compute (60 years, 1951-2010)		FRA compute (5,000 events)	
Alternative (1)	AAD ($ million) (2)	Increase in AAD from existing[1] ($ million) (3)	EAD ($ million) (4)	Increase in EAD from existing[2] ($ 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^2 (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.

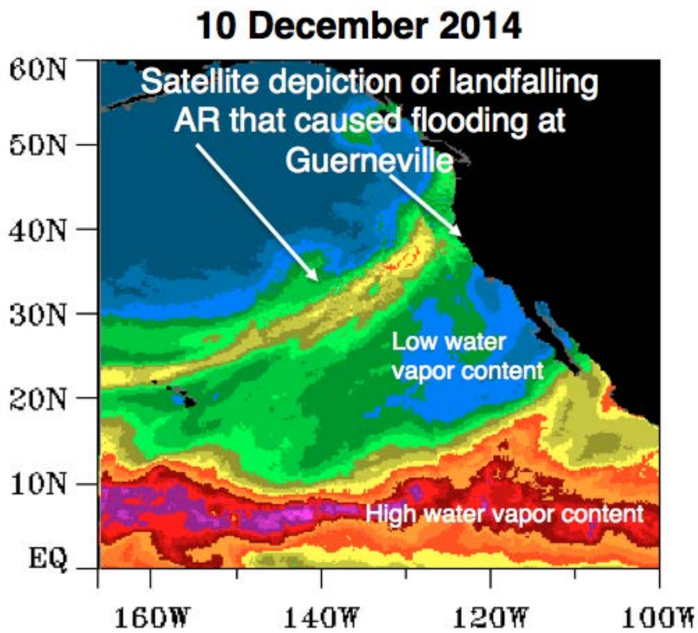

Figure 1: SSMI imagery of a landfalling AR on 10 December 2014 (from the CW3E report)

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.

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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 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.