Section 2.7 Reservoir Management Tools

2.7.1 Overview

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

Two variants of the EFO model served as the basis for the research and development activities reported in this section: 1) operations when the variable flood control pool is extended to the top of the summer conservation pool (111,000 ac-ft) for the entire year (called the EFO alternative) and 2) when the variable flood control pool is limited to 80,050 ac-ft from November through March (called the Hybrid alternative). Figure 2.7.1 shows the existing guide curve in the 1986 Water Control Manual (WCM) and the variable flood control pool associated with the Hybrid alternative for Lake Mendocino. When storage is above the shaded area, the Corps will release stored water as quickly as safely feasible to return to 80,050 ac-ft. In the EFO alternative, the entire pool up to the 111,000 ac-ft level is available for conditional storage. At 111,000 ac-ft the reservoir is 3 feet below the emergency spillway crest.





The structure of the EFO leverages forecast skill in the ESPs to make "informed" release decisions. As ESP skill improves, EFO or EFO-type approaches could be modified to allow more wintertime use of reservoir storage. Thus, the EFO model provides a pathway for research investments in observations and science that contribute to improved skill to make their way into operational use. The WestWRF reforecast (Section 2.3.5) provides a good example. Here, the downscaling of the GEFSv10 reforecasts by

WestWRF is expected to provide improved QPFs for the Russian River Basin. In principle, processing these higher resolution reforecasts through the CNRFC's HEFS (to generate new ESP inflow forecasts) and applying EFO to them provides an objective way to quantify and demonstrate the benefits of research efforts associated with WestWRF. (Unfortunately, processing WestWRF reforecasts through the CNRFC's HEFS has not been completed in time to be included here).

Research and further development of the EFO model was used to refine the EFO-type operational alternatives described and evaluated in Section 5. Additionally, the work on scaling historical flood events provided a methodology for estimating frequency curves associated with flood impacts, spillway use, and reservoir storage larger than any that occurred during recent decades.

Highlights of this task include the following accomplishments:

- Modification of the EFO computational time step from daily to hourly (section 2.7.2)
- Extension of EFO-model considerations downstream to Guerneville; initially stopped at Healdsburg for the PVA (section 2.7.2).
- Scaling of historical events to explore even larger extremes (section 2.7.3)
- Risk curve refinements and evaluations (section 2.7.4) reflecting
 - o Optimization attempts
 - Seasonal curves
 - Multi-objective curves

2.7.2 Improvements to the EFO model

Since the PVA, the EFO model has been refined significantly in support of FIRO. One such improvement was to increase the time step from daily to hourly. The EFO model used for the PVA was developed to simulate conditions at a daily time step, so that changes in releases and flows were routed to all downstream model junctions in a single time step. To support real-time operations under the 2019 and 2020 major deviations, and the hydrologic analyses completed for the Hydrologic Engineering Management Plan (HEMP) study, the EFO model was refined to simulate release decisions and flows at an hourly time step. To support an hourly time step simulation, the model was modified to allow hydrologic routing using the Lag and K methodology (NOAA National Weather Service, 2005) currently used by the National Weather Service. The Lag and K routing was developed based on the graphical routing method originally developed by Linsley et al. in 1975. The time lag (Lag in hours) and attenuation (K) parameters were provided by CNRFC and are the same values currently used in their hydrologic forecasting models. Additionally, algorithms were added to the EFO model to calculate reservoir release schedules that account for the time lag and attenuation of hydrographs when evaluating for maximum downstream flow constraints.

The second major refinement to the EFO model was to revise it to include an additional model junction at the USGS Russian River at the Hacienda Bridge (USGS 11467000) streamflow gaging station (located just upstream of Guerneville). This additional model junction incorporates local unimpaired flow forecasts from the CNRFC for Guerneville and defined inputs for releases from Lake Sonoma from the

HEC- ResSim model of the Russian River. Additionally, model rules were formulated for the EFO and Hybrid alternatives that limit releases from Lake Mendocino to avoid adding to flows above flood stage (35,000 cfs) at the Guerneville junction.

2.7.3 Scaling of historical events to estimate extremes

The EFO model developed for the PVA was evaluated for conditions and events during 1985-2010 and utilizing a 61-member ensemble hindcast made available by the CNRFC. This period only included one major flood event, February 1986. Although a major event, it was only estimated to have a 25-year return period event based on an average 3-day inflow of 6300 cfs. Therefore, it was decided to scale the three largest observed events in the available 1985-2010 hindcast period, February 1986, New Year's 1997, and New Year's 2006, to have flood volumes equal to 200 and 500 year return period estimates from the frequency analysis provided by HEC (Figure 2.7.2). The methodology used by the CNRFC was to scale the maximum 5-day Mean Areal Precipitation (MAP) for each event until the average 3-day inflows matched the 200 and 500-year return period values. These 5-day scaled MAP values are shown in Figure 2.7.3, along with the observed values and the observed 5-day rainfall for the record December 1964 event and the observed 5-day MAPs for the three cases being simulated.

The number of days used in the simulations varied from 37 to 39 with ~26 days before and ~12 days after the main runoff event (Table 2.7.1). Both the Meteorological Ensemble Forecast Processor ensemble output and the observed precipitation were scaled. Unimpaired streamflow was simulated by processing the scaled precipitation observations through the hydrology model. The multiplication factors applied to the maximum 5-day precipitation to arrive at the appropriate 3-day inflows are shown in (Table 2.7.1). This scaling factor was also applied to the 1-day, 3-day, and 7-day inflows for each of the cases. The results of the simulated unimpaired inflow to Lake Mendocino are also provided in Table 2.7.1. Note that the duration of rainfall during the 2006 event was much shorter and as a result the scaling using a 5-day factor resulted in extremely high 1-day amounts and streamflow peaks.



Figure 2.7.2 Return periods of average daily flows into Lake Mendocino for 1, 3, 7, and 15 days. (Faber, 2018)



Figure 2.7.3 5-day MAP for Lake Mendocino Watershed observed in December 1964 and for each of the three cases along with the results of scaling to the 5-day 200- and 500-year return periods for '86, '97, and '06 events.

Two metrics were used to assess the impacts of these large simulated events on reservoir operations and downstream flood flows. These included (1) average spill volume and (2) peak flows at Hopland (from the new hourly version of EFO and fixed rule curves). These metrics were compared to those from a simulation of existing Water Control Manual operations and for context, historical observations at Calpella (above Lake Mendocino pool) and Hopland. Table 2.7.1 shows the peak scaled inflows and peak Calpella and Hopland flows.

Table 2.7.1. Simulated peak inflows into and emergency spillway releases from Lake Mendocino and flows at Hopland and for all scaled events for the EFO and Hybrid alternatives using a fixed risk curve. Note that simulation of existing Water Control Manual operations yields slightly higher peaks at Hopland. (* USGS gage at Calpella, ** prior to Coyote Valley Dam construction.)

Year	Scaling	Lake Mendocino Peak	Lake Mendocino Spill Volume (1000 ac-ft)			Hopland Peak Flow (1000 cfs)		
	Factor	Inflow (1000 cfs)	EFO	Hybrid	Existing WCM	EFO	Hybrid	Existing WCM
1955	obs	13.30*						45.00**
1964	obs	18.70*						41.50
1986	obs	11.20			0.00			32.90
	200-year	15.08	13.42	8.90	32.07	36.28	36.27	42.52
	500-year	17.21	26.39	18.01	38.80	42.54	41.59	50.61
1997	obs	8.27*			0.00			20.00
	200-year	17.78	0.00	0.00	42.60	42.60	42.60	42.60
	500-year	21.48	8.21	1.41	51.91	50.95	50.95	51.91
2006	obs	14.60*			0.00			35.60
	200-year	26.04	20.21	20.57	58.56	51.19	51.20	58.56
	500-year	30.21	33.80	31.03	70.67	65.37	68.89	70.67

The scaled-1986 simulations yielded peak inflows to Lake Mendocino and the peak flows at Hopland that are below their floods of record, 1964, and 1955, respectively. This was an expected outcome for Hopland because Coyote Valley Dam was not completed until 1957. The scaled-1997 simulations yielded peaks below the floods of records for the 200-year scaling. The scaled-2006 simulations all exceed the flood of records by significant margins. As noted earlier, the 2006 event did not scale well to the 1-day flows. One does see, however, that the peak flows for all scaled event simulations produce flows at Hopland for the EFO and Hybrid alternatives that are below those simulated with existing operations. Thus, even in these extremely large events peak flows are reduced downstream mitigating flooding with simulated FIRO operations. Additionally, uncontrolled emergency spillway releases for the EFO and Hybrid alternative are lower or eliminated in the case of the 1997 200-year scaled event than existing operations for all for the scaled event simulations indicating a reduced risk of unwanted releases from the emergency spillway.

The scaled-1986 simulations provide the most insight into the performance of the EFO and Hybrid alternatives associated with emergency spillway activation. Figure 2.7.4 shows the storage, spill, inflows, and flows at Hopland and Guerneville for the 1986 event scaled to 200-year and 500-year return periods. Due to forecast informed pre-releases, storage levels for the EFO and Hybrid alternative are reduced significantly in advance of the flood event (well below the existing operations alternative). Emergency spillway releases were produced for each scaled scenario and each alternative. However, the magnitude and duration of spillway releases are significantly lower for the EFO and Hybrid alternative

relative to the existing operations alternative. The EFO alternative produced larger spills than the Hybrid alternative. As a result of the reduced spills, the EFO and Hybrid alternatives also showed reduced peak flows and flood duration downstream at Hopland relative to existing operations. Flows further downstream at Guerneville show close agreement for all alternatives and all scenarios. Additional insight on the use of scaled events is provided in Section 5.



Figure 2.7.4 Simulated storage (1st) inflows and spills (2nd), Hopland flows (3rd), and Guerneville flows (4th) for the EFO, Hybrid, and existing WCM operations for the 1986 flood event scaled to the 200 and 500-yr return period events. Color key is noted in each diagram. Flood Stage at Hopland and Guerneville are noted.

2.7.4 Risk curve refinements and evaluations

The EFO model utilizes the ESPs to characterize risk of exceeding a reservoir storage threshold. A central component of this methodology is a risk tolerance curve that is used to compute informed and appropriate release schedules for Lake Mendocino. The risk tolerance values for the 15 forecast time

steps are not independent from each other. Therefore, given 61 possible risk tolerance values (61 ensemble members) at each time step, there are 15^{61} possible risk tolerance curves. Given the very large number of possibilities, a brute force method for optimization would be impractical. Therefore, for this study, a heuristic method was developed to provide an adequate curve that could be used to develop and evaluate the EFO methodology, but likely not the truly optimal curve that might be achieved with more formal optimization methods. The risk tolerance curve used for this study was developed by modeling numerous curves and selecting from among the curves tested the one that best met project objectives of improving storage reliability for downstream water supply and environmental flows without increasing flood risk downstream.

To generate the candidate risk tolerance curves to be evaluated, storage results from a perfect forecast operations (PFO) alternative were used. For each day of the model simulation period (1985 – 2010), forward looking modeled ensemble storage levels assuming no reservoir releases were generated using the HEFS hindcasts with the beginning storage determined by the PFO storage level at that time step. Forecasted probabilities or risk of exceeding the storage threshold of 111,000 acre-feet were calculated for each of the 15 days of the hindcast. This process is illustrated in Figure 2.7.5 for simulation day February 9, 1986, where the risk tolerance curve provided in the inset plot is one of the candidate curves evaluated. This process generated 9404 risk tolerance curves (1 curve for each day of simulation), which was reduced to 1773 unique curves.



Figure 2.7.5 Development of candidate risk tolerance curves using storage results from the PFO alternative.

Each of the candidate risk tolerance curves was simulated with the Lake Mendocino model for the full hindcast simulation period, 1985 to 2010. An objective function consisting of 4 decision variables (provided in the equation below) was developed to evaluate the simulations.

J = (%INC May10 Storage + %DEC May10 Storage Variability + %DEC Flooding) x Spill

Where %INC May10 Storage is calculated as the percent increase in mean May 10 (the end of the flood management season for Lake Mendocino) storage relative to the existing WCM operations alternative. %DEC May10 Storage Variability is calculated as percent decrease in May 10 storage standard deviation relative to existing WCM operations. %DEC Flooding is calculated as the percent decrease in total flow volume greater than flood stage (8,000 cfs) at the Hopland junction relative to existing WCM operations.

During the process of information gathering for this study, reservoir operators expressed a strong aversion to spillway releases. Therefore, to capture the importance of this criteria, Spill is defined as a Boolean decision variable multiplier such that if there are any simulated spillway releases then Spill is set to a value of 0, and if there are no spillway releases then Spill is set to a value of 1.

Results of the objective function computations for each of the 1,773 simulations are provided in Figure 2.7.6. Many of the candidate risk tolerance curves resulted in a spillway release, and therefore have objective function values of 0. Two of the risk tolerance curves (circled in red), show the highest objective function value of 0.77, and therefore both might be considered as "relatively optimal solutions."





The two "relatively optimal" risk tolerance curves are shown as the solid lines in Figure 2.7.7. The curves are in-agreement for the first 4 days of the forecast window with a risk tolerance of 0%. Beyond day 4, differences between the curves shows that the choice of risk tolerance is not unique to achieve the same objective. To create a final curve that is smooth and more intuitive, a 3rd degree polynomial was

fit to the two candidate curves using a least squares regression method (shown as the dotted black line). The objective function value for the interpolated curve is 0.77, indicating optimal performance relative to the other candidate curves evaluated.



Figure 2.7.7 Highest ranked candidate risk tolerance curves and fitted 3rd degree polynomial.

In addition to the optimization of the risk curve, we researched the effects of changing the risk curve by season given that the largest storms occur during December through January. The EFO model was modified to allow monthly risk curves to be used. This was done to explore the impacts of removing false alarms produced by the HEFS inflow forecasts, especially for forecast lead-times beyond day 8. It was shown in the PVA that the GEFS mean precipitation had a high false alarm rate for the watershed beyond day 8 and especially beyond day 10. A series of tests were performed to modify the risk curves to increase the end of season (May 10) water storage but not allow spills or increase flooding downstream. These series of tests produced two different risk curves: One for the primary flood season of Dec-Feb and another for Mar-Nov. These two risk curves are shown in Figure 2.7.8 along with the standard single EFO risk curve.

Risk Tolerance



Figure 2.7.8 Existing and modified seasonal risk curves noted as "variable" in the text. For these simulations on the blue risk curve (variable) and red risk curve (fixed) are used since all three scenarios were in the Dec-Feb time frame.

Figure 2.7.9 shows the exceedance probability of the May 10 water storage in Lake Mendocino comparing EFO model scenario using the fixed risk and variable risk curves, the Hybrid scenario using the fixed and variable risk curves, the existing WCM operations scenario, and the EFO model using perfect forecasts (observations). The EFO model using the variable risk curve provides 96% of the perfect forecast water storage on May 10th.



Figure 2.7.9 Exceedance probability for May 10 storage for Lake Mendocino utilizing both fixed and variable risk curves for the EFO and Hybrid scenarios compared to a perfect forecast and existing operations.

2.7.5 Multi-Objective Hybrid Alternative

At the request of the USACE, Sonoma Water developed an alternative to the Hybrid alternative called the Multi-Objective Hybrid. This alternative utilizes multiple storage threshold objectives for evaluating risk and formulating flood control releases. The primary objective is to evaluate and respond to risk of exceeding the maximum conservation level of the reservoir of 111,000 acre-feet, consistent with the original Hybrid alternative developed for the PVA. The Multi-Objective Hybrid also includes an additional, secondary objective of limiting storage greater than the variable flood control space shown in Figure 2.7.1. Because the consequences of detaining water above the variable flood control space are not as great as exceeding maximum conservation level, this approach uses a relaxed risk tolerance threshold for this secondary objective. Figure 2.7.10 provides an example for the Multi-objective Hybrid from February 25, 2019, just 2-days before a large flood that impacted many regions along the Russian River.



Figure 2.7.10 Multi-objective Hybrid with shaded regions showing observed conditions and white regions showing forecast conditions. 1st (top) panel shows forecast storage; 2nd panel shows projected releases; 3rd panel shows forecasted risk; and 4th and 5th panels show forecasted Hopland and Guerneville streamflow respectively.

2.7.6 Conclusion and Recommendations

The EFO alternative is a viable alternative of FIRO for Lake Mendocino. Utilizing research and operations approaches has demonstrated that implementation of EFO would assist in operations to meet the FIRO project goals of improving storage reliability to meet water supply and ecosystem needs, while not increasing downstream flood risk. The scaling of extreme events highlights the benefits of the various EFO approaches in terms of flood risk reduction. Additionally, the heuristic approach that has been used to modify the risk curve has shown the potential utility in optimizing the critical component of the model. Given the importance of the EFO model to FIRO implementation, continued research, experimentation, and improvement beyond that developed for the FVA is essential.

The following recommendations will benefit FIRO results:

- Develop and optimize risk tolerance curves incorporating more sophisticated optimization methodologies.
- Explore multi-objective approaches to improve storage reliability and flood risk reductions.
- Reorganize and generalize the EFO code to facilitate development of EFO models for other reservoir systems.
- Develop synthetic ensemble forecasts to evaluate and optimize EFO under a wider range of hydrologic possibilities.

2.8 Conclusions

The developed observational data sets and the research performed throughout the Lake Mendocino FIRO project described above, have formed a foundation on which to build the implementation of FIRO at Lake Mendocino. The extensive observations in the Russian River serve as an example of the importance of observations to verify and initialize models as well as study hydrometeorological conditions important for FIRO. The research has developed direct applications to illustrate the viability of FIRO, such as with the EFO model, in addition to demonstrating important approaches and modeling capabilities to improve forecasts and integration of these forecasts.

Implementation of FIRO at Lake Mendocino is not a singular event. FIRO creates an environment where ongoing research investments in forecasts and their application yields ever-improving reservoir management outcomes. It is a commitment to research and research to operations. The research conducted and reported as a part of this FVA is emblematic of this commitment and represents the beginning.