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RESEARCH ARTICLE

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Key Points:

- Ensemble Forecast Operations for Lake Mendocino is a new probabilistic decision support system for reservoir flood control operations
- Ensemble Forecast Operations utilizes ensemble streamflow predictions to manage to forecasted risk of exceeding critical storage levels
- Evaluation of Ensemble Forecast Operations demonstrates improved reservoir storage reliability for water supply and ecosystems

Supporting Information:

- Supporting Information S1

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Forecast Informed Reservoir Operations Using Ensemble Streamflow Predictions for a Multipurpose Reservoir in Northern California

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Abstract Ensemble Forecast Operations (EFO) is a risk-based approach of reservoir flood control operations that incorporates ensemble streamflow predictions (ESPs) made by the California-Nevada River Forecast Center. Reservoir operations for each member of an ESP are individually modeled to forecast system conditions and calculate risk of reaching critical operational thresholds. Reservoir release decisions are simulated to manage forecasted risk with respect to established risk tolerance levels. EFO was developed for Lake Mendocino, a 111,000 acre-foot reservoir near Ukiah, California, to evaluate its viability to improve reservoir storage reliability without increasing downstream flood risk. Lake Mendocino is a dual use reservoir, owned and operated for flood control by the United States Army Corps of Engineers and operated for water supply by Sonoma Water. EFO was simulated using a 26-year (1985–2010) ESP hindcast generated by the California-Nevada River Forecast Center, which provides 61-member ensembles of 15-day flow forecasts. EFO simulations yield generally higher storage levels during the flood management season while maintaining needed flood storage capacity by strategically prereleasing water in advance of forecasted storms. Model results demonstrate a 33% increase in median storage at the end of the flood management season (10 May) over existing operations without marked changes in flood frequency for locations downstream from Lake Mendocino. EFO may be a viable alternative for managing flood control operations at Lake Mendocino that provides multiple benefits (water supply, flood mitigation, and ecosystems) and provides a management framework that could be adapted and applied to other flood control reservoirs.

1. Introduction

A central challenge of water resources management in the 21st century is to provide reliable supplies with both rising demands from increasing populations and rising uncertainty in the magnitude and timing of water supply availability due to climate change (Pierce et al., 2013; Swain et al., 2018). Multipurpose water supply reservoirs, which are designed for both water supply and downstream flood protection purposes (Willis et al., 2011), are vulnerable to this challenge.

Under conventional management practices for several existing multipurpose reservoirs, available storage is allocated according to storage guide curves (also called rule curves) or targets that define the maximum allowable water supply storage level for each day of the year. In reservoirs charged with providing flood control, a flood control space is reserved above the water supply pool as defined by the guide curve to detain flood flows and reduce flooding downstream. Guide curves were developed to reflect average seasonal runoff patterns and basin conditions using available hydrologic information (typically decades ago at the time of reservoir construction and updated as conditions warranted) (Howard, 1999). Seasonal variability is accounted for by requiring a larger empty space in the reservoir during the flood-prone season to accommodate the larger expected runoff volumes (Willis et al., 2011). Because guide curves are ultimately developed to maintain a low risk of flooding downstream of the reservoir, a common

criticism is that they are often overly conservative for flood protection at the expense of water supply storage (Yao & Georgakakos, 2001).

An additional concern with static guide curves is that they are usually based on historical precipitation patterns estimated from data collected during the first half of the twentieth century, and therefore, they cannot adequately capture variations in climate or allow flexibility to adapt to long term trends in hydroclimates due to climate change (Willis et al., 2011). In general, climate change is expected to increase the magnitude of extreme precipitation episodes in California, which will likely increase flood risk (Dettinger, 2011; Pierce et al., 2013), but warming may also reduce snowmelt runoff that refills many western reservoirs after the flood risk ends each year (Pierce et al., 2013). Additionally, watershed characteristics affecting water supply availability such as runoff efficiency and evapotranspiration are continually evolving, and increased urban development and water demand will further strain water supplies (Milly et al., 2008).

A novel approach to addressing water supply management challenges posed by significant departure year over year of the seasonal runoff patterns from their climatological average, climate change, and changing antecedent conditions is through the incorporation of medium range (0–15 days) hydrologic forecasts and modeling into reservoir management (Faber & Stedinger, 2001). Hydrologic forecasts integrate predictions of regional weather and watershed conditions to provide predictions of reservoir inflow (Lettenmaier & Wood, 1993). These inflows can dynamically inform reservoir release decisions to maximize storage for water supply, while also maintaining sufficient storage capacity to detain flood flows for forecasted storms. This management approach has the potential to significantly increase water supply without increasing flood risk.

The first practical challenge in implementing such forecast-based reservoir operations is the development of decision supports that integrate forecast information into reservoir release decisions to meet water resources objectives. Previous studies show that such a decision support system is feasible, such as Yao and Georgakakos (2001) for Folsom Lake in Northern California and Regonda et al. (2011) for the Gunnison River Basin in Colorado.

An equally important challenge is that hydrologic forecasts are significantly uncertain, and proper consideration of this uncertainty is needed to fully and safely realize the benefits for reservoir operation (Zhao et al., 2011). Ensemble streamflow predictions (ESPs), which are stochastic hydrologic predictions, are designed to represent forecast uncertainties. Many reservoir operation studies that incorporate ESPs focus on optimization techniques such as linear and/or dynamic programming to develop an optimal reservoir operation policy for long range management (Faber & Stedinger, 2001; Kim et al., 2007) or short range flood hedging policies (Hui, Lund, & Zhao, 2016). Although studies demonstrating optimization techniques have shown promising results (e.g., Kim et al., 2007), their use has often been criticized as being complicated and difficult to understand and therefore not intuitive for reservoir operators (Rayner et al., 2005). This criticism has led to development of decision support systems that do not rely on formal optimization approaches (Howard, 1999; Nohara et al., 2016; Zhao et al., 2011). These studies demonstrate that expected future states of the target reservoir using each member of the ESP could effectively show potential risks of preliminary release to water supply and flooding.

This study describes the development, implementation, and evaluation of a model for forecast informed flood control operations for Lake Mendocino, a multipurpose rainfed reservoir in Northern California, based on short to medium range (1 to 15 days) inflow forecasts. The probabilistic decision support system and approach, termed Ensemble Forecast Operations (EFO), incorporates ESP forecasts to adaptively manage reservoir storage to provide downstream flood control and limit unwanted emergency spillway releases, while improving storage reliability for water supply and ecosystems. This study builds on previous research efforts by conducting a realistic assessment of a forecast informed decision support system for a real reservoir that incorporates ESP forecasts generated operationally by the California Nevada River Forecast Center and considers all the primary operational constraints for both water supply and flood control management.

2. Background

Lake Mendocino is near the headwaters of the Russian River in Mendocino County, approximately 105 miles north of San Francisco, CA (Figure 1). Water released from Lake Mendocino flows into the Russian River,



Figure 1. Map of the Russian River watershed including the Potter Valley Project.

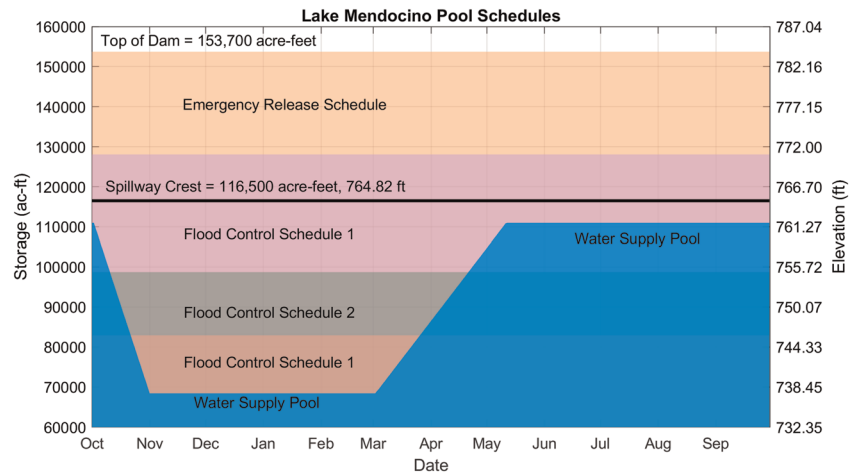


Figure 2. Lake Mendocino water control diagram.

which provides water for a thriving vinicultural region that also includes numerous municipalities in Mendocino and Sonoma Counties. In addition, the Russian River supports three species of salmon that are listed as threatened or endangered under the Endangered Species Act. Current land use is dominated by agriculture (viniculture and orchards), sheep and cattle grazing, suburban and exurban development, and the urban centers of Santa Rosa (population 160,000) and Windsor/Healdsburg (population 30,000) (Opperman et al., 2005).

The region's Mediterranean climate creates a hydrologic regime that causes periodic flooding for reaches downstream of Lake Mendocino. Floods in the Russian River watershed normally have short duration, developing 24 to 48 hr from the beginning of a storm but rapidly receding within 2 – 3 days (U.S. Army Corps of Engineers [USACE], 1984). Floods occur in the rainy season from November to April, and larger storms can inundate the portions of the alluvial valleys and urban areas (cities of Ukiah, Hopland, Healdsburg, and Guerneville) adjacent to the river (USACE, 2003). 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).

Lake Mendocino is a dual use reservoir formed by construction of Coyote Valley Dam in 1959, which is owned and operated for flood control by the USACE and is operated by the Sonoma County Water Agency (Sonoma Water) for water supply. Lake Mendocino has a total capacity of 116,500 acre-feet (ac-ft), which includes a water supply pool of between 68,400 and 111,000 ac-ft, depending on the time of year as shown in Figure 2. Lake Mendocino receives natural inflows from the approximately 105 square mile watershed area impounded by the Coyote Valley Dam as well as transbasin imports from the Eel River through the Potter Valley Project, a hydroelectric facility approximately 12 miles upstream that is owned and operated by the Pacific Gas and Electric Company.

The Coyote Valley Dam includes two structures for releasing water from Lake Mendocino: (1) the controlled outlet and (2) the emergency spillway. The controlled outlet is a single conduit used to convey water supply, flood control, or emergency releases depending on the reservoir storage level. Maximum release capacity of the controlled outlet is approximately 7,500 cubic feet per second (cfs) when storage levels are within the Emergency Release Pool (greater than 128,100 ac-ft). The emergency spillway is an uncontrolled release structure designed to only convey water when storage exceeds 116,500 ac-ft. Emergency spillway releases are typically avoided and are designed to occur only during extreme floods (1 in 50 year event). Since construction of the Coyote Valley Dam, the emergency spillway has only been activated once, during the flood of December 1964 when lake inflows exceeded 14,000 cfs.

Gages maintained by the U.S. Geological Survey (USGS) and USACE measure river stage and flow to support operation of Lake Mendocino. These gages provide real-time information to reservoir operators to help determine release schedules for flood prevention, downstream water supply, and environmental flows. Six primary gages used to support model development are described in this paper (Figure 1).

Operational decisions at Lake Mendocino are governed by rules in the Coyote Valley Dam Water Control Manual (USACE, 2003). Those rules define the Lake Mendocino guide curve, which allocates available storage to a flood control pool at the top of the reservoir and a water supply pool below that (Figure 2). The USACE determines the schedule and amount of water released from Lake Mendocino during flood control operations when storage levels exceed the water supply storage pool. Rules of the water control manual require the flood control pool to be empty except during periods of high flows downstream. The water control manual sets a maximum flow of 8,000 cfs at the Hopland gage, which is the flood stage as established by NOAA's National Weather Service (NWS). When flows at the Hopland gage exceed this target, flood runoff is temporarily detained in the reservoir's flood control pool and then later released at rates that avoid exceeding the Hopland gage maximum flow. Releases from the reservoir are constrained by rules that limit maximum releases and the rate of change of release (ramping rates) to minimize rapid changes in stage downstream and avoid fish stranding.

Sonoma Water is the local, nonfederal sponsor for Lake Mendocino and makes water supply releases when Lake Mendocino storage levels are within the water supply pool (Figure 2). Water supply release decisions are made to comply with Sonoma Water's water right permits issued by the California State Water Resources Control Board and with a 2008 Biological Opinion issued by NOAA's National Marine Fisheries Service (2008). Sonoma Water makes release decisions to (1) meet downstream demands of agricultural and residential water users and several public and municipal systems and (2) maintain minimum in-stream environmental flows in the Upper Russian River to its confluence with Dry Creek (Sonoma Water, 2016).

To meet the needs of both flood control and water supply, the allocation of Lake Mendocino water supply storage varies by season, as shown in Figure 2. In the rainy season (November through February), more storage space is allocated for the flood control pool with the bottom of the flood control pool (top of the water supply pool) at 68,400 ac-ft. In the dry season (early May through September), the water supply capacity increases to 111,000 ac-ft, due to reduced flood risk.

The Lake Mendocino watershed experiences large variations in the annual amount and timing of precipitation, and the occurrence of a few large storms (often in the form of atmospheric rivers) can be the difference between an ample water year and a drought year (Dettinger et al., 2011). Water supply capture in Lake Mendocino is sensitive to yearly timing or distribution of rainfall due to the variable water supply pool. Given the constraints of the current guide curve, the lake must receive significant inflow in the spring (past 1 March) to meet the water supply needs for the remainder of the year. Years with dry spring seasons are challenging for water supply because the region typically receives little precipitation during the summer and fall. Additionally, a 2006 change in operations of the Potter Valley Project to comply with environmental regulatory requirements has resulted in a 39% reduction in average water year inflow into Lake Mendocino, further contributing to potential water shortages.

Water year 2013 provides a useful example of how flood control operations with the current guide curve for Lake Mendocino can impact water supply. In December 2012, a series of large storms caused a dramatic rise in Lake Mendocino storage, causing the water level to encroach into the flood control pool (Jasperse, 2015). Because the reservoir level was in the flood control pool, the USACE released water until the reservoir level returned to the guide curve level to make flood space for potential future storm events. However, the following 12 months were the driest in the historical record causing the reservoir level to decrease to concerningly low levels for water supply. This dry period was the beginning of a multiyear drought which extended to Spring of 2016 (Flint et al., 2018), during which Sonoma Water had to file multiple Temporary Urgency Change Petitions with the California State Water Resources Control Board to reduce releases from Lake Mendocino and preserve storage. Had the reservoir operations been more flexible and able to use forecast information to inform operations, it may have been possible to save some of the water released in December 2012, which would have reduced water shortages over the multiyear drought.

The experiences from the recent drought motivated Sonoma Water, Scripps Institution of Oceanography and USACE to evaluate the viability of forecast informed reservoir operations (FIRO) for Lake Mendocino to benefit water supply without impairing flood management capacity. FIRO is a water management strategy that uses data from watershed monitoring programs and improved weather and hydrologic forecasting to help water managers selectively retain or release water from reservoirs in a flexible manner that more

accurately reflects natural variability of meteorology and hydrology (FIRO Steering Committee, 2015). FIRO is a nonstructural alternative to improving efficiency of multipurpose reservoirs in that it seeks to modernize operations by incorporating state-of-the-art forecast information without the need of modifying existing infrastructure. To guide the Lake Mendocino FIRO project, a steering committee was formed in 2014 with representatives from multiple disciplines (flood/environmental/water supply managers, engineers/hydrologists, and meteorologists/atmospheric scientists) from multiple agencies including the USACE, Sonoma Water, Scripps Institution of Oceanography, NOAA, USGS, U.S. Bureau of Reclamation, and the California Department of Water Resources. A work plan was developed by the FIRO Steering Committee (2015) to establish a framework for evaluating whether FIRO is a viable strategy to safely manage storage levels, that is, to maintain existing flood control capabilities while also improving storage reliability for water supply and ecosystems.

The evaluation of FIRO for Lake Mendocino was enabled by the existence of forecasts of runoff throughout the Russian River watershed from the California Nevada River Forecast Center. Daily ESP forecasts from the NWS Hydrologic Ensemble Forecast System (HEFS) (Demargne et al., 2014) include the five river locations in the Upper Russian River (Figure 1). These ESP forecasts are a 61-member ensemble designed to account for the uncertainties in the medium range (15 day) weather forecasts, which are derived from several sources, one of which is the National Centers for Environmental Prediction Global Ensemble Forecast System version 10. The existence of these operational flow forecasts meant that FIRO could be evaluated for Lake Mendocino without significant investment in weather and hydrologic forecasting models.

In July 2017, the FIRO Steering Committee completed a preliminary viability assessment of FIRO for Lake Mendocino (FIRO Steering Committee, 2017). This study found that a forecast-based decision support system could be a viable solution to meet project goals of improving the water supply reliability of Lake Mendocino without increasing the flood risk to downstream communities. This forecast-based decision support system, termed EFO in this study, is presented in section 3.3.1 of this paper.

3. Methods

The study involved running a reservoir system simulation model for Lake Mendocino and evaluating operational outcomes for three different management alternatives, one of which included the use of ESP forecasts. These components are described below.

3.1. Reservoir System Operations Model

The Lake Mendocino Operations (LMO) model was developed to evaluate FIRO alternatives for Lake Mendocino, including EFO described in detail in section 3.3.1. The model simulates Lake Mendocino operations and hydrologic conditions in the Upper Russian River from the Potter Valley Project to the Healdsburg gage at a daily time step from 1985 to 2010, the period of record for which information about historical flows and forecasts is available. The model applies reservoir operation rules of Lake Mendocino and water balance calculations to simulate storage levels in Lake Mendocino and flow conditions at four points (junctions) downstream of the reservoir. The water balance calculation junctions are graphically shown in Figure 3. Model junctions correspond with system features including the Potter Valley Project and Coyote Valley Dam, existing river discharge gage locations, and major confluence points.

The model was developed to simulate Lake Mendocino releases for flood control operations, water supply operations, emergency operations, and uncontrolled spillway releases. Lake Mendocino storage level calculations obey the mass balance shown in Equation 1:

$$S_T = S_{T-1} - E_T + 1.9835 \times (Q_T^{Lm} - L_T^{Lm} - Rel_T^{Flood} - Rel_T^{Emgc} - Rel_T^{WS} - Rel_T^{Spill}) \quad (1)$$

where storage (S) at a given timestep (T ; days) is equal to the previous day's storage (S_{T-1}), minus evaporative losses (E_T), plus total daily reservoir inflow (Q_T^{Lm}), minus daily upstream losses associated with water diversions (L_T^{Lm}), and minus total daily reservoir release. Reservoir releases consist of flood control releases (Rel_T^{Flood}), emergency releases (Rel_T^{Emgc}), water supply releases (Rel_T^{WS}), and uncontrolled spillway releases (Rel_T^{Spill}). Each term in Equation 1 is in ac-ft and 1 cfs for 24 hr is 1.9835 ac-ft.

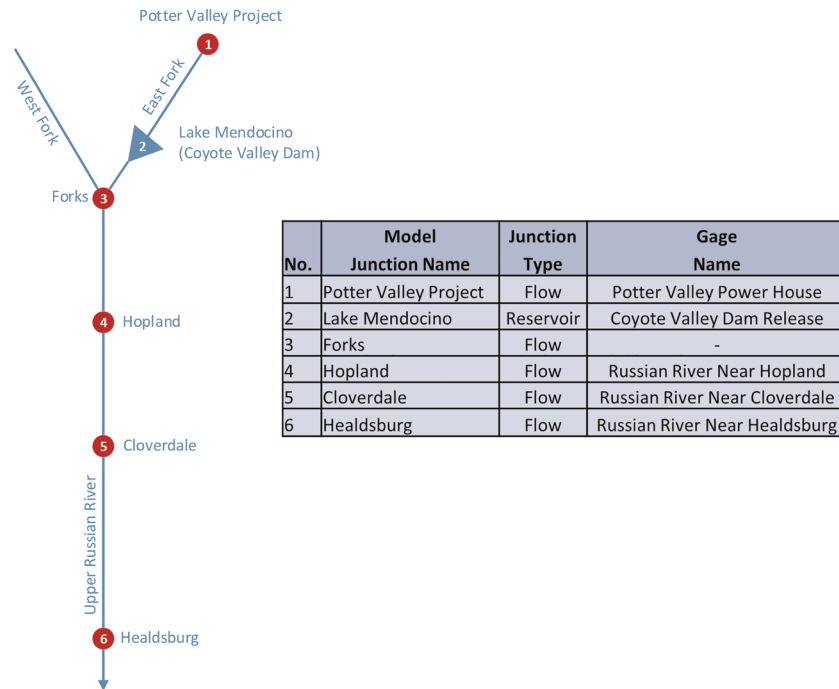


Figure 3. LMO model schematic with numbered water balance calculation junctions.

Simulation of flows downstream of Lake Mendocino also obeys basic mass balance principles, as shown in Equation 2:

$$Q_T = Q_T^{US} + Q_T^{UI} - L_T \quad (2)$$

where model junction flow (Q) at a given timestep (T ; days) is equal to flow from the upstream model junction (Q_T^{US}), plus unimpaired flow reach gains (Q_T^{UI}), and minus reach water loss (L_T). Each term in Equation 2 is in cfs. Hydrograph travel times between model junctions during high flows (i.e., Hopland > 8,000 cfs) are less than 24 hr; therefore, changes in releases and flows are routed to all downstream model junctions in the same single time step.

3.2. Data Inputs

For the simulation of EFO, the primary inputs of the LMO model are the ESP forecasts prepared by the California Nevada River Forecast Center with the HEFS. This forecasting system has been operational for the Russian River since 2012, which only provides a limited period to evaluate forecast-based alternatives. To provide a more comprehensive period for analysis, retrospective ensemble forecasts (i.e., hindcasts) of Lake Mendocino inflow and the downstream watersheds were generated by the California Nevada River Forecast Center using the HEFS model over a 26-year period from 1985 to 2010. This period includes the February 1986 flood, which is the second largest inflow event for Lake Mendocino (December 1964 is the largest) since the construction of Coyote Valley Dam. The hindcast simulates an hourly, 61-member flow forecast, with a forecast horizon of 15 days (Hamill et al., 2013). The hydrology and atmospheric models used in the hindcast process are as consistent as possible with what is used operationally; however, the hindcasting procedure is automated, and information that is available to hydrologic forecasters in real-time operations to refine the forecasts is not included in the hindcast. Therefore, it is not an exact representation of operational methods but is a long-term, consistent, realistic sample of forecasts for testing alternative reoperation strategies. The hindcasts are used as inputs in the LMO model at three model junctions, Lake Mendocino, West Fork, and Hopland (junctions 2 to 4). A more detailed description of the hindcast used for this study is provided in a supporting information document (supporting information; Delaney et al., 2020).

An assessment of HEFS Lake Mendocino inflow hindcast was completed for this study, summarized in the supporting information, and found a systematic bias of the hindcast to under forecast conditions for the months December through March, which are the primary months of flood control operations for EFO. However, HEFS ensemble spread provides a good representation of the forecast uncertainty and met the assumption of equal probability for the upper range of forecasts (90 to 100 percentile stratified subset conditioned on the ensemble median), for lead times of 4 to 15 days.

The LMO model defines data inputs for all primary sources and sinks of the system water balance, which include unimpaired reach gains from natural runoff (unimpaired flows also prepared by the California Nevada River Forecast Center), water imports from the Eel River through the Potter Valley Project, and reach water loss due to consumption and other sinks. The LMO model incorporates other input data to simulate operations of Lake Mendocino such as release constraints for flood control and water supply operations. Model input data are further described in the supporting information.

3.2.1. Model Testing

A historical scenario was developed for the period 2000 to 2010, the timeframe in which operational data was readily accessible, for the purpose of model testing. This scenario simulated historical hydrology and operational constraints for comparison to observed storage levels and system flows to evaluate the accuracy of model assumptions. Results from the model test successfully demonstrated that the primary model assumptions, such as the unimpaired flows, estimated reach losses, and reservoir release constraints, accurately simulate observed conditions in the Upper Russian River during water supply and flood control operations of Lake Mendocino. These results support the use of the LMO model for the comparative analysis of alternatives completed for this study and to discriminate impacts between reservoir management alternatives. Results of the model testing are further described in the supporting information.

3.3. Flood Control Operation Alternatives

For this study, three flood control operation alternatives for Lake Mendocino were simulated: EFO, Perfect Forecast Operations (PFO), and Existing Operations (EO). These alternatives used the same assumptions for the following data inputs: unimpaired flows, PVP transfers, system losses, water supply operations, maximum release constraints, release ramping rates, and the uncontrolled spillway operation. These alternatives are summarized below.

3.3.1. EFO

This study examines potential of EFO for Lake Mendocino, which is a probabilistic decision support system that incorporates ESP forecasts prepared by the California Nevada River Forecast Center to assess and mitigate forecasted risk of reservoir storage levels exceeding a storage threshold. For this analysis, the storage threshold was set to the maximum conservation storage level of 111,000 ac-ft. This threshold is the maximum allowed dry season storage under existing operations and is 3 ft below the emergency spillway crest, to provide a margin of safety in preventing unwanted emergency spillway releases. Forecasted risk (r_1, r_2, \dots, r_{15} , with the subscript representing the forecast day) is defined by the percent of ensemble members exceeding the storage threshold to the total number of equally likely ensemble members. Forecasted risk is evaluated against a risk tolerance curve (R_1, R_2, \dots, R_{15}) as shown in Figure 4. The risk tolerance curve is used by the model to inform flood release decisions, much like a guide curve is used in existing operations. The model estimates the required release to mitigate forecasted risk to levels at or below the risk tolerance curve. Risk tolerance values vary within the forecast window, with a value of 0% (no risk appetite) for the first 5 days to manage to the most extreme (wettest) ensemble members due to higher confidence in the forecast and shorter duration to respond to events in this timeframe. Risk tolerance increases each day past day 5 considering decreasing forecast skill and more time to respond to a forecasted storm event.

The risk tolerance curve used for this study was developed using a heuristic methodology intended to provide a curve that is sufficient for testing and evaluating EFO but likely not optimized to a level needed for full implementation. The process involved simulating numerous curve shapes and evaluating the performance of the curves using an objective function. The objective function was developed through stakeholder engagement and based on the project objectives to maximize storage reliability, while minimizing occurrences of downstream flooding and emergency spillway releases. Development of the risk tolerance curve is further described in the supporting information.

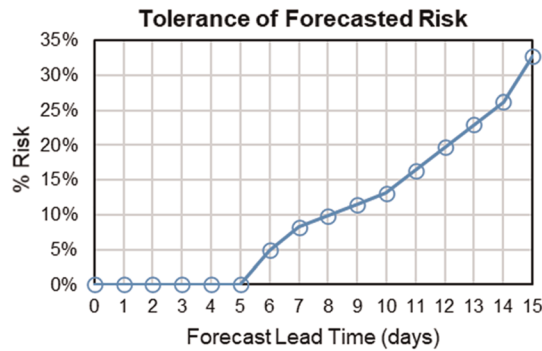


Figure 4. EFO risk tolerance curve.

With EFO, for each day of the simulation from 1985 to 2010, the LMO model uses the hindcasted flows for Lake Mendocino inflow, West Fork, and Hopland local flows to perform forward looking 15-day simulations of storage and downstream conditions using each of the 61 ensemble members to calculate a flood control release based on forecasted risk. The flowchart in Figure 5 provides an overview of the computational steps to calculate flood control releases. A more detailed flowchart is provided in the supporting information.

EFO incorporates a rolling-horizon approach for calculating reservoir flood control releases, which consider multiple future horizons to inform operations. The decision horizon is how long the generated release decision is implemented, and the forecast horizon is how long hydrologic conditions can be predicted (Zhao et al., 2011). At each

daily time step (T), the model uses the hindcasts to simulate future conditions to the end of the 15-day forecast horizon ($t = 1:15$). Each of n ($n = 61$) flow hindcast ensemble members is independently modeled to evaluate future release decisions ($Rel_{1n}, Rel_{2n}, \dots, Rel_{15n}$) to maintain storage levels ($S_{1n}, S_{2n}, \dots, S_{15n}$) at or below the 111,000 ac-ft threshold. However, the decision horizon is only 1 day, because the process is repeated the next day with the updated forecast. The first release decision (Rel_{1n}) for each ensemble member is evaluated to set the release for the current time step.

The model repeats this rolling-horizon process to calculate flood control releases for each simulation time step. For a given time step (T), after the model completes a forecast simulation and calculates a flood control release, the model uses this release along with other release requirements (spill, emergency, and minimum requirements) to calculate storage and downstream flows using the unimpaired flows, which are treated as observations (supporting information).

To illustrate modeling of EFO, an example simulation day, $T = 8$ February 1986, is used to demonstrate the computational steps of the model for flood control releases. This date is just 10 days before the 18 February 1986 flood event, the largest event in the model simulation period, where simulated Hopland junction flows exceeded 25,000 cfs, well above the flood stage of 8,000 cfs.

Beginning at the first forecast time step ($t = 1$), the LMO model forecasts storage for each hindcast ensemble member assuming no reservoir release. For each forecast day ($t = 1:15$), the storage forecast ensemble members are evaluated to see if they exceed the storage threshold of 111,000 ac-ft. If the forecasted risk (r_t) across all ensemble members exceeds the risk tolerance (R_t) specified for that forecast day then the LMO model calculates a release that will reduce the forecasted risk below the risk tolerance. This can be illustrated for the 8 February simulation day in Figure 6, which shows the forecasted storage ensemble assuming no releases in the top panel and the forecasted risk in the bottom panel. In this example, 14 of the storage forecast members exceed the storage threshold on day 8 ($t = 8$) of the forecast, resulting in a risk (r_8) of 23.0% which exceeds the risk tolerance (R_8) of 9.8% for this forecast day.

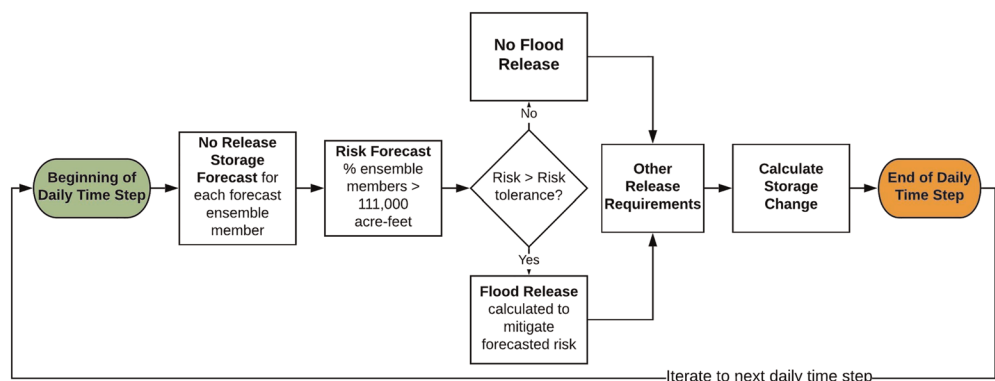


Figure 5. Main computational steps of EFO.

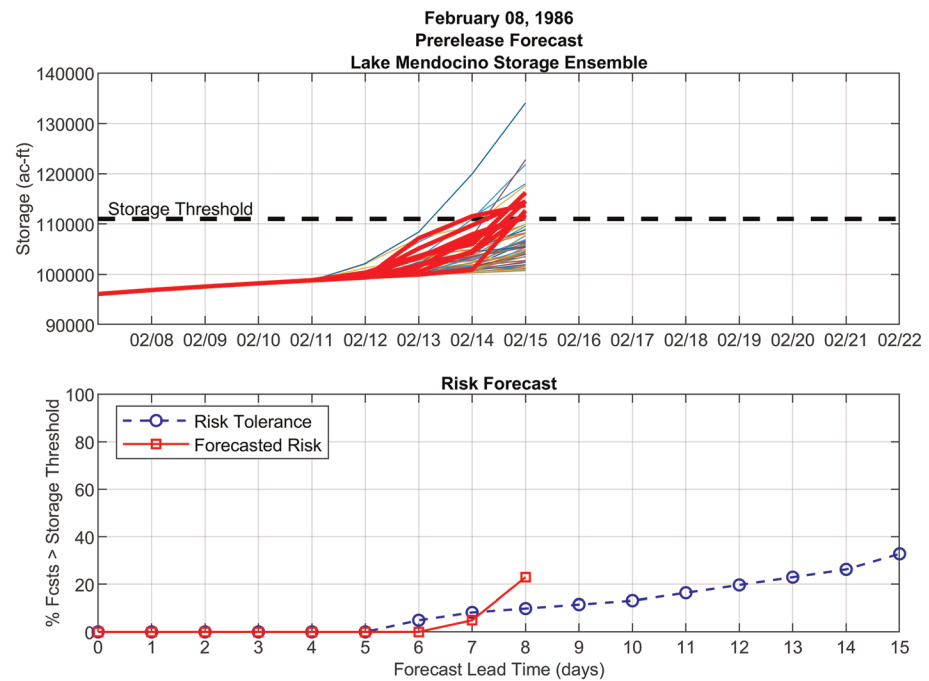


Figure 6. EFO forecasted storage (top panel) and risk (bottom panel) for 8 February 1986; top panel shows risky ensemble members for forecast time step 8 highlighted in red.

If forecasted risk exceeds the risk tolerance, risky members are selected, which are the ensemble members above the storage threshold that need to be brought below the storage threshold to meet the tolerance threshold. These risky members are used to calculate forecast release schedules ($Rel_1, Rel_2, \dots, Rel_t$) sufficient to reduce the forecasted storage (S_t) to the 111,000 ac-ft storage threshold. Forecast release schedules are only calculated when there are risky members ($r_t > R_t$),

Ensemble members that exceed the storage threshold are ranked, and risky members are selected as the number of lowest ranked members that will meet the risk tolerance. This can be illustrated for the example simulation day in Figure 6. The top panel shows the risky members highlighted in red that the model selected for forecasting flood release schedules. The risk tolerance for time step 8 (R_8) is 9.8% therefore only 6 of the 61 forecasted storage ensemble members can exceed the storage threshold. In this example, 14 ensemble members exceeded the storage threshold; therefore, the lowest 8 ranked ensemble members were selected as risky members.

Release schedules are calculated for each of the risky members to bring the forecasted storage to the storage threshold level. Initial release schedules are calculated by taking the volume difference between the risky member and the storage threshold and equally distributing that difference to each time step up to the current forecast day (t). For the 8 February 1986 example, the highest ranked risky member exceeds the storage threshold by 5,249 ac-ft, and as illustrated in Figure 7, the initial release schedule (shown as the dashed blue line) is this total volume equally distributed with a release of 331 cfs to each of the 8 days of the forecast.

The initial forecasted release schedule is evaluated against the forecasted release limit (shown as the solid red line in Figure 7) to assess whether this initial release is feasible based on forecasted storage and downstream flow conditions. The forecasted maximum release limit (L_1, L_2, \dots, L_t) is calculated considering the release constraints of the maximum flood control release regulations, the downstream flow limit of 8,000 cfs at the Hopland Gage (described in section 2), and ramping rates (supporting information).

If the initial forecasted release schedule exceeds the forecasted release limit for any of the forecast time steps, then the release schedule is adjusted to the release limit for that release time step. The adjusted release volume is then equally redistributed to the preceding release time steps. This is illustrated for the 8 February 1986 example in Figure 7, where the initial release exceeds the maximum allowable at forecast

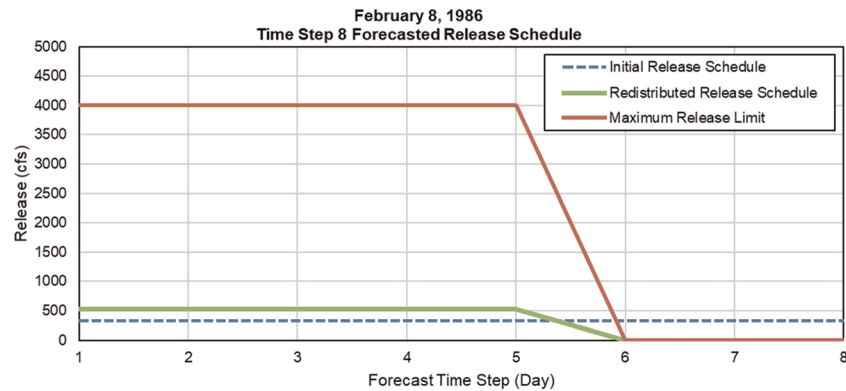


Figure 7. The 8 February 1986 calculated EFO release schedule to forecast time step 8 for a single risky member.

days 6–8 ($t = 6, 7, 8$). The adjusted release (shown as the solid green line in Figure 7) is set to the maximum allowable release for forecast days 6–8, and the volume that the release was adjusted is then equally redistributed to release days 1 through 5, which results in a release of 529 cfs for days 1 through 5 and 0 cfs for days 6 through 8.

This process of calculating a release schedule is completed for each of the risky members. Although the model estimates future release schedules for the risky members for all future time steps, the day 1 release is of primary interest. The maximum day 1 release of all the lowest ranked ensemble members (risky members highlighted in red in Figure 6) is considered the release required to bring the forecasted risk (r_t) below the risk tolerance (R_t) for the given forecast time step. For the 8 February 1986 example, the day 1 release of 529 cfs is the maximum of all risky members for forecast day 8 (the same ensemble member used for the release schedule example provided in Figure 7). In other words, with a forecast horizon of 8 days the maximum day 1 release of all risky members is 529 cfs.

The forecasted release schedules are applied to each of the 8 risky ensemble members to recalculate storage levels to the current forecast time step. This is illustrated for the example simulation in Figure 8. This figure shows that forecasted storage levels have been reduced to the storage threshold (111,000 ac-ft) for the risky members and forecasted risk has been reduced below the risk tolerance level for forecast day 8 ($t = 8$). The green highlighted storage ensemble member has a simulated maximum day 1 release of 529 cfs (as discussed above), which is the release required to reduce forecasted risk for time step 8 (r_8) below the risk tolerance level (R_8) of 9.8%.

The LMO model then moves to the next forecast time step (for the 8 February 1986 simulation example this would be forecast time step $t = 9$) and repeats the process of estimating release schedules for selected risky storage members and incrementally evaluates each forecast time step until it reaches day 15 ($t = 15$). The model selects the release for the current time step as the maximum day 1 release for all forecast time steps. This is illustrated for the 8 February 1986 example in Figure 9, which shows the maximum day 1 release for all forecast time steps in the table on the right-hand side of the figure and the forecast storage ensembles and risk for days 1 to 15 ($t = 1:15$) on the left-hand side of the figure. For this example, forecast day 14 ($t = 14$) had the highest day 1 flood control release of 1,240 cfs (highlighted in green in the table). This is the maximum day 1 release for all forecast time steps, and therefore, this is the required release to reduce the forecasted risk below the risk tolerance levels for all forecast time steps. The plot in the upper left panel shows the ensemble of storage levels with the applied release schedules for each time step. The risk plot in the lower left panel of Figure 9 shows forecasted risk for no release (red dotted line with diamond marker labeled prerelease) and post release (red solid line with square markers) storage levels. It can be seen that post release risk is reduced at or below the risk tolerance levels for all forecast time steps and significantly reduced compared to prerelease risk levels.

The model uses the calculated flood control release and other calculated release requirements to compute end of time step storage (S_T) and downstream flows for the current simulation time step ($T = 8$ February

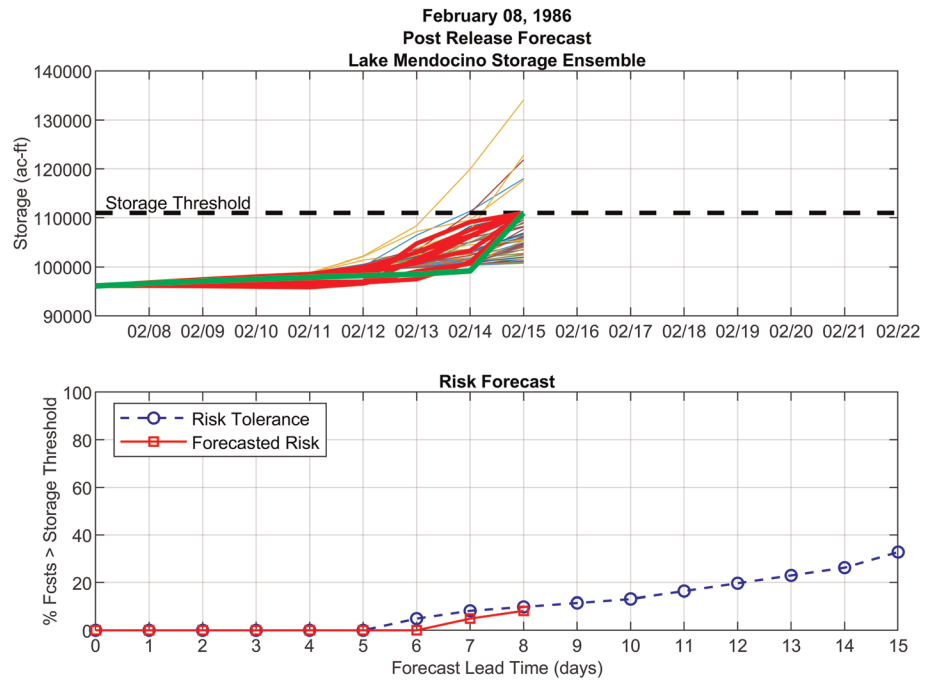


Figure 8. EFO forecasted storage for 8 February 1986 (top panel) and risk (bottom panel) with calculated releases applied to forecast time step 8.

1986 for the simulation example). The model then iterates to the next simulation time step ($T = 9$ February) and repeats the EFO process to determine a flood control release.

In addition to setting flood control releases, the risk tolerance curve of EFO also defines the delegation of operations between flood control and water supply. Under current operations of Lake Mendocino, as discussed in section 2, delegation of operations is determined by storage level. If storage is above the guide curve, the USACE is responsible for flood control operations, and if the level is below the guide curve,

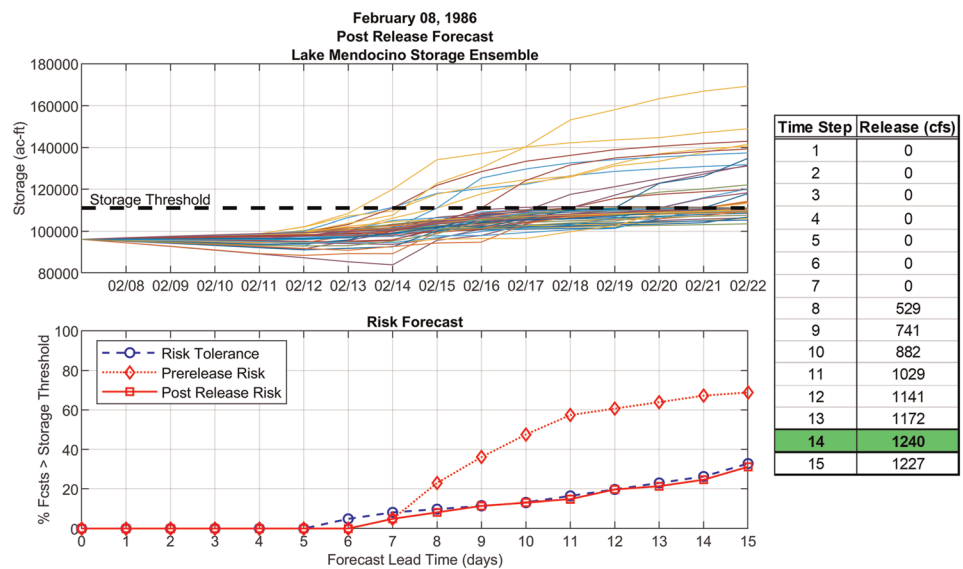


Figure 9. EFO post release forecasted storage (top panel) and risk (bottom panel) for 8 February 1986 with bottom panel showing prerelease (red dotted line with diamond markers) and post release (red solid line with square markers) risk levels; table on right side shows the maximum day 1 release for each forecast time step.

Sonoma Water is responsible for water supply operations. With EFO, the risk tolerance curve is used in a similar manner as the guide curve is used for current operations. If forecasted risk is greater than the risk tolerance curve, then the LMO model simulates flood control operations as described above, but if forecasted risk is below the risk tolerance curve, then the model simulates water supply operations consistent with existing practices.

3.3.2. PFO

PFO is designed to simulate forecast informed operations that incorporate perfect forecast skill, and although not realistic, this alternative represents the maximum hypothetical benefit that can be achieved both for water supply and flood protection. The perfect forecast case simulates flood control releases similar to EFO, 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 just a single member data set; therefore, the risk tolerance is fixed at 0% for all forecast time steps. Like EFO, PFO incorporates a storage threshold of 111,000 ac-ft.

3.3.3. EO

An alternative was developed that simulates existing flood control operations as defined in the water control manual to assess the current system reliability and a basis for comparing operating alternatives in terms of impacts to water supply and flood risk. Reservoir releases are largely controlled by the reservoir pools defined in the WCM as shown in Figure 2.

The existing flood control pool (shown in Figure 2) is defined as the zone of the reservoir pool which extends from the top of the water supply pool to an elevation of 771 ft above mean sea level (msl) or 128,100 ac-ft storage. For EO, the top of the water supply pool is seasonally varying with a wet season storage threshold of 68,400 ac-ft (737.5 ft msl) from 1 November to 28 February and a dry season storage threshold of 111,000 ac-ft (761.8 ft msl) from 10 May to 30 September. When simulated storage levels are within the flood control pool (above the storage guide curve), the model increases releases from storage until levels are returned to the top of the water supply pool. These flood control releases are limited by the flood control release constraints, the downstream flow limit of 8,000 cfs at the Hopland gage, and ramping rates (supporting information).

4. Results

4.1. February 1986 Simulation Example

Simulation results of the EO and EFO alternatives for February 1986 further demonstrate the modeling approach and contrast the operational differences. For simplicity and ease of explanation, PFO is not included in this figure. The flood event of February 1986 is the largest inflow event in the simulation period and the second largest recorded inflow event for Lake Mendocino. Figure 10 shows hydrographs of Lake Mendocino storage (top panel), inflow and release (middle panel), and flows at the Hopland junction (bottom panel). This figure has been divided into four periods. Period 1: dry forecast period (1–7 February); period 2: wet forecast period (8–14 February); period 3: flood event period (15–20 February); and period 4: post flood event period (21–28 February).

Beginning with period 1, the top panel of Figure 10 shows storage levels of EFO (red solid line) encroached well above the storage guide curve (green dashed line). The storage level for the end of period 1 at time step $T = 7$ February 1986 is 96,114 ac-ft. This is because the forecast for this period has been relatively dry and forecasted risk has not resulted in significant flood control releases for EFO. In contrast, storage levels for EO (blue solid line) are at the storage guide curve, consistent with the current operational practices. The middle panel shows releases for both scenarios relatively low, with the EO release (blue solid line) approximately equal to inflow to maintain storage at the guide curve. The bottom panel shows downstream flows at the Hopland junction also relatively low due to moderate storm activity.

In period 2, beginning on 8 February, flood control releases for EFO increase significantly from 310 to 1,240 cfs as shown in the middle panel of Figure 9. A detailed description of the computation steps of the EFO alternative to simulate the 8 February release was provided in section 3.3.1. After 8 February, flood control releases for EFO increase further and reach up to the maximum release of 4,000 cfs where they are sustained at approximately this level until 14 February. As shown in the top panel of Figure 10, the preflood event releases result in drawing down storage to a level of 55,409 ac-ft on 14 February, which is well below the

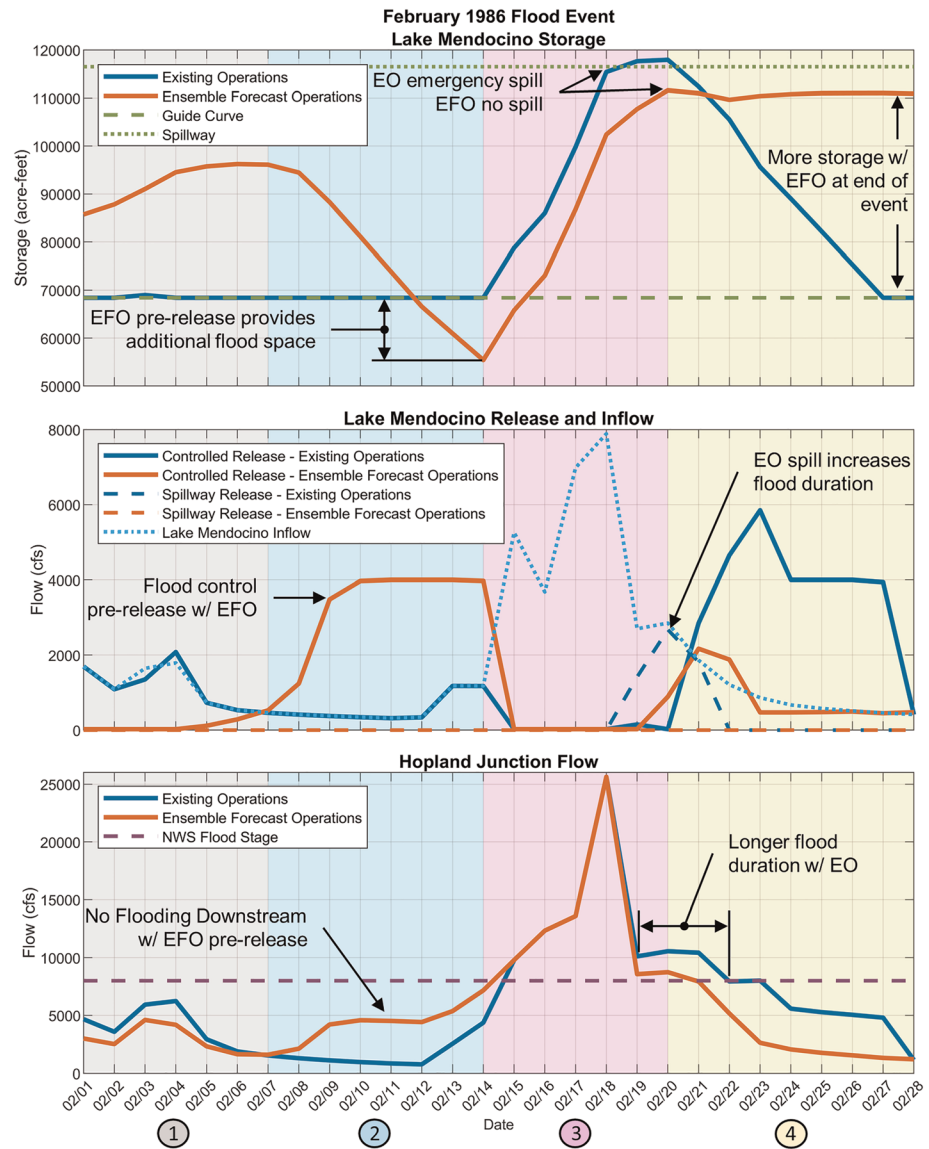


Figure 10. Lake Mendocino storage (top panel), Lake Mendocino release and inflow (middle panel), and Hopland junction flow (bottom panel) for the February 1986 flood event divided into 4 periods: (1) dry forecast period, (2) wet forecast period, (3) flood event period, and (4) post flood event period.

storage guide curve level established in the water control manual. In addition, since the releases are modest and made in advance of the flood event, they do not contribute to any downstream flooding as shown in the bottom panel of Figure 9. In contrast, the storage levels for EO as shown in Figure 10 are maintained at the guide curve during period 2.

Period 3 of Figure 10 shows system conditions during the flood event. Both EFO and EO maintain very low releases during the flood event as shown in the middle panel of Figure 10, to prevent contributing to flood conditions downstream as shown in the bottom panel. High reservoir inflows and low releases result in rapid rises in storage levels for both scenarios as shown in the top panel of Figure 10. The storage level of EFO crests to approximately 111,598 ac-ft, which is just above the 111,000 ac-ft management target but still below the emergency spillway crest level of 116,500 ac-ft, shown as the green dotted line in the top panel of Figure 10. In contrast, EO peaks at a storage level of 117,940 ac-ft, above the emergency spillway crest level. This results in an uncontrolled spillway release for EO, which lasts for 3 days and reaches a peak release of 2,680 cfs as shown with the blue dashed line of the middle panel of Figure 10. This uncontrolled spillway

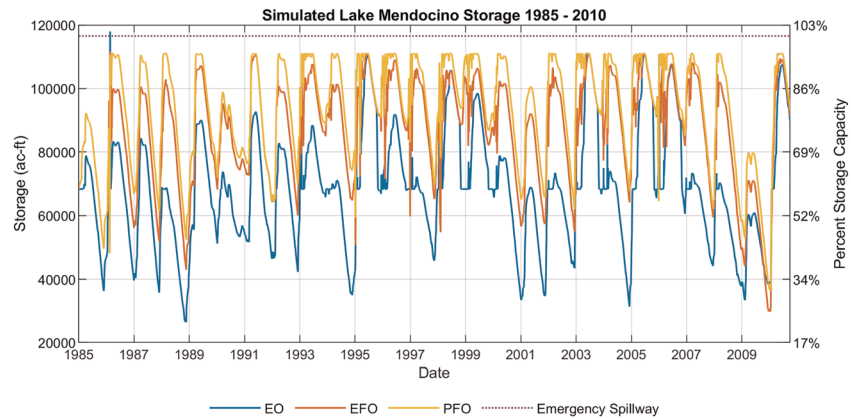


Figure 11. Lake Mendocino simulated storage levels for all scenarios from 1985 to 2010.

release occurs as flows at the Hopland junction are receding and does not contribute to an increase in peak flows on 18 February, as shown in the bottom panel of Figure 10, but extends flows above flood stage for a day when compared to EFO.

For post flood event conditions in period 4 of Figure 10, the water that refilled the reservoir during the flood event of period 3 is retained for EFO because of a dry forecast resulting in low forecasted risk levels. In contrast, for EO, the water in the reservoir from the flood is released to return storage to the guide curve and maintain flood space for future possible events. If this were the last storm event for the season, EFO would provide a storage benefit of approximately 42,000 ac-ft relative to EO.

4.2. Lake Mendocino Storage

Figure 11 is a plot of simulated daily Lake Mendocino storage levels from 1985 to 2010. The plot shows a significant increase in simulated storage for PFO and EFO relative to EO for almost all years simulated. Some wet years, such as 1995, 1998, 2003, 2005, 2006, and 2010, do not have a significant benefit in peak annual storage. These years all had high late-season rainfall (after 1 March) allowing EO storage to reach the approximate maximum level of the guide curve of 111,000 ac-ft.

Minimum annual storage level in 2009 shows a decline for EFO and PFO relative to EO even though the winter peak storage is higher for EFO and PFO. The EFO and PFO alternatives have more water available for most years in the simulation, which can result in the model simulating wetter water supply conditions, higher downstream minimum instream flow requirements (supporting information) and therefore higher water supply releases. The higher release and downstream flows for EFO and PFO cause storage levels for 2009 to draw down below EO.

As shown in Figure 11, simulated storage for EO exceeds the crest of the emergency spillway (116,500 ac-ft, black dashed line) for one event in February 1986. The total simulated volume of the uncontrolled spillway release for the 1986 event is 11,720 ac-ft for EO. In contrast, EFO and PFO do not have any uncontrolled spillway releases during the entire simulation period.

Exceedance probability of 10 May Lake Mendocino storage over the simulation period is shown in the left panel of Figure 12; 10 May is considered the end of the flood control management season, because this is the date that the guide curve reaches a maximum level of 111,000 ac-ft and stays at this level until 1 October. Model simulation results for PFO and EFO show increases in end of flood management storage exceedance levels relative to EO for the entire distribution. PFO and EFO show the largest benefit relative to EO between the 50% and 93% exceedance, with an increase in median storage (shown as the horizontal line in the box plots provided in the right panel of Figure 12) of approximately 28,438 and 22,829 ac-ft, respectively. EFO achieves approximately 80% of the benefit of PFO for median increase in storage. The driest years such as 2009, as shown at the top of the distribution, do not appear to have as much storage benefit for PFO and EFO compared to EO, because there are no flood control releases. However, dry years such

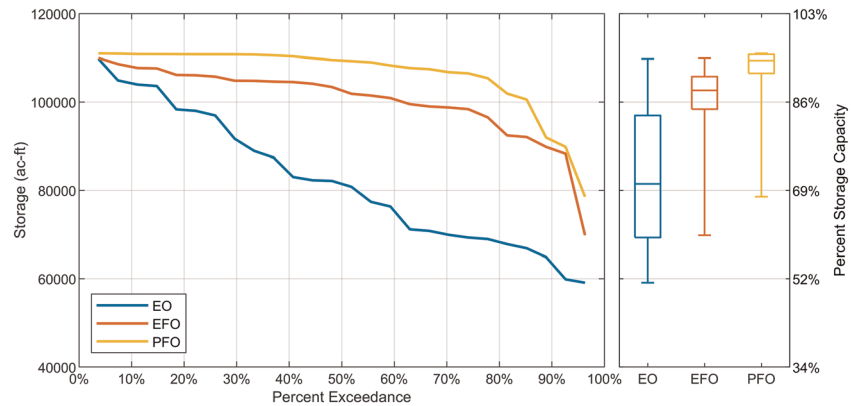


Figure 12. Percent exceedance of simulated 10 May (end of flood managements season) storage of Lake Mendocino storage for 1985–2010 (left panel), and box plots of 10 May storage (right panel); whiskers represent the range of storage; lower and upper ranges of the boxes represent the lower and upper quartiles, respectively; and the horizontal line in the box shows the median.

as 2009 actually see the greatest benefit from these alternatives because there is more carry-over storage from the previous year to maintain higher releases for water supply and ecosystems.

The simulation results also show that both FIRO alternatives (PFO and EFO) decrease variability of end of flood management storage relative to EO. A decrease in variability and higher averages indicates that the operational scenario can better manage to the simulated hydrologic variability and improve reservoir storage reliability. A measure of variability in storage at the end of the flood management season is indicated by the

interquartile range of 10 May storage levels for each alternative as shown in the box plots provided in Figure 12. The interquartile ranges are 27,650, 7,374, and 4,299 ac-ft for the EO, EFO and PFO alternatives, respectively. PFO has the greatest decrease of interquartile range relative to EO of 23,350 ac-ft, while EFO also has a significant reduction of 20,276 ac-ft.

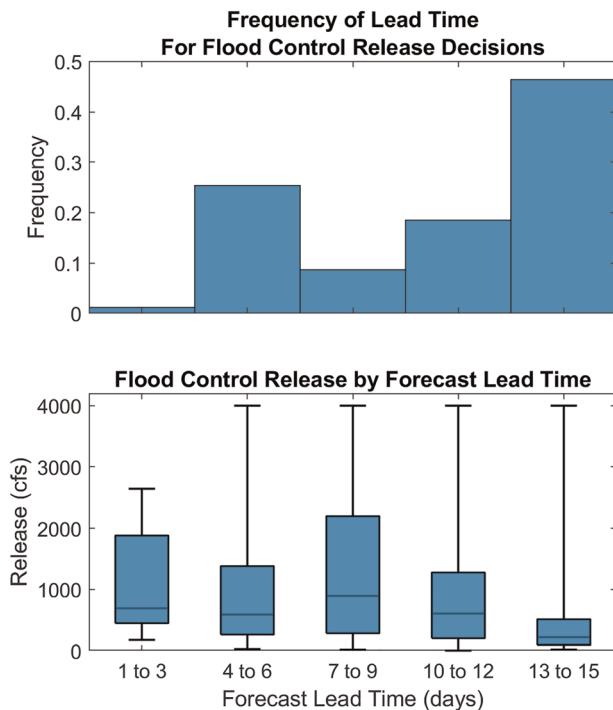


Figure 13. Frequency of EFO forecast lead time for flood control releases (top panel) with lead time lumped in 3-day bins. Box plots of EFO flood control release conditioned to forecast lead time (bottom panel). Whiskers represent the range of releases; lower and upper ranges of the boxes represent the lower and upper quartiles, respectively, and the horizontal line in the box shows the median.

4.3. Reservoir Releases

Reservoir flood control releases for EFO are summarized in Figure 13, where the top panel shows the frequency of forecast lead times for determining flood control release decisions (i.e., forecast day 14 was used to set the release for the example provided in section 3.3.1), and the bottom panel shows a box and whisker plot of daily flood control releases conditioned on the day of forecast lead time. These results show that EFO relies heavily on the longest-lead forecasts, setting flood control releases most often using the 13 to 15-day lead time; however, because it is taking advantage of those longest leads, the releases that far ahead are (at median) smaller than releases set with the shorter lead times. The number of releases at shorter lead times in the 7 to 13-day range declines in number from the 13- to 15-day range but increase in volume. By 4 to 6 days, releases increase again in number (still not as much as at 13- to 15-day range) to adjust for increased forecast certainties, while declining again slightly in required volumes. Due to the heavy utilization of the lead times 4 to 15 days, EFO shows infrequent utilization of the 1- to 3-day lead time to set releases just prior to storm arrival. These results show that the 4- to 15-day lead times are the most important in terms of frequency and magnitude of release for EFO and are supported by the assessment of the HEFS hindcast that was completed in the

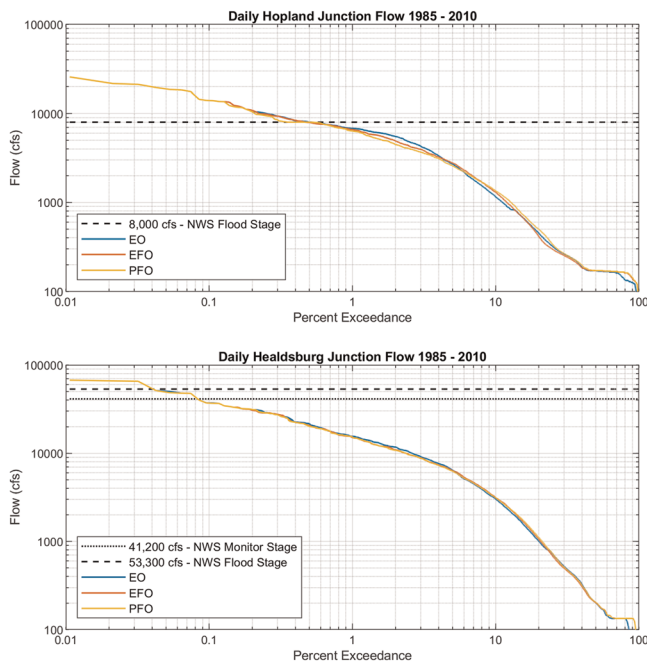


Figure 14. Percent exceedance of simulated flow for Hopland, Cloverdale, and Healdsburg model junctions of all scenarios for 1985–2010.

supporting information, which showed that the higher range of forecasts (90 to 100 percentile stratified forecasts when conditioned on the ensemble median) showed the greatest reliability for the 4- to 15-day lead times.

4.4. Downstream Flow Conditions

Downstream flows for PFO and EFO match closely to EO. Exceedance probability of daily flows for the Hopland and Healdsburg model junctions is provided in Figure 14 in the top and bottom panels, respectively. Plotted lines are provided which indicate flood stage for the Hopland and Healdsburg model junctions and monitor stage for the Healdsburg junction. Frequency of flows for PFO and EFO closely matches EO above flood stage at the Hopland junction and monitor stage at the Healdsburg junction.

The 2008 Biological Opinion issued by National Marine Fisheries Service recommends a minimum instream flow of 125 cfs during the rearing season (June–September) for endangered juvenile salmonids in the Upper Russian River. The increased water supply reliability afforded by EFO and PFO increases the occurrence of wetter water supply conditions (supporting information) and an increased frequency of flows that exceed the Biological Opinion recommended minimum flows during the rearing season relative to EO. This indicates increased storage reliability for Lake Mendocino to maintain downstream flows needed for critical fisheries habitat.

5. Summary and Conclusions

This study evaluates EFO, a novel, probabilistic decision support system for Lake Mendocino that uses a risk tolerance curve to guide reservoir release decisions with 15 days of ensemble forecast. EFO incorporates ESP forecasts from the operational real-time Hydrologic Ensemble Forecast System (HEFS) of the National Weather Service's California Nevada River Forecast Center, considering all primary constraints for flood control and water supply operations. The model was tested against historical storage levels and downstream flows, showing accurate simulation of historical reservoir operations.

The retrospective evaluation (from 1985 to 2010) of EFO shows improved reservoir storage reliability compared to EO, leading to improved water supply for downstream users and environmental flows. EFO simulations generally yield higher storage levels during the flood management season while maintaining needed flood storage capacity by strategically prereleasing water in advance of forecasted storms. The higher storage levels maintained in the winter and spring result in improved storage reliability for the dry season. Specifically, EFO simulations yield a 33% increase in median storage at the end of the flood management season (10 May) compared to EO. PFO, which uses observed hydrology to simulate a hypothetical perfect forecast, would be the maximum benefit that can be achieved with EFO. Comparison of PFO to EFO shows that water supply storage reliability could improve by as much as another 20% with future improvements in hydrologic forecasting skill.

Despite the generally increased storage levels, EFO not only yields no increase in flood risk relative to EO but, in fact, improves flood control capacity by lowering reservoir levels below the guide curve ahead of large storms, thereby limiting or reducing unwanted releases through the emergency spillway. This was demonstrated for the 1986 flood event where simulated EO storage levels rose above the spillway crest resulting in a release through the uncontrolled spillway. In contrast, EFO releases water to evacuate adequate reservoir space in advance of the flood, and as a result, storage remains below the spillway crest.

EFO provides useful metrics to support management of multiple objectives for multipurpose reservoirs. For instance, under current operations at Lake Mendocino, delegation of operations is determined by storage level relative to the guide curve. The risk tolerance curve used by EFO, in addition to providing a threshold for formulating flood release decisions, can also assist in the delegation of operations much like the guide

curve for current operations. When forecasted risk is below the risk tolerance curve, management of the reservoir pool could be delegated to Sonoma Water for making water supply releases, and when forecasted risk is above the risk tolerance curve, the United States Army Corps of Engineers could manage the reservoir pool for flood control operations.

The promising results of this analysis warrant further investigations of EFO for Lake Mendocino. The retrospective assessment includes five events that would result in flood damage downstream (events when flows at Hopland exceed 15,000 cfs) with the largest event in February 1986, which is the second largest flood event in the historical record. None of the large events simulated here equal the “flood of record” in December 1964, an approximate 100 year return period event. The 1964 flood cannot be simulated due to the lack of data to generate hindcasts for this event. Research is underway to develop ensemble-based forecasts for still larger flood events (200- to 500-year return period) by artificially upscaling events in the hindcast period to further evaluate the flood mitigation capabilities of EFO. These efforts also include expanding modeling to simulate hydraulics and flood damages, expanding the geographic domain of the model to incorporate other flood sensitive areas further downstream, and increasing temporal resolution to an hourly time step.

Evaluations of the HEFS Lake Mendocino inflow hindcast (described in the supporting information) found a systematic bias of the hindcast to under forecast conditions for the flood-prone months, December through March; however, the hindcast demonstrated greatest reliability to bound forecast uncertainties for the upper range of forecasts for the 4- to 15-day lead times. Analysis of reservoir releases showed that EFO effectively leverages the hindcast for flood control operations at lead times where the hindcast demonstrates the greatest reliability. This is further evidenced by model results that show the hindcast can skillfully guide operations to avoid uncontrolled spillway releases or increases in downstream flooding. Further evaluations of hindcast errors and biases could help to prioritize efforts to improve forecasts and/or post processing of hydrologic forecast products to better support EFO and related forecast informed reservoir operation options.

The risk tolerance curve was developed using a heuristic methodology (described in the supporting information) intended to provide a curve that is sufficient for the proof-of-concept evaluation of EFO presented in this study. However, robustness testing of the risk tolerance curve demonstrated that the curve shape is sensitive to the particular sequence of inflows used to train the curve. Additional research could be pursued to further refine the methods for developing risk tolerance curves to reduce possible overfitting and to incorporate more extreme events in curve training and testing. Incorporation of more extreme hydrology would also likely require further refinement to the objective function to maintain consistency with management objectives. Further research could also be pursued to evaluate other reservoir operation methodologies that incorporate optimization techniques such as the flood hedging policies studied by Hui et al. (2016) and evaluating longer forecast lead times to better support other beneficial uses such as water supply and ecosystems (Turner et al., 2019).

EFO provides an adaptive framework for forecast informed flood control operations of Lake Mendocino that could help meet future water resource challenges when faced with increases in hydrologic variability and changes in extreme weather that are predicted to occur with climate change. This EFO framework may be useful for other reservoir systems where multipurpose outcomes are managed. Evaluation of EFO for other systems would require that ESP forecasts are available or developed and that historical forecasts or hindcasts are available for an adequate historical period to support an assessment of viability. This study evaluated a dual objective approach of water supply and flood control. However, the risk tolerance concept could also be applied to account for additional system objectives through the development of the risk tolerance curve and/or forecasting and managing to risk for multiple system parameters such as multiple storage thresholds, power production, habitat, reservoir limnology, and/or downstream conditions of flow, stage, and water quality. The EFO concept could also be evaluated for systems with multiple reservoirs where operations might seek to balance risks to meet a desired outcome.

Transferability of EFO to other systems is based on the interplay between streamflow forecast skill and reliability (at a continuum of lead times) and the operational constraints and limits of the reservoir that are unique to each project. A useful area of research could be a regional study of the EFO methodology for multiple multipurpose reservoir systems of varying size, function and location. Such a study could provide further insight on the implications of transferability of EFO to other systems.

Data Availability Statement

All data (inputs, code, and model results) used in the study are publicly available on GitHub in a public repository (<https://github.com/hydrophile/WRR-Manuscript-Lake-Mendocino-EFO-Model.git>). Permission was granted by the Chief of Engineers, USACE, to publish this manuscript.

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