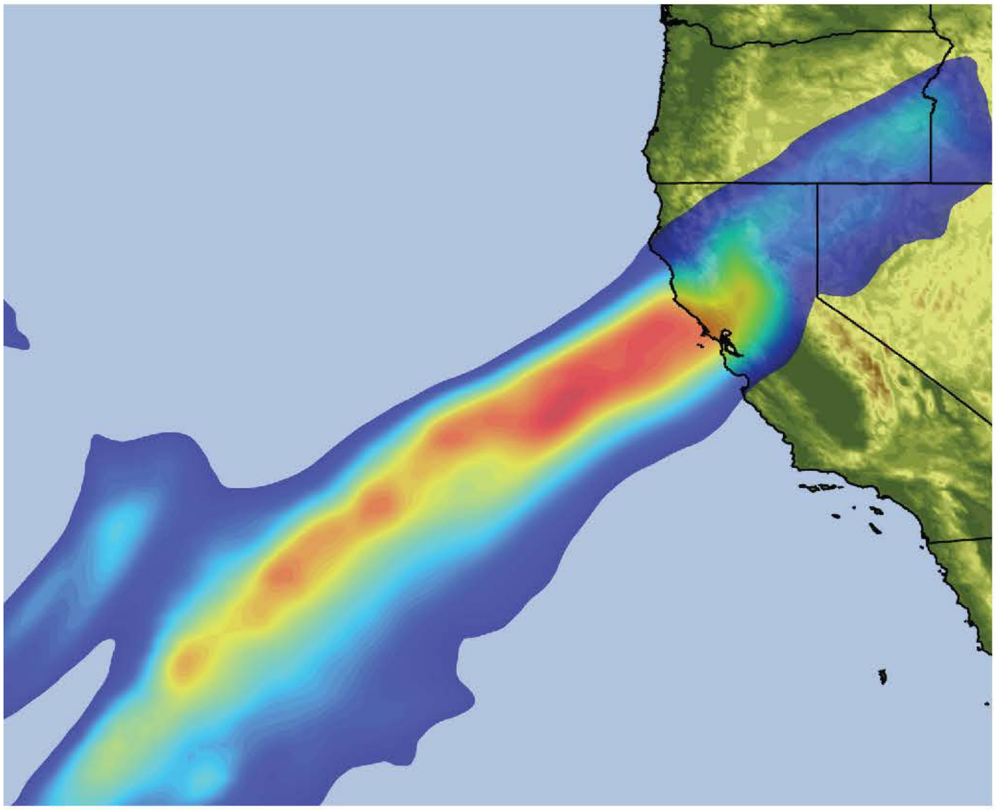
Yuba-Feather
FORECAST INFORMED RESERVOIR OPERATIONS

Preliminary Viability Assessment

Appendices

December 2022



Yuba-Feather FIRO Steering Committee

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- **John James:** Yuba Water (Co-chair)
- **John Leahigh:** California Department of Water Resources (DWR) (Co-chair)
- **Michael Anderson:** DWR
- **Cary Talbot:** USACE, Engineer Research and Development Center
- **Alan Haynes:** California Nevada River Forecast Center
- **Joseph Forbis:** USACE
- **Molly White:** DWR
- **Steven Lindley:** NOAA Fisheries

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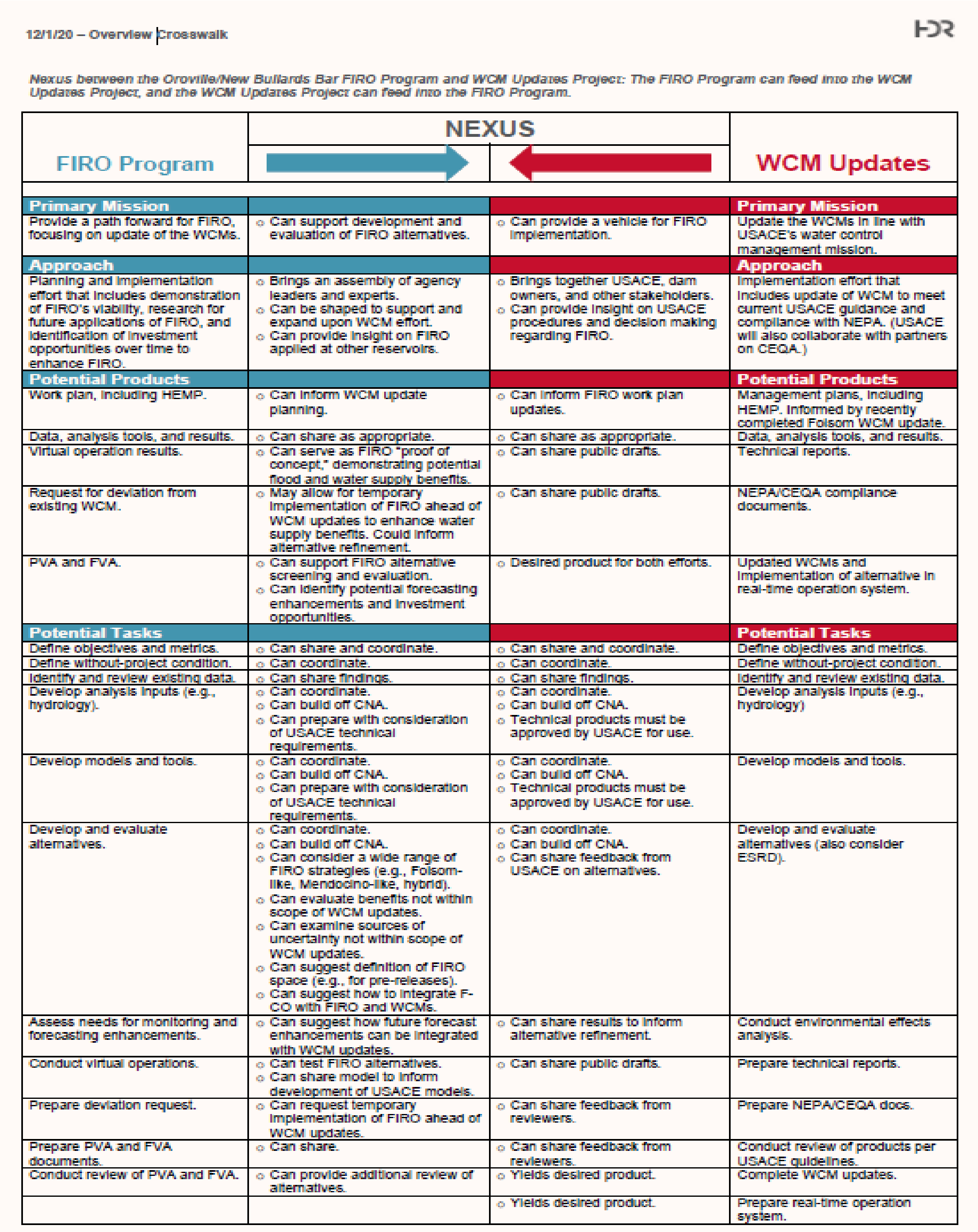
Appendix A—FIRO/WCM Overview Crosswalk (Section 3)



12/1/20 – Overview Crosswalk

Nexus between the Oroville/New Bullards Bar FIRO Program and WCM Updates Project: The FIRO Program can feed into the WCM Updates Project, and the WCM Updates Project can feed into the FIRO Program.

FIRO Program	NEXUS		WCM Updates
	→	←	
Primary Mission			**Primary Mission**
Provide a path forward for FIRO, focusing on update of the WCMs.	○ Can support development and evaluation of FIRO alternatives.	○ Can provide a vehicle for FIRO implementation.	Update the WCMs in line with USACE's water control management mission.
Approach			**Approach**
Planning and implementation effort that includes demonstration of FIRO's viability, research for future applications of FIRO, and identification of investment opportunities over time to enhance FIRO.	○ Brings an assembly of agency leaders and experts. ○ Can be shaped to support and expand upon WCM effort. ○ Can provide insight on FIRO applied at other reservoirs.	○ Brings together USACE, dam owners, and other stakeholders. ○ Can provide insight on USACE procedures and decision making regarding FIRO.	Implementation effort that includes update of WCM to meet current USACE guidance and compliance with NEPA. (USACE will also collaborate with partners on CEQA.)
Potential Products			**Potential Products**
Work plan, including HEMP.	○ Can inform WCM update planning.	○ Can inform FIRO work plan updates.	Management plans, including HEMP. Informed by recently completed Folsom WCM update.
Data, analysis tools, and results.	○ Can share as appropriate.	○ Can share as appropriate.	Data, analysis tools, and results.
Virtual operation results.	○ Can serve as FIRO "proof of concept," demonstrating potential flood and water supply benefits.	○ Can share public drafts.	Technical reports.
Request for deviation from existing WCM.	○ May allow for temporary implementation of FIRO ahead of WCM updates to enhance water supply benefits. Could inform alternative refinement.	○ Can share public drafts.	NEPA/CEQA compliance documents.
PVA and FVA.	○ Can support FIRO alternative screening and evaluation. ○ Can identify potential forecasting enhancements and investment opportunities.	○ Desired product for both efforts.	Updated WCMs and implementation of alternative in real-time operation system.
Potential Tasks			**Potential Tasks**
Define objectives and metrics.	○ Can share and coordinate.	○ Can share and coordinate.	Define objectives and metrics.
Define without-project condition.	○ Can coordinate.	○ Can coordinate.	Define without-project condition.
Identify and review existing data.	○ Can share findings.	○ Can share findings.	Identify and review existing data.
Develop analysis inputs (e.g., hydrology).	○ Can coordinate. ○ Can build off CNA. ○ Can prepare with consideration of USACE technical requirements.	○ Can coordinate. ○ Can build off CNA. ○ Technical products must be approved by USACE for use.	Develop analysis inputs (e.g., hydrology)
Develop models and tools.	○ Can coordinate. ○ Can build off CNA. ○ Can prepare with consideration of USACE technical requirements.	○ Can coordinate. ○ Can build off CNA. ○ Technical products must be approved by USACE for use.	Develop models and tools.
Develop and evaluate alternatives.	○ Can coordinate. ○ Can build off CNA. ○ Can consider a wide range of FIRO strategies (e.g., Folsom-like, Mendocino-like, hybrid). ○ Can evaluate benefits not within scope of WCM updates. ○ Can examine sources of uncertainty not within scope of WCM updates. ○ Can suggest definition of FIRO space (e.g., for pre-releases). ○ Can suggest how to integrate F-CO with FIRO and WCMs.	○ Can coordinate. ○ Can build off CNA. ○ Can share feedback from USACE on alternatives.	Develop and evaluate alternatives (also consider ESRD).
Assess needs for monitoring and forecasting enhancements.	○ Can suggest how future forecast enhancements can be integrated with WCM updates.	○ Can share results to inform alternative refinement.	Conduct environmental effects analysis.
Conduct virtual operations.	○ Can test FIRO alternatives. ○ Can share model to inform development of USACE models.	○ Can share public drafts.	Prepare technical reports.
Prepare deviation request.	○ Can request temporary implementation of FIRO ahead of WCM updates.	○ Can share feedback from reviewers.	Prepare NEPA/CEQA docs.
Prepare PVA and FVA documents.	○ Can share.	○ Can share feedback from reviewers.	Conduct review of products per USACE guidelines.
Conduct review of PVA and FVA.	○ Can provide additional review of alternatives.	○ Yields desired product.	Complete WCM updates.
		○ Yields desired product.	Prepare real-time operation system.

Appendix B—FIRO and WCM Alignment Workshop Agendas (Section 3)

Yuba-Feather Water Control Manual Update/ FIRO Coordination Workshop Day 1
December 4, 2020
Virtual

- Objectives of the workshop:
- Familiarize attendees with the overall processes for the Water Control Manual update and the Forecast-Informed Reservoir Operations Viability Assessment.
- Give a high-level view of the goals, objectives, and timelines of both processes – in paragraph form in the read-ahead material, and in the introductory sessions.
- Identify ways to align the parallel tasks and analyses in both projects.
- Create connections between the teams involved in both processes to facilitate collaboration going forward. Identify potential points in both processes where this communication needs to take place.
- Identify synergies and economies of scale to maximize efficiency of both processes and to minimize duplication of effort.
- The workshop will inform the FIRO Yuba-Feather Work Plan and the Water Control Manual HEMP.

Read-ahead materials:

- Objectives of Yuba-Feather Water Control Manual Update
- Lake Mendocino Final Viability Assessment Introduction
- Process Crosswalks
- F-CO, FIRO, WCM alignment document

Yuba-Feather Water Control Manual Update/ FIRO Coordination Workshop: Day 2
December 14, 2020
Virtual

Objectives of the workshop:

- Familiarize attendees with the overall processes for the Water Control Manual update and the Forecast-Informed Reservoir Operations Viability Assessment.
- Give a high-level view of the goals, objectives, and timelines of both processes – in paragraph form in the read-ahead material, and in the introductory sessions.
- Identify ways to align the parallel tasks and analyses in both projects.
- Create connections between the teams involved in both processes to facilitate collaboration going forward. Identify potential points in both processes where this communication needs to take place.
- Identify synergies and economies of scale to maximize efficiency of both processes and to minimize duplication of effort.

- The workshop will inform the FIRO Yuba-Feather Work Plan and the Water Control Manual HEMP.

Read-ahead materials:

- Objectives of Yuba-Feather Water Control Manual Update
- Lake Mendocino Final Viability Assessment Introduction
- Process Crosswalks
- F-CO, FIRO, WCM alignment document

Materials are available here.
Recorded sessions from Day 1 of the workshop are available here.

Yuba-Feather Water Control Manual Update/ FIRO Coordination Workshop: Day 3
January 12, 2021
Virtual

Objectives of the workshop:

- Familiarize attendees with the overall processes for the Water Control Manual update and the Forecast-Informed Reservoir Operations Viability Assessment.
- Give a high-level view of the goals, objectives, and timelines of both processes – in paragraph form in the read-ahead material, and in the introductory sessions.
- Identify ways to align the parallel tasks and analyses in both projects.
- Create connections between the teams involved in both processes to facilitate collaboration going forward. Identify potential points in both processes where this communication needs to take place.
- Identify synergies and economies of scale to maximize efficiency of both processes and to minimize duplication of effort.
- The workshop will inform the FIRO Yuba-Feather Work Plan and the Water Control Manual HEMP.
- Explore concepts for FIRO implementation, now and in the future.

Read-ahead materials:

- Objectives of Yuba-Feather Water Control Manual Update
- Lake Mendocino Final Viability Assessment Introduction
- Process Crosswalks
- F-CO, FIRO, WCM alignment document

Read-ahead materials are available here.
Recorded sessions from Day 1 and Day 2 of the workshop are available here.
Interactive Mural board is available here.

Appendix C—Hydrologic Engineering Management Plan (HEMP) (Section 4)

C.1 Summary

Efforts to improve the coordinated operations of Oroville (ORO) and New Bullards Bar (NBB) dams formally began in 2006 with the Forecast-Coordinated Operations (F-CO) Program. That program has been tremendously successful in developing a common operating picture for reservoir operators, improving the observation network, and integrating single-value and, more recently, ensemble streamflow forecasts into the coordinated decisions process.

The Forecast-Informed Reservoir Operations (FIRO) program for the Yuba-Feather system is an extension of the F-CO effort and leverages the experience of FIRO efforts for Lake Mendocino and Prado Dam. The FIRO effort introduces research to improve forecasts and formally integrates streamflow forecasts into the water management decision process (Water Control Plan for the US Army Corps of Engineers (USACE) or Section 7 dams). An inter-agency inter-disciplinary steering committee (SC) was formed for the Yuba-Feather FIRO Project in June 2019.

The objective of this Hydrologic Engineering Management Plan (HEMP) is to identify through appropriate detailed technical analyses and other considerations candidate FIRO strategies for ORO and NBB dams, along with how they might be implemented in real-time operation by USACE, State Water Project (SWP) and Yuba Water Agency (YWA). A second HEMP will be developed to develop and manage system operations that meet the objectives of the F-CO Program.

The California Department of Water Resources (DWR) State Water Project (SWP) completed a Comprehensive Needs Assessment (CNA) for Oroville Dam resulting from the 2017 Oroville Dam spillway incident. Information and recommendations from this assessment have been integrated into this document.

YWA is in the process of adding a new water control structure to NBB Dam that will dramatically improve the capacity to release stored water more quickly and at lower storage levels. This analysis assumes the conditions associated with this completed construction project.

This HEMP is managed by the Yuba-Feather FIRO SC. To be consistent with USACE guidance for conduct of similar technical studies the SC prepared this HEMP as *…a technical outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem* (*Engineering Pamphlet 1110-2-9*).

This HEMP includes the following:

1. Statement of objective and overview of technical study process to provide information needed for this assessment.
2. Identification of tasks to be completed for the technical analysis. (Table C-1).
3. Identification of candidate FIRO alternatives to be analyzed. (Table C-2).
4. Specification of requirements for all FIRO alternatives that will be considered. (Table C-3).

5. Identification of hard criteria as well as project and system-wide considerations. (Tables Table C-4,Table C-5, Table C-6).

6. Identification of initial tentative performance metrics for FIRO alternative evaluation. (Table C-7).

7. Identification of the project team members and their roles and responsibilities for conducting, reviewing, and approving of the hydrologic engineering study. (Tables Table C-8, Table C-9, Table C-10).

8. Risks to the success of this study and mitigation actions are shown in Table 11.

C.2 Objective of Technical Analysis, Overview of Process, and Tasks to be Completed

The objective of the hydrologic engineering study described herein is to identify and evaluate FIRO alternatives for ORO and NBB dams in a systematic, defendable, repeatable manner, thus providing information to the SC so that it may identify the best FIRO strategy for NBB Dam.

The process used to meet the hydrologic engineering study objective is a "nominate-simulate-evaluate-iterate" process, consistent with the process used commonly by USACE for water resources planning studies. Tasks in this process, as applied for technical analyses to support the ORO Dam CAN and the NBB Dam FIRO Viability Assessment, and include the following:

1. A set of feasibility criteria and performance metrics is developed for assessing and comparing FIRO alternatives. This set will be applied to all alternatives, thereby permitting the project delivery team (PDT) to compare and rank alternatives for consideration by the SC.

2. A set of alternative FIRO strategies is nominated by the PDT. The strategies are screened to ensure they meet specified requirements, which are described below.

3. Performance of the river-reservoir system with each FIRO strategy is simulated using a common set of meteorological and hydrological conditions. HEC-ResSim more likely will act as the "gatekeeper" for all alternatives to ensure that the physical constraints and attributes of the system are consistently applied.

4. Simulation results are used to evaluate the viability and performance of each strategy. The evaluation uses metrics identified in Task 1, comparing each alternative to performance for the *without-project* (baseline) condition, which is operation following the water control plan (WCP) included in the current water control manual (WCM). If results of the evaluation inform refinements to FIRO strategies, the simulation and evaluation tasks are repeated with enhanced strategies to the extent that resources allow.

5. The PDT uses the technical analysis results to rank the alternatives and submits the rankings to the SC for consideration.

These tasks are described in more detail in Table C-1. Major tasks are listed in column 1 and subtasks in column 3.

***Table C-1.** Tasks and Subtasks to be Completed for Hydrologic Engineering Study of FIRO Strategies*

Major Task (1)	Description (2)	Subtasks (3)
Task 1. Select performance metrics	Both quantitative and qualitative measures of performance will be identified. Methods of computation of quantitative measures will be described.	**Task 1.1.** With appropriate input from subject matter experts, formulate candidate set of quantitative and qualitative measures of performance. Define methods for assessing these for typical FIRO strategies. Screen set to select feasible metrics for ALL likely alternatives to permit objective comparison of strategies. Prepare technical memo. Submit to SC for review. **Task 1.2.** Receive comments from SC. Revise selected set of performance metrics as required. **Task 1.3**. If necessary, design, develop, and test software applications (scripts, spreadsheets, etc.) to apply selected metrics.
Task 2. Nominate/formulate alternative FIRO strategies that will be considered	Each alternative FIRO strategy to be considered will be identified and described, along with the method by which performance with the strategy will be evaluated.	**Task 2.1**. With appropriate input from subject matter experts, formulate candidate set of FIRO strategies to be considered. Describe each strategy in memo, submit proposed list/memo to SC for approval. **Task 2.2.** Receive comments from SC and revise list as appropriate. Get SC agreement to proceed with comparison. **Task 2.3**. Identify software applications that will be used to model FIRO strategies.
Task 3. Side studies	Identify, conduct, document, and incorporate outcomes of "side studies" that affect the simulation and evaluation of alternatives.	**Task 3.1.** Identify any additional "side studies" that must be completed to provide information required for simulation. Details of side studies will be identified in this subtask, with scope of work and schedule submitted to SC for approval. **Task 3.2.** Undertake and complete side studies, as approved by SC. Document findings. Incorporate findings in selected FIRO strategy models or procedures.
Task 4. Simulate performance with each alternative	Each alternative FIRO strategy will be simulated with the HEC- ResSim model with a consistent set of hydrologic boundary conditions and system constraints (identified in Table C-3).	**Task 4.1.** Considering all FIRO strategies to be evaluated, identify boundary conditions and initial states of the system to be considered in simulation for comparison. Document. **Task 4.2.** Simulate performance of ORO and NBB dams with candidate strategies. Prepare technical memo describing application of each strategy. Prepare database of results (for use in Task 5).

Major Task (1)	Description (2)	Subtasks (3)
Task 5. Using results of simulation, evaluate each alternative in terms of identified performance metrics	Each alternative FIRO strategy will be analyzed and the appropriate performance metric statistics computed.	**Task 5.1.** Using database of results from the HEC-ResSim simulation of each FIRO strategy (from Task 4.2) apply software applications (scripts, spreadsheets, etc.) from Task 1.3 to compute performance metrics for each strategy. **Task 5.2.** Revise FIRO strategies and performance metrics as necessary to ensure fair, repeatable comparisons. This subtask acknowledges initial uncertainty about compatibility of strategies and metrics. **Task 5.3.** Document results of evaluation in technical memo.
Task 6. Compare the alternatives by comparing the metrics	Each alternative FIRO strategy evaluation will be compared against the baseline and against each other.	**Task 6.1.** Using results from Task 5, prepare charts, tables, etc. to compare performance of strategies. Prepare technical memo with this information and submit to SC for information. **Task 6.2.** Refine strategies if evaluation and comparison expose opportunities for "quick gains" through minor adjustments to strategies. Repeat subtasks Task 4.2 through Task 5.1 with revised results. **Task 6.3.** Prepare final technical memo on simulation, evaluation, and comparison. Submit for SC review. Receive SC comments and revise technical memo as needed.
Task 7. Brief SC on findings and facilitate the selection of a preferred approaches to be refined in the FVA	Each alternative FIRO strategy comparison will be scrutinized, a preferred approaches and refinements for the FVA identified and documented and presented to the SC.	**Task 7.1.** Using results of comparison from Task 6, rank alternatives considering individual metrics from Task 1. Document findings. **Task 7.2.** Provide comparisons and ranking to SC. **Task 7.3.** Document recommended refinements for the FVA process.

C.3 FIRO Alternatives to be Evaluated

Selection of candidate FIRO alternatives has been completed by the Water Resources Engineering (WRE) Team (Task 2). These candidate alternatives were delivered to the Corps WCM Update Team and will be evaluated through the procedures defined in this document. The existing WCM operations for both ORO and NBB will also be evaluated to establish the performance baseline. **Table C-2** shows the list of WCP alternatives to be evaluated.

Table C-2. *List of WCP alternatives to be evaluated.*

ID	Dam	Alt	Alt Description	Operation Principle
1	ORO	EO	Existing Operations	Exiting WCP from current WCM.

ID	Dam	Alt	Alt Description	Operation Principle
2	ORO	PresFcst_1	Use best-estimate forecast volumes to inform guide curve TOC computation and inflow-based releases.	Relies on an elevation-based guide curve that is computed based on forecast inflow volumes. When in the flood control pool, intent is to evacuate the storage in a controlled manner to reduce downstream peak flows. Stepped releases are proposed.
3	ORO	IterFcst_1	Use ensemble streamflow forecast members to determine a release based on an iterative process to maintain the same dam risk profile as current operations.	Identify a "minimally-changed release" through the flood event. This release (or pattern) is identified as the maximum release that is needed to balance the use of the flood pool but not result in adverse dam safety concerns. The operation seeks to answer the question, what is the release needed to make it through this event safely? Use the forecast information, and the associated uncertainty to identify the release.
4	ORO	EFO	Ensemble Forecast Operations (EFO) Model using the full range of reservoir storage.	Manages risk of exceeding a defined critical storage threshold using a developed risk curve and ensemble streamflow forecasts. Full range of storage is available for release decisions.
5	ORO	EFO Hybrid	Hybrid EFO Model limited to a defined FIRO Space.	Manages the risk of exceeding a defined critical storage threshold using a developed risk curve and ensemble streamflow forecasts. FIRO release decisions limited to the define FIRO Space.
6	NBB	EO	Existing Operations	Existing WCP from current WCM.
7	NBB	FIRO GC	FIRO Guide Curve. FIRO for flood control and water supply using a forecast-based guide curve to specify drawdown in advance of flood events and conditional storage of water in the gross pool when forecast is dry.	Evacuate volume above FIRO guide curve over less than one day time window. Increases storage utilization to mitigate high downstream flood releases.

ID	Dam	Alt	Alt Description	Operation Principle
8	NBB	FIRO RS	FIRO Release Schedule. FIRO for flood control using a forecast-based release schedule to specify drawdown in advance of flood events.	Evacuate conservation space to absorb forecast event, reducing peak releases and peak storage in NBB.
9	NBB	EFO	Ensemble Forecast Operations (EFO) Model using the full range of reservoir storage.	Manages risk of exceeding a defined critical storage threshold using a developed risk curve and ensemble streamflow forecasts. Full range of storage is available for release decisions.
10	NBB	EFO Hybrid	Hybrid EFO Model limited to a defined FIRO Space.	Manages the risk of exceeding a defined critical storage threshold using a developed risk curve and ensemble streamflow forecasts. FIRO release decisions limited to the define FIRO Space.

Requirements of all candidate strategies are shown in Table C-3. Table C-4, Table C-5, and Table C-6 show additional constraints and objectives that should be met by all the alternatives. The operational considerations in Table C-5 and Table C-6 are used to create the evaluation metrics provided in Table C-7.

Table C-3. *Requirements of all alternative WCP strategies*

ID	Description
1	The candidate FIRO strategy must satisfy all relevant USACE engineering regulations (ERs), including, but not limited to, the following: • ER 1105-2-100 *Planning Guidance Notebook* • ER 1105-2-101 *Risk Assessment for Flood Risk Management Studies* • ER 1110-2-240 *Water Control Management* • ER 1110-2-1156 *Safety of Dams Policy and Procedures* • ER 1110-2-1941 *Drought Contingency Plans* • EM 1110-2-3600 *Management of Water Control Systems* • ER 1110-2-8156 *Engineering and Design Preparation of Water Control Manuals* • EM 1120-2-1420 *Engineering Requirements for Reservoirs*
2	The analytical tools required for implementation of the candidate FIRO strategy must be compatible with the USACE's Corps Water Management System (CWMS) software. In addition, results of any analyses completed with software not currently certified for use by USACE must be demonstrated to produce results consistent with USACE software results.

ID	Description
3	Streamflow forecasts used by the candidate FIRO strategy must be those provided by the California-Nevada River Forecast Center (CNRFC) of the National Weather Service. Simulated streamflow forecasts must be consistent with the skill characteristics of those issued by the CNRFC. As appropriate for the alternative, the forecast used can be ensemble and/or single value.
4	The FIRO strategy must satisfy the hard (inviolable) operation constraints shown in Table C-2.
5	The FIRO strategy should represent, and to the extent possible, meet the operation objectives shown in Table C-3 and Table C-4.
6	Software development needed to implement the FIRO alternative must be limited for the Viability Assessment, as the objective is to select from amongst a set of readily available (or nearly so) strategies.
7	Simulations should be computed at an hourly time step.

Table C-4. *Hard (Inviolable) Operational Constraints that Must be Satisfied by All FIRO Strategies*

ID	Limiting Condition	Description
1	Satisfy ORO Water Control Manual Flood Control Diagram	Meet all specific requirements stated on current Flood Control Diagram
2	Satisfy ORO Water Control Manual Emergency Spillway Release Diagram (ESRD)	Meet all specific requirements stated on current Emergency Spillway Release Diagram (ESRD)
3	Satisfy NBB Water Control Manual Flood Control Diagram	Meet all specific requirements stated on current Flood Control Diagram
4	Satisfy NBB Water Control Manual Emergency Spillway Release Diagram (ESRD)	Meet all specific requirements stated on current Emergency Spillway Release Diagram (ESRD)
5	Do not assume Marysville Dam is in place	The 1972 WCM operation assumes storage is available in Marysville Reservoir. Marysville Reservoir was never built.
6	Satisfy release rate of change constraints associated with increases and decreases	As documented
7	Include function of new NBB secondary spillway	The FIRO alternatives must incorporate the function of the new NBB secondary spillway
8	Do not require other than currently available streamflow forecasts	CNRFC deterministic and ensemble streamflow forecasts are available up to 4 times per day during major runoff events. For evaluation purposes, forecast updates will be once per day.

Table C-5. *Operational Considerations that Should be Evaluated in the Hydrologic Engineering Study.*

ID	Operational Consideration	Description
1	Reduce the frequency of critical release exceedance from ORO and NBB	Alternative should decrease the frequency of critical releases from both dams
2	Reduce the frequency of ORO releases that result in more than 180,000 cfs in the Feather River at Yuba City	Maximum F-CO flow target for ORO
3	Reduce the frequency of NBB releases that result in more than 180,000 cfs in the Yuba River at Marysville	Maximum F-CO flow target for NBB
4	Reduce the frequency of releases from ORO and NBB that result in more than 300,000 cfs in the Feather below Yuba City and 320,000 cfs in the Feather River below the Bear River.	Combined F-CO flow targets for ORO and NBB
5	Avoid negative impacts to spring refill	Alternatives should not reduce the ability of ORO and NBB to meet water supply delivery objectives
6	Avoid the use of the ORO emergency spillway	Operational objective for dam safety
7	Avoid negative impacts on hydropower generation	Hydropower production should be maintained or possibly enhanced
8	End of flood season storage	Consider the effect of FIRO operation on storage at the end of the flood season (through the end of May).

Table C-6. *System-Wide Operational Considerations that Should be Evaluated in the Hydrologic Engineering Study.*

ID	Operational Consideration	Description
1	Implementation of F-CO of Lake Oroville and NBB Reservoir	Consider and support the existing YF F-CO program.
2	Operational resiliency	The FIRO alternative should be resilient to a wide range of hydrologic events within the watershed. For example, the operation should be resilient to a range of storm-centering and events of key frequencies occurring within the Yuba and Feather watersheds.

C.4 Metrics for Evaluating Viability and Efficiency of Alternatives

The efficiency of FIRO will be evaluated with a set of measurable statistics (Task 1). These will be used in the same manner (to the maximum extent possible) to assess each alternative objectively. An initial list of metrics and the manner of computing or calculating each is shown in Table C-7.

Table C-7. *List of Metrics for Evaluation of WCP Alternatives (listed in Table C-2).*

ID	Metric Description	Category	Likely Method of Computation	
M1	Flood Season maximum discharge frequency from ORO Dam	Flood risk management	Frequency curve.	See Simulation Plan.
M2	Flood Season maximum pool elevation frequency function of ORO Dam	Flood risk management	Frequency curve.	See Simulation Plan.
M3	Flood Season maximum discharge frequency from NBB Dam	Flood risk management	Frequency curve.	See Simulation Plan.
M4	Flood Season maximum pool elevation frequency function of NBB Dam	Flood risk management	Frequency curve.	See Simulation Plan.
M5	Flood Season maximum flow-frequency curves at key downstream locations	Flood risk management	Frequency curve. See Simulation Plan. CVHS frequency analysis. Key downstream locations are Yuba River at Marysville, Feather River at Yuba City, Yuba and Feather River Confluence, and Feather River near Nicolaus.	
M6	ORO Reservoir storage at the end of Flood Season (spring refill)	Water supply	Reservoir routing. See Simulation Plan. Include detailed metrics on potentially the following: Changes in reservoir storage levels	
M7	NBB Reservoir storage at the end of Flood Season (spring refill)	Water supply	Reservoir routing. See Simulation Plan. Include detailed metrics on potentially the following: Changes in reservoir storage levels	
M8	ORO Hydropower production	Hydropower management	See Simulation Plan. Changes in monthly and annual megawatt production output frequency curve.	
M9	NBB Hydropower production	Hydropower management	See Simulation Plan. Changes in monthly and annual megawatt production output frequency curve.	

C.5 Bookend Analysis

To better understand the maximum benefit of forecasts, all non-baseline alternatives will be configured and run with full foresight of future streamflow conditions for the full lead time of the forecasts utilized (perfect forecasts).

The “bookends” will be established by the baseline alternative and the results of the perfect forecast simulations for the FIRO alternatives for each dam. The current position between the two “bookends” will be established through the evaluation of each non-baseline alternative in Table C-2 using currently available forecasts.

C.6 Project Delivery Team Members and their Roles

The PDT for evaluation of FIRO alternatives includes subject matter experts who will complete the analyses described herein, report on the findings and understandings, and recommendations in memo form to the YF FIRO SC. This work effort is led by the YF FIRO PVA Water Resources Engineering Team. PDT members are identified in **Table C-8**.

Table C-8. *New Bullards Bar Dam FIRO Alternatives Evaluation Technical Analysis PDT Members*

● Yuba-Feather FIRO steering committee
● SWP technical staff and consultants (HDR)
● YWA technical staff and consultants (MBK)
● USACE Headquarters staff (HQ)
● USACE Engineering Research and Development Center (ERDC) staff
● USACE, South Pacific Division (SPD) staff
● USACE, Sacramento District (SPK) staff
● Center for Western Weather and Water Extremes, Scripps Institution of Oceanography at University of California, San Diego. Includes Robert K. Hartman Consulting Services (RKHCS) and Sonoma Water staff under contract to support FIRO efforts.

The PDT members have one of four roles, consistent with established project management planning, as shown in Table C-9. These roles vary by hydrologic engineering task. Table C-10 shows roles assigned to PDT members for the analysis described herein.

Table C-9. *Project Roles*

ID	Role	Description of Duties
R	Responsible	Responsible for completing the analyses described herein.
A	Accountable	Answerable for correct and thorough completion of task; ensures requirements are met; delegates work to those responsible.
C	Consulted	As SMEs, offer opinions through two-way communication with those responsible and accountable, about conduct of analyses.
I	Informed	Keep up to date on progress through two-way communication.

Table C-10. *PDT Roles by Task*

Major Task	Steering Committee	SWP/YWA Tech Staff and Consultants	USACE HQ	USACE ERDC	USACE SPD	USACE SPK	CW3E
Task 1. Select performance metrics	I	R	I	C	C	R	R
Task 2. Nominate/formulate alternative FIRO strategies that will be considered	C	R	I	C	C	R	R
Task 3. Side studies	C	R	I	C	C	R	R
Task 4. Simulate performance with each alternative	I	R	I	I	I	C	R
Task 5. Using results of simulation, evaluate each alternative in terms of identified performance metrics	I	R	I	I	I	C	R
Task 6. Compare the alternatives by comparing the metrics	I	R	I	I	C	C	R
Task 7. Brief SC on findings and facilitate the selection of a preferred alternative	I	R	I	I	I	R	R

C.7 Schedule for Completion of Technical Analysis

Figure C-1 shows the schedule for completion of the project tasks. All work on all tasks will be completed by December 31, 2021.

(To be developed).

Figure C-1. *Schedule for completion of hydrologic engineering study to recommend FIRO strategy for ORO and NBB dams.*

C.8 Risks to Success of Study

Risks to the success of this study and mitigation actions are shown in Table C-11.

Table C-11. *Project Risks*

Potential Failure Mode	Actions PDT can take to Mitigate
Simulation or evaluation software does not function as expected.	Limit analysis to use of software that is readily available and has been stress tested.
Necessary data—including hydrological, meteorological, water use, vulnerability— are not readily available.	Limit analysis to use of best-available data.
Key personnel are not available to complete tasks.	Ensure back up staff for all critical tasks.
Critical path tasks fall behind schedule due to unforeseeable distractions and disruptions.	Limit project activities to those that are necessary to satisfy objectives.
PDT disagrees about technical analysis procedures.	Defer to PDT project assignments (see above).
Nature of alternative FIRO strategy prevents evaluation with selected metrics.	Disqualify alternative from further consideration unless metrics can be adjusted and applied in uniform manner for all alternatives.

Appendix D—FIRO Alternative WCP Attributes (Section 4)

MEMORANDUM

DATE:	Wednesday, August 25, 2021
PREPARED BY:	Yuba-Feather FIRO Program
REVIEWED BY:	FIRO Steering Committee and USACE Sacramento District
From	Donna Lee, CFM; Nathan Pingel, PE; Rob Hartman; Ben Tustison, PE
SUBJECT:	Preliminary Viability Assessment of At-Site Operations: Developing a FIRO Guide Curve for New Bullards Bar

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Date:	Wednesday, August 25, 2021
Project:	Yuba-Feather FIRO Program
To:	FIRO Steering Committee and USACE Sacramento District
From:	Donna Lee, CFM; Nathan Pingel, PE; Rob Hartman; Ben Tustison, PE
Subject:	Oroville and New Bullards Bar alternative attributes

D.1 Situation

The Yuba-Feather Forecast-Informed Reservoir Operations (FIRO) Program is conducting a preliminary viability assessment (PVA) of FIRO for Oroville and New Bullards Bar dams. FIRO is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and hydrological forecasts (AMS 2021). Oroville and New Bullards Bar dams are multi-purpose projects, operated for flood control, water supply, power generation, recreation, and conservation (USACE 1970 and 1972).

Oroville Dam lies on the Feather River and is owned and operated by the California Department of Water Resources (DWR). New Bullards Bar Dam lies on the Yuba River and is owned and operated by Yuba Water Agency (YWA). The reservoirs are operated as a system for flood control.

Flood operation rules at each dam are prescribed by the U.S. Army Corps of Engineers (USACE) and documented in water control manuals (WCM). The USACE Sacramento District (SPK) is currently updating the WCM for each dam to reflect the current state of the reservoir system (without Marysville Dam, which was planned but never constructed), reflect current USACE guidance, and to update flood operation rules. This will include evaluation of flood operation alternatives that explicitly consider inflow forecasts in release decision making. The simultaneous WCM updates effort provides the opportunity for the FIRO Program to inform SPK's alternative evaluation.

Through close coordination with SPK, the FIRO Program has structured the PVA schedule and deliverables to feed into the WCM update process. The goal of the PVA is to provide proof-of-concept that FIRO is viable at Oroville and New Bullards Bar. As part of the PVA, the FIRO Program water resources engineering (WRE) team will develop and evaluate flood operation alternatives and provide the results to SPK. SPK will consider the alternatives during its development and screening process.

Figure D-1 illustrates how products from the PVA process will feed into the WCM updates process.

FIRO alternative development will be achieved in phases, with at-site alternative attributes considered first. At-site attribute development will focus on understanding individual capabilities and performance of each dam compared to existing WCM operation. Following this phase, system operation will be developed based on the most-promising at-site attributes. System operation will focus on coordinated joint release decision making for Oroville and New Bullards Bar to avoid exceeding the maximum objective flow at the Yuba-Feather confluence and downstream.

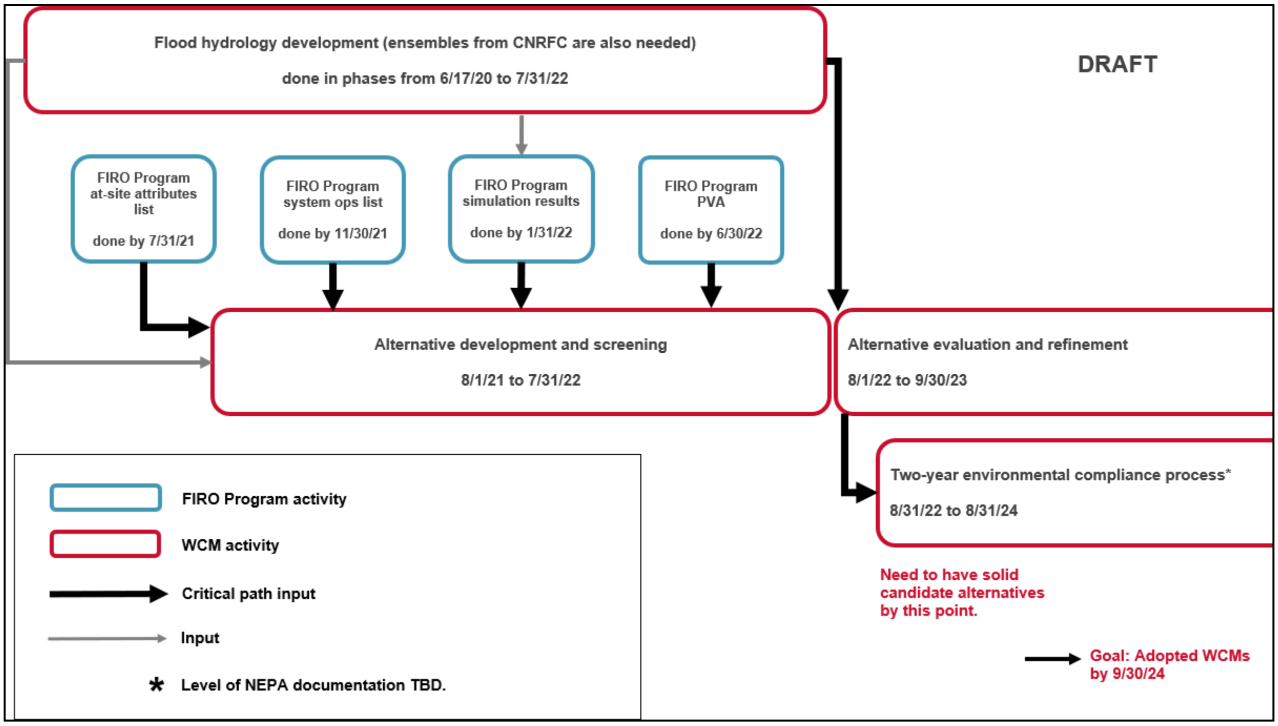

Figure D-1. *Draft FIRO Program-WCM updates alternative development schedule crosswalk (provided by SPK August 2021). WCM updates schedule subject to change.*

D.2 Task

The WRE team's first task was to describe conceptually the attributes that it proposes to develop and evaluate. The attributes for this task focus on at-site operation, prior to consideration of system operation in a subsequent task. The conceptual description serves to inform SPK of FIRO Program activities and ensures that SPK and the FIRO Program avoid duplication of effort.

D.3 Actions

To achieve the task, the WRE leadership team:

1. Obtained relevant information from the SPK WCM updates effort. This included:
   - Flood operation objectives and considerations (USACE 2021). SPK, DWR, and YWA, developed a draft list of flood operation objectives and considerations for each dam, shown in Attachment D-1. Objectives must be met by candidate operations alternatives. Considerations should be addressed but are not requirements.
   - Alternative development framework. SPK/HDR developed a framework to describe flood operation alternatives (USACE 2021). The framework comprises two tables, shown in Attachment D-3. The first table identifies the reservoir operation principle, or the general approach to use of storage and releases. The second table identifies reservoir operation attributes, which include definition of space used to manage flood flows, type of forecast input used, method to determine magnitude of releases, limits on releases, type of system operation, and type of emergency operation for dam safety.
2. Led a series of collaborative team workshops to:
   - Gain an understanding of FIRO alternatives that have been developed for other dams. Team members gave presentations on previous foundational studies including the Folsom Dam Water Control Manual Update (USACE 2019), Lake Mendocino FIRO Program (FIRO Program 2020), Oroville Comprehensive Needs Assessment (CNA) (DWR 2020), New Bullards Bar Secondary Spillway evaluation (YWA 2020), and the Forecast-Coordinated Operations Program decision support system (Ford Engineers 2008).
   - Establish criteria for evaluating proposals. These included, for example, meeting the flood operation objectives specified in the list from SPK and having the strong potential for implementation in the WCMs. The criteria are included in Attachment D-2.
   - Brainstorm and discuss proposals for alternatives from the WRE team. Members of the WRE team used the WCM updates framework to develop proposals. These are included in Attachment D-4 and D-5.
   - Gain feedback from SPK, DWR, and YWA in the context of the evaluation criteria.
3. Refined evaluation proposals based on agency feedback and prepared this memorandum for the record.

D.4 Results

WRE team members developed eight at-site alternative proposals, four for Oroville and four for New Bullards Bar. The proposals are included in Attachment D-4 and D-5 and summarized below.

- Oroville (one proposal) – A proposal similar to the forecast-based operation (F-BO) alternative developed for Folsom Dam that incorporates a forecast-based top of conservation elevation in conjunction with a forecast-based release rule. Ensemble forecast input is processed to a single value.
- New Bullards Bar (one proposal) – A proposal with attributes similar to the F-BO alternative developed for Folsom Dam. The alternative incorporates a forecast-based top of conservation elevation. Ensemble forecast input is processed to a single value.
- New Bullards Bar (one proposal) – A proposal with attributes similar to the F-BO alternative developed for Folsom Dam. The alternative incorporates a forecast-based release rule. Ensemble forecast input is processed to a single value.
- Oroville and New Bullards Bar (two proposals) – For each dam, a proposal similar to the Lake Mendocino ensemble forecast operation (EFO) alternative. Each member of the ensemble forecast input is considered and releases are determined based on tolerable risk of exceeding a critical threshold. Rather than prescribing a guide curve, EFO operation permits use of reservoir storage from the top of the flood management space with an undefined bottom, referred to as FIRO space.
- Oroville and New Bullards Bar (two proposals) – For each dam, a proposal similar to the Lake Mendocino hybrid alternative. A portion of the reservoir is designated as FIRO space, and EFO operation is used in that space as described in the previous bullet. Outside the FIRO space, traditional guide curve operation is used.
- Oroville (one proposal) – An alternative similar to the hybrid alternative developed for Lake Mendocino that uses a pool-elevation frequency curve to inform hazard tolerance and aims to minimize changes in release magnitude.

The WRE team shared the alternative tables and proposals with SPK on July 27 via the Google Drive as part of the WRE team workshop series. Throughout the workshop series, agency technical leads provided feedback, and no proposals were eliminated at this stage.

D.5 Next steps

The WRE leadership team will facilitate the following next steps:

1. Facilitate review of the proposals by the FIRO Steering Committee (SC) and integrate feedback from the SC.

2. Update the FIRO Program hydrologic engineering management plan (HEMP) to refine concept design, plan model development, and plan at-site alternative analysis. This will include specification of hydrologic information used, model configuration details, simulations that will be executed, screening metrics, and assumptions and limitations. Process consistency and comparability of results will be considered. The HEMP will also

provide a schedule for alternative development and evaluation and identify roles and responsibilities.

3. Facilitate review of the HEMP by the SC and integrate feedback from the SC.

4. Execute the HEMP for at-site analysis, including:

   - Develop the model framework for each model. This includes configuration of the base model, including physical representation of reservoirs, existing WCM operation rules, and system inflow/computation points. This phase includes model verification.
   - Parameterize models. This includes specification and refinement of model parameters through iterative testing and supplementary analysis.
   - Finalize the analysis. This includes evaluation of attributes based on metrics defined for PVA at- site analysis. Results from this phase will be used for comparison to identify the most-promising at-site attributes and to inform development of system operation.

D.6 References

American Meteorological Society (2021). *Glossary of Meteorology*. https://glossary.ametsoc.org/wiki/Forecast-informed_reservoir_operations. Accessed August 2021.

David Ford Consulting Engineers (2008). *Oroville-New Bullards Bar Forecast-Coordinated Operations: Decision Support System Technical Documentation*. Prepared for Yuba Water Agency. Dec. 12.

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USACE (1970). *Oroville Dam and Reservoir: Report on Reservoir Regulation for Flood Control*. SPK. August.

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YWA (2020). *New Bullards Bar Secondary Spillway: Evaluation of Flood Management Performance for Candidate Secondary Spillway Outlets*. Prepared by MBK Engineers. August 24.

Attachment D-1: WCM updates draft flood operation objectives and considerations

NBB/ORO WCMs Update – Objectives – DRAFT

I. Objectives related to Water Control Diagram (WCD)*

a. **New Bullards Bar:** *Yuba River below NBB through mouth of Yuba*
    i. Coordinate operations in Y-F watershed to minimize exceedence of:
        1. 180,000 cfs in the Yuba River at Marysville and
        2. without necessity for Marysville Dam-Lake

b. **Oroville:** *Feather River below ORO up to Yuba-Feather confluence*
    i. Coordinate operations in Y-F watershed to minimize exceedence of:
        1. 180,000 cfs in the Feather River upstream of Yuba River and
        2. without necessity for Marysville Dam-Lake,
        3. without necessity for Lake Oroville emergency spillway use, and
        4. without exceeding 150,000 cfs released from Lake Oroville.

c. **Combined System ORO / NBB:** *Confluence of Yuba-Feather to confluence of Feather-Bear*
    i. Coordinate operations in Y-F watershed to minimize exceedence of:
        1. 300,000 cfs in the Feather River below Yuba River,
        2. 320,000 cfs in the Feather River below Bear River, insofar as possible, and
        3. without necessity for Marysville Dam-Lake

II. Objectives related to Probable Maximum Flood (PMF) - Emergency Spillway Release Diagram – ESRD

a. Combined System ORO / NBB: N/A

b. **New Bullards Bar:** NBB Dam specific passage of PMF (including Secondary Spillway) with a minimum of 2 feet of freeboard (from the dam crest 1965 feet (NGVD29))

c. **Oroville:** ORO Dam specific passage of PMF with a minimum of 3 feet of freeboard. This freeboard amount is subject to revision pending input from either Federal Energy Regulatory Commission (FERC) or DWR Division of Safety of Dams (DSOD).

*Includes Standard Project Flood (SPF) being one routing within the suite of storm hydrology patterns being currently used in evaluating performance of a new WCD.

I. Considerations related to Water Control Diagram (WCD)*

a. **New Bullards Bar:** *Yuba River below NBB through mouth of Yuba*

- i. Incorporate Secondary Spillway
- ii. Investigate "FIRO Space" above and below TOC, at a minimum consider a FIRO "pre-release" space below TOC
- iii. Reshape portion of WCD to improve water supply due to greater flexibility leading up to and during the spring refill period without imposing additional flood risk (FIRO Water Supply space)
- iv. Investigate 50,000 cfs maximum WCD spill release from New Bullards Bar
- v. Investigate acceptable pre-release flow range within FIRO space
- vi. Investigate tiered advance release strategy with progressively more aggressive releases as forecast magnitude increases and uncertainty decreases.

b. **Oroville:** *Feather River below ORO up to Yuba-Feather confluence*

- i. Document how snowpack and snowmelt runoff are implicitly accounted for in the inflow forecast
- ii. Revise flood control operations to not adversely impact water supply and, if possible, improve water supply due to greater flexibility leading up to and during the spring refill period without imposing additional flood risk

c. **Combined System ORO / NBB:** *Confluence of Yuba-Feather to confluence of Feather-Bear*

- i. Incorporate Forecast Coordinated Operations (F-CO)
- ii. Incorporate Forecast Informed Reservoir Operations (FIRO)
- iii. Incorporate more explicit defined cutback responsibility between NBB/ORO for downstream constraints more clearly. Disambiguate Yuba River shared downstream 180/120 kcfs constraint.
- iv. Incorporate adaptability into the WCM so that improvements in forecast ability can easily be incorporated in the future.

*Includes Standard Project Flood (SPF) being one routing within the suite of storm hydrology patterns being currently used in evaluating performance of a new WCD.

II. Considerations related to Probable Maximum Flood (PMF) - Emergency Spillway Release Diagram – ESRD

a. **Combined System ORO / NBB:** N/A

b. **New Bullards Bar:**

   i. NBB Dam specific passage of the PMF without exceeding 115,000 cfs through the primary spillway (unless necessary for dam safety).

   ii. Forecast-Informed ESRD

c. **Oroville:**

   i. ORO Dam specific passage of PMF with 5 feet of freeboard. This freeboard amount is subject to revision pending input from either the Federal Energy Regulatory Commission (FERC) or DWR Division of Safety of Dams (DSOD).

   ii. Forecast-Informed ESRD

*Includes Standard Project Flood (SPF) being one routing within the suite of storm hydrology patterns being currently used in evaluating performance of a new WCD.

Attachment D-2: FIRO Program alternative proposal evaluation criteria

Criteria are applicable to both Oroville and New Bullards Bar.

No.	Criteria
1	Has potential to meet objectives and factor in considerations from WCM updates document.
2	Has potential to be implemented in WCM.
3	Acceptable level of effort required.
4	Can meet schedule constraints.
5	Alternative is consistent with existing USACE authority. No storage reallocation study is required.
6	Alternative explicitly considers streamflow forecasts in release decision making.
7	Alternative considers/accounts for uncertainty in streamflow forecasts.
8	Alternative is practical for real-time use, considering usability by operators, including runtime and the ability to backcheck model computations, and need for integration into F-CO and CWMS decision support systems.
9	Alternative is practical for use during emergencies and provides operators adequate guidance for determining releases during blackouts.
10	Has potential to enhance flood risk management.
11	Has potential to enhance water supply reliability as a secondary goal to enhancing flood risk management.
12	Method for determining release decisions can be clearly explained and easily understood.
13	Release decision making is not dependent on source of forecast inputs.

Attachment D-3: FIRO Program alternative principles and attributes summary, using WCM updates table templates

Table D3-1. Potential reservoir operation principles: the general approach to use of storage and releases

Dam	Alt	Alt Description	Operation Principle
NBB	FIRO Guide Curve	FIRO for flood control and water supply using a forecast-based guide curve to specify drawdown in advance of flood events and conditional storage of water in the gross pool when forecast is dry.	• Evacuate volume above FIRO guide curve over less than one day time window. • Increases storage utilization in the reservoir to mitigate high downstream flood releases. • Use 95%, 75%, 50%, 25%, 5% NEP ensemble members to test release decisions.
NBB	FIRO Release Schedule	FIRO for flood control using a forecast- based release schedule to specify drawdown in advance of flood events.	• Evacuate conservation space with increasing release steps to absorb forecast event, reducing peak releases and peak storage at NBB.
NBB	Ensemble Forecast Operations	FIRO for flood control using ensemble streamflow predictions to inform a risk- based operation.	• Flood control release decisions are formulated by managing forecasted risk of exceeding a defined storage threshold to a specified risk tolerance level. • Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
NBB	Hybrid Ensemble Forecast Operation	Defines a portion of reservoir pool for FIRO using ensemble streamflow predictions to inform a risk-based operation	• FIRO pool is defined as a portion of existing flood pool and conservation pool. • When storage levels are within the FIRO pool, flood control release decisions are formulated by managing forecasted • risk of exceeding a defined storage threshold to a specified risk tolerance level. • Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
ORO	Prescriptive Forecast_ 1	Use best-estimate forecast volumes to inform guide curve (TOC) computation and inflow-based releases	• This alternative relies on a guide curve (elevation based) • that is computed based on forecasted inflow volumes. When in the flood control pool, intent is to evacuate the flow in a controlled manner to reduce downstream peak flows (not release inflow). Stepped releases are proposed.

Dam	Alt	Alt Description	Operation Principle
ORO	ORO Iterative Forecast_1	Use ensemble members to determine a release for the reservoir based on an iterative process to maintain same dam risk profile as current operations.	• Goal of this operation is to identify a “minimally-changed release” through the flood event. This release (or release pattern) is identified as the maximum release that is needed to balance the use of the flood pool but not result in adverse dam safety concerns. So, the operation seeks to answer the question, what is the release that I need to make through this event to safely pass the event. Use the forecast information, and the uncertainty of that, to identify this release.
ORO	Ensemble Forecast Operations	FIRO for flood control using ensemble streamflow predictions to inform a risk- based operation	• Flood control release decisions are formulated by managing forecasted risk of exceeding a defined storage threshold to a specified risk tolerance level. • Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
ORO	Hybrid Ensemble Forecast Operations	Defines a portion of reservoir pool for FIRO using ensemble streamflow predictions to inform a risk-based operation	• FIRO pool is defined as a portion of existing flood pool and conservation pool. • When storage levels are within the FIRO pool, flood control release decisions are formulated by managing forecasted • risk of exceeding a defined storage threshold to a specified risk tolerance level. • Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.

Table D3-2. Potential reservoir operation attributes: These include space used to manage flood flows, type of forecast input used, method to determine magnitude of releases, limits on releases, type of system operation, and type of emergency operation for dam safety. For the FIRO Program, at-site alternative attributes will be assessed first with further consideration of system operation and ESRD as a subsequent task.

		Space used for flood management				Forecast input for forecast-based or forecast-informed alternatives				Magnitude of release					Limits on releases		System operation		ESRD	
Dam	Alt	Single guide curve	u/s credit	Guide curve w/ wetness index	Forecast-based guide curve	FIRO space	Deterministic forecast	Ensemble forecast - processed	Ensemble forecast - full use	Inflow-based release rule	Forecast inflow-based release rule	Elevation-based release rule	Forecast elevation-based release rule	Risk-tolerance based releases	Max rate of change rule	d/s objective flows	Operated as a system	Operated as a system with EFO	Traditional ESRD	Forecast - based ESRD
NBB	FIRO Guide Curve				X	X		X				X	X		X	X	X		X	

OTHER:

- Space used for flood management spans traditional conservation and flood zones
- Drawdown to GC in less than one day.
- Ensemble forecast processed to X% exceedance volume each 6 hr for 1-, 2-, 3-, 5-, 7-day volumes.
- Use 95%, 75%, 50%, 25%, 5% NEP ensemble members to test release decisions.
- Do not decrease releases before the event peak.

		Space used for flood management				Forecast input for forecast-based or forecast-informed alternatives				Magnitude of release					Limits on releases		System operation		ESRD	
Dam	Alt	Single guide curve	u/s credit	Guide curve w/ wetness index	Forecast-based guide curve	FIRO space	Deterministic forecast	Ensemble forecast - processed	Ensemble forecast - full use	Inflow-based release rule	Forecast inflow-based release rule	Elevation-based release rule	Forecast elevation-based release rule	Risk-tolerance based releases	Max rate of change rule	d/s objective flows	Operated as a system	Operated as a system with EFO	Traditional ESRD	Forecast - based ESRD
NBB	FIRO Release Schedule	X				X		X			X				X	X	X		X	

OTHER

- Flood control zone unchanged; additional drawdown into conservation pool in advance of forecast flood event. This space is unbounded, but is limited by the combination of forecast lead-time used in FIRO release schedule and the physical capacity of the spillways.
- Ensemble forecast processed to X% exceedance volume each 6 hr for 1-, 2-, 3-, 5-, 7-day volumes.
- Do not decrease releases before the event peak.

		Space used for flood management				Forecast input for forecast-based or forecast-informed alternatives				Magnitude of release					Limits on releases		System operation		ESRD	
Dam	Alt	Single guide curve	u/s credit	Guide curve w/ wetness index	Forecast-based guide curve	FIRO space	Deterministic forecast	Ensemble forecast - processed	Ensemble forecast - full use	Inflow-based release rule	Forecast inflow-based release rule	Elevation-based release rule	Forecast elevation-based release rule	Risk-tolerance based releases	Max rate of change rule	d/s objective flows	Operated as a system	Operated as a system with EFO	Traditional ESRD	Forecast - based ESRD
NBB	Ensemble Forecast Operations					X			X					X	X	X	X		X	

OTHER

- Top of flood pool would be held at 1956 ft, which is consistent with current operations. The bottom of the flood pool would be undefined however prereleases would rarely draw storage below the crest of the secondary gated spillway (1870 ft) because release capacity is greatly reduced below this elevation.
- Releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool.

Dam	Alt	Space used for flood management				Forecast input for forecast-based or forecast-informed alternatives				Magnitude of release					Limits on releases		System operation		ESRD	
		Single guide curve	u/s credit	Guide curve w/ wetness index	Forecast-based guide curve	FIRO space	Deterministic forecast	Ensemble forecast - processed	Ensemble forecast - full use	Inflow-based release rule	Forecast inflow-based release rule	Elevation-based release rule	Forecast elevation-based release rule	Risk-tolerance based releases	Max rate of change rule	d/s objective flows	Operated as a system	Operated as a system with EFO	Traditional ESRD	Forecast - based ESRD
NBB	Hybrid Ensemble Forecast Operation	X				**X**	X		**X**	X				**X**	**X**	**X**	**X**		**X**	

OTHER

- Flood control: FIRO Space defined as existing water conservation pool.
- Water supply: FIRO Space defined as water conservation pool plus 100 KAF
- Flood releases mandatory above FIRO space
- Flood releases calculated using forecasts in FIRO Space
- FIRO pool releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool.
- May look at a dual objective approach that also evaluates risk of exceeding the defined flood pool encroachment level.

ORO	Prescriptive Forecast_1				X	**X**		X			X				**X**	**X**	**n/a for at-site**		**n/a for at-site**	

OTHER:

- Flood space is used to reduce downstream flows from the forecasted inflow. Release magnitudes are determined from a “table lookup”.
- Use of current variable flood space is the FIRO space. Used for 1/10 and 1/200 bounds. (Previous work.) A variation of ⅕ and 1/50 variable space could also be used to evaluate effectiveness. Target that TOC is set at bottom of variable space before occurrence of SPF, based on 3 day volume

ORO	Iterative Forecast_1					**X**			**X**					**X**	**X**	**X**	**n/a for at-site**		**n/a for at-site**	

OTHER:

- Ideally, a release change increase would be limited to once per day during FIRO space operation.
- This alternative relies on a hazard tolerance curve based on current pool elevation-probability. The operation targets to keep a constant 375k ac-ft of flood storage; balance between flood and water supply. Thus, the goal is to keep the pool at that storage/elevation but releasing up to the “current dam risk” (elevation- probability curve) to balance the storage vs release of flood water.
- Hazard tolerance curve would be set based on pool elevation volume at elevation 890 ft (11 ft below emergency spillway crest). So, the goal would be to not exceed 890 ft at any point during the event.
- Variable flood space is set between 375k ac-ft of flood storage with maximum “pre-release” limit to 750k ac-ft. The variable space is defined by EFO.

Dam	Alt	Space used for flood management				Forecast input for forecast-based or forecast-informed alternatives				Magnitude of release					Limits on releases		System operation		ESRD	
		Single guide curve	**u/s credit**	**Guide curve w/ wetness index**	**Forecast-based guide curve**	**FIRO space**	**Deterministic forecast**	**Ensemble forecast - processed**	**Ensemble forecast - full use**	**Inflow-based release rule**	**Forecast inflow-based release rule**	**Elevation-based release rule**	**Forecast elevation-based release rule**	**Risk-tolerance based releases**	**Max rate of change rule**	**d/s objective flows**	**Operated as a system**	**Operated as a system with EFO**	**Traditional ESRD**	**Forecast - based ESRD**
ORO	Ensemble Forecast Operations					**X**			**X**					**X**	**X**	**X**	**X**		**X**	

OTHER:

- Top of flood pool would be held at 900 ft, which is consistent with current operations. The bottom of the flood pool would be undefined however prereleases would rarely draw storage below the crest of the secondary gated spillway (815 ft) because release capacity is greatly reduced below this elevation.
- Releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool.

Dam	Alt	Single guide curve	u/s credit	Guide curve w/ wetness index	Forecast-based guide curve	FIRO space	Deterministic forecast	Ensemble forecast - processed	Ensemble forecast - full use	Inflow-based release rule	Forecast inflow-based release rule	Elevation-based release rule	Forecast elevation-based release rule	Risk-tolerance based releases	Max rate of change rule	d/s objective flows	Operated as a system	Operated as a system with EFO	Traditional ESRD	Forecast - based ESRD
ORO	Hybrid Ensemble Forecast Operations	X				**X**	X		**X**	X				**X**	**X**	**X**	**X**		**X**	

OTHER:

- Flood Control: FIRO Space defined by full range of existing variable flood control space.
- Water Supply: FIRO Space defined by full range of existing variable flood control space plus 300 KAF
- Flood releases mandatory above FIRO Space
- Flood releases calculated using forecasts in FIRO Space
- FIRO pool releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool.
- May look at a dual objective approach that also evaluates risk of exceeding the defined flood pool encroachment level.

DEFINITIONS

Single guide curve = Uses one guide curve (guide curve can vary according to the time of year)

Upstream storage credit = Storage used for flood management varies based on storage levels at upstream reservoirs

Guide curve based on wetness index = Guide curve selected based on ground saturation in watershed

Forecast-based guide curve = Computed based on inflow forecast

FIRO space = Space where FIRO operation can be used. (Official definition forthcoming.)

Deterministic forecast = Single inflow value forecast

Ensemble forecast – processed = Set of forecasts considering meteorological uncertainty processed to a single inflow value

Ensemble forecast – full use = Set of forecasts considering meteorological uncertainty, each member is considered during release decision making

Inflow-based release rule = Magnitude of release is based on actual or forecast inflow as well as flood control space used **Forecast inflow-based release rule** = Magnitude of release is based on forecast inflow (various forecast durations are considered) **Elevation-based release rule =** Magnitude of release based on pool elevation

Forecast elevation-based release rule = Magnitude of release is based on forecast pool elevation (various forecast durations are considered)

Risk-tolerance based releases = Select release based on tolerable risk of exceeding a given pool elevation, downstream flow, or another threshold

Max rate of change rule = Limits changes in outflow magnitude over specific time durations

d/s objective flows = Identifies magnitude of flow to avoid exceeding at a location downstream

Operated as a system = Multiple reservoirs operated for common objectives

Operated as a system with EFO = Coordinated releases between reservoirs in a system are computed based on ensemble forecast and tolerable risk of not meeting desired objectives

additional ESRD = Releases to protect the integrity of the dam are computed based on current pool elevation and rate of rise. ESRDs are provided for dams with controlled spillways.

Forecast-based ESRD = Releases to protect the integrity of the dam are computed with consideration of forecasted inflow volume. ESRDs are provide for dams with controlled spillways.

Attachment D-4: Alternative proposals – Oroville

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	Oroville
Alternative name:	PrescriptiveForecast_1 (aka "Folsom like")
Shorthand description:	Use best-estimate forecast volumes to inform guide curve (TOC) computation and inflow-based releases
Prepared by:	NP
Date:	7/6/2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases? For example, evacuate flood space as quickly as possible.
- How is space used for flood management determined?
- How are forecasts used as input?
- How is release magnitude determined?
- What limits on releases are included?
- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?

This alternative relies on a guide curve (elevation-based) that is computed based on forecasted inflow volumes. When in the flood control pool, intent is to evacuate the flow in a controlled manner to reduce downstream peak flows (not release inflow). Stepped releases are proposed.

Flood space is used to reduce downstream flows from the forecasted inflow. Release magnitudes are determined from a "table lookup."

Coordinated operations are informed similar to the current paradigm. (Future alternatives will use an ensemble-simulated-informed process.)

Use of current variable flood space is the FIRO space. Used for 1/10 and 1/200 bounds. (Previous work.) A variation of ⅕ and 1/50 variable space could also be used to evaluate effectiveness. This would be screened here first and refined before integrating with other alternatives. Phase 1 is the proof of concept. Move to Phase 2 quickly to refine TOC computation and balance the use of reducing downstream flows and flood storage. (The previous work may use too much of the flood space for common events and may not draw down fast enough in anticipation of large inflows. Anticipate using SPF events to refine the operation.)

Target that TOC is set at bottom of variable space before occurrence of SPF, based on 3-day volume.

2. What are the pros to using this approach?

- Ease in application, operations fit on 11x17. And "tried and true" based on approved Folsom manual.
- Operations use a forecast but are not specific as to where the forecast comes from or how generated. Future improvements to forecast skill will be directly reflected in the performance operation.

3. What are the cons or challenges to using this approach?

- May not maximize the amount of information available on forecast inflow uncertainty.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

- Consistent with approved operation plans (Folsom.)

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

- HEC-ResSim model
- Forecast information (perfect foresight used for development, test with imperfect forecasts.)

6. In months, how long would it take to model and evaluate this approach for the PVA?

- 4 weeks for full system routings

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Describe the framework of the alternative and the parameters that would need to be defined. This work would build off DWR CNA efforts.	Table of TOC as a function of forecast volumes, Table of releases as a function of forecast volumes	1
2	Model framework	Develop proof of concept of the alternative in HEC-ResSim. Proof of concept would be based on work completed for DWR CNA efforts.	Model with selected event simulations. Inflow/outflow hydrographs	1

Phase No.	Phase name	Description	Output	Duration (weeks)
3	Parameterization	Refine alternative to minimize adverse impacts: Compute pool-elevation frequency curves and compare those to a baseline. Is the variable flood space being used too sparingly/too aggressively. Iteratively change TOC and release tables (adjust knobs to fine tune operation) For flood routings, note pool elevation at time of max flood storage (bottom of variable space) for range of events. Water supply analysis - Period of record run for WS reliability focusing on TOC computation. Build off CNA work at this point. Need to assess max flood space achieved for large flood events before peak inflow (pool drawdown hits TOC)	Refined tables from Phase 1	4
4	Finalization	Final simulation of design events and period of record	Completed set of TOC and inflow-based rules	2

Additional studies that would support phase 3 include:

- Routing of design inflow events at top of variable flood space and at bottom of variable flood space. This could establish a range of current use of flood pool to serve as a benchmark. Could be useful for all alternative comparisons.

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	Oroville
Alternative name:	Ensemble Forecast Operations (EFO)
Shorthand description:	FIRO for flood control using ensemble streamflow predictions to inform a risk-based operation
Prepared by:	CW3E
Date:	12 August 2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases?
  - With Ensemble Forecast Operations flood control release decisions are formulated by managing forecasted risk of exceeding a defined storage threshold to a specified risk tolerance level. The storage threshold will be the top of the flood pool; however this may be adjusted in the design process.
  - Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
- How is space used for flood management determined?
  - The top of the flood pool would be held at 900 ft, which is consistent with current operations. The bottom of the flood pool would be undefined however prereleases would rarely draw storage below the crest of the secondary gated spillway (815 ft) because release capacity is greatly reduced below this elevation.
- How are forecasts used as input?
  - Each hydrologic forecast ensemble member is individually routed through a reservoir operations model to simulate reservoir storage levels and downstream flows.
- How is release magnitude determined?
  - Releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool (or lower level if modified in the design process).
  - ESRD
  - Required minimum release
- What limits on releases are included?
  - Rate of change
  - Maximum channel capacity downstream of Oroville (150K cfs)
  - Downstream constraint at Yuba City (180K cfs)

  - Downstream constraint at Feather below Yuba (300K cfs) assuming baseline operations for New Bullards Bar
  - Operational limits on outlet structures
  - Power operations
- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?
  - Yet to be determined, but possibly based on evaluation of flood risk based on as modeled with the hydrologic ensemble forecast.

2. What are the pros to using this approach?

Ensemble Forecast Operations (EFO) fully incorporates forecast uncertainty through simulation of all hydrologic forecast ensemble members with a reservoir operations model. The evaluation of the forecast completed by the model is simple in concept and is easily understood by most people. Through the evaluation of forecasted risk this approach provides a recommended release schedule to an operator and also provides useful forecast metrics for situational awareness and decision support. This methodology is very adaptive to future advancements in forecast skill and reliability. Previous evaluations of this methodology at Lake Mendocino and Prado Dam have demonstrated skillful use of CNRFC ensemble forecasts to manage flood risk and increase water supply.

3. What are the cons or challenges to using this approach?

This approach requires the use of a reservoir operations model to route hydrologic forecast ensemble members and evaluate forecasted risk for recommended release decisions.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

This approach is consistent with the management goals of the reservoir for flood control and water supply, but the methods to achieve these goals differ from traditional guide curve operations that have been used in the past. A water control diagram for this approach could include a risk tolerance curve and a discussion of the evaluation and management of forecasted risk using hydrologic ensemble forecasts, and include ESRD operations, ramping rates, and downstream flow constraints of the Feather River below Oroville Dam, Yuba City, and downstream of the Yuba River confluence.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

Evaluation of the EFO alternative will be completed with the existing Ensemble Forecast Operations (EFO) model that was developed for Lake Mendocino and further refined for Prado Dam. This model will also be used to simulate baseline operations and results will be compared to baseline ResSim simulations for model validation. Perfect forecast operations (PFO) will be developed for initial alternative refinement. When hindcasts become available PFO results will be used for development of a risk tolerance curve and full evaluation of alternatives that incorporate forecast uncertainty. A ResSim model may also be formulated to route EFO releases (defined as a release overrides) to points downstream and allow for direct comparison of other alternatives evaluated by the water resources engineering group.

6. In months, how long would it take to model and evaluate this approach for the PVA?

Approximately 2 months after receipt of hindcasts for development of alternatives for Oroville. Coordinated operations of Oroville and New Bullards Bar reservoirs would require additional **time.**

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Description of modeling approach	1-page document	0.1
2	Model framework	Construct modeling system software. Prepare inputs per simulation plan.	Verified working model prototype with physical representation, WCM rules, and system points.	2
3	Parameterization	Develop and refine model parameters. Tasks 1, 2, and 3.	Functioning model capable of generating informative results	4
4	Finalization	Some iterative refinement of configuration and refinement. Tasks 4 and 5.	Evaluation metrics and documentation.	2

Tasks in support of Phases 3 and 4.

Task No.	Task name	Description	Output
1	EFO Model Verification	EFO model will be parameterized to simulate baseline operations for verification with the baseline HEC-ResSim model.	Reservoir storage levels, downstream flows, and verification statistics.
2	Perfect Forecast Operations	Develop model that uses perfect forecasts (observed hydrology) to make release decisions for scaled 1986 and	Reservoir storage levels and downstream flows
3	EFO Risk Tolerance	Develop risk tolerance curves for exceeding max conservation and/or spillway crest. This will be developed with a daily simulation timestep.	Risk tolerance curve, objective function and optimization results
4	Alternatives simulation	Update model to support hydrologic routing and hourly time step. Simulate alternatives using the identified risk tolerance curve. This may include development of a ResSim model to incorporate EFO releases as overrides.	Reservoir storage levels and downstream flows
5	Post processing	Prepare metrics and figures to summarize model simulation results	Figures and tables
6	Documentation		slides or memo documenting framework and performance

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	Oroville
Alternative name:	Hybrid Ensemble Forecast Operations (EFO)
Shorthand description:	Defines a portion of reservoir pool for FIRO using ensemble streamflow predictions to inform a risk-based operation
Prepared by:	CW3E
Date:	12 August 2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases?
  - With Hybrid EFO the FIRO pool is defined as a portion of existing flood pool and conservation pool.
  - When storage levels are within the FIRO pool, flood control release decisions are formulated by managing forecasted risk of exceeding a defined storage threshold to a specified risk tolerance level. The storage threshold will be the top of the flood pool (900 ft); however this may be adjusted in the design process.
  - Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
- How is space used for flood management determined?
  - 2 possible alternatives:
    - Flood Control: FIRO Space defined by full range of existing variable flood control space.
    - Water Supply: FIRO Space defined by full range of existing variable flood control space plus 300 KAF
  - Flood releases mandatory when storage above FIRO Space
  - Flood releases calculated using the EFO approach when storage is in FIRO Space.
- How are forecasts used as input?
  - Each hydrologic forecast ensemble member is individually routed through a reservoir operations model to simulate reservoir storage levels and downstream flows.
- How is release magnitude determined?
  - FIRO pool releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool.

    - A dual objective approach may be evaluated that additionally evaluates risk of exceeding the defined flood pool encroachment level (top of the FIRO pool).
    - ESRD
    - Required minimum release

- What limits on releases are included?
    - Rate of change
    - Maximum channel capacity downstream of Oroville (150K cfs)
    - Downstream constraint at Yuba City (180K cfs)
    - Downstream constraint at Feather below Yuba (300K cfs) assuming baseline operations for New Bullards Bar
    - Operational limits on outlet structures
    - Power operations

- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?
    - Yet to be determined
    - Evaluation of flood risk in the Feather below Yuba based on evaluation of ensembles.

2. What are the pros to using this approach?

The Hybrid alternative defines a constrained portion of the pool for FIRO, and therefore limits potential impacts to flood control or water supply that could result from bad forecasts. When storage levels are within the defined FIRO pool, release are determined using the Ensemble Forecast Operations (EFO) approach that fully incorporates forecast uncertainty through simulation of all hydrologic forecast ensemble members with a reservoir operations model. The evaluation of the forecast completed by the model is simple in concept and is easily understood by most people. Through the evaluation of forecasted risk this approach provides a recommended release to an operator and also useful forecast metrics for situational awareness and decision support. This methodology is very adaptive to future advancements in forecast skill and reliability. Previous evaluations of this methodology at Lake Mendocino and Prado Dam have demonstrated skillful use of CNRFC ensemble forecasts to manage flood risk and increase water supply.

3. What are the cons or challenges to using this approach?

This approach requires the use of a reservoir operations model to route hydrologic forecast ensemble members and evaluate forecasted risk for recommended release decisions.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

The Hybrid alternative provides a storage guide curve to define the FIRO pool, and when storage levels are above or below this pool, operation will be consistent with guide curve type operations. This approach is consistent with the management goals of the reservoir for flood control and water supply, but the methods to achieve these goals differ from traditional guide curve operations that have been used in the past. A water control diagram for this approach could include the defined FIRO space and a description of the evaluation and management of forecasted risk using hydrologic ensemble forecasts when storage is within the FIRO space. A water control diagram would also include ESRD operations, ramping rates, and downstream flow constraints of the Feather River below Oroville Dam, Yuba City, and downstream of the Yuba River confluence.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

Evaluation of the Hybrid alternative will be completed with the existing Ensemble Forecast Operations (EFO) model that was developed for Lake Mendocino and further refined for Prado Dam. This model will also be used to simulate baseline operations and results will be compared to baseline ResSim simulations for model validation. Perfect forecast operations (PFO) will be developed for initial alternative refinement. When hindcasts become available PFO results will be used for development of a risk tolerance curve and full evaluation of alternatives that incorporate forecast uncertainty. A ResSim model may also be formulated to route EFO releases (defined as a release overrides) to points downstream and allow for direct comparison of other alternatives evaluated by the water resources engineering group.

6. In months, how long would it take to model and evaluate this approach for the PVA?

Approximately 2 months after receipt of hindcasts for development of alternatives for Oroville. Coordinated operations of Oroville and New Bullards Bar reservoirs would require additional time.

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Description of modeling approach	1-page document	0.1
2	Model framework	Construct modeling system software. Prepare inputs per simulation plan. Leverages work from ORO EFO model.	Verified working model prototype with physical representation, WCM rules, and system points.	1
3	Parameterization	Develop and refine model parameters. Tasks 1, 2, and 3. Leverages work from ORO EFO model.	Functioning model capable of generating informative results	2
4	Finalization	Some iterative	Evaluation metrics	2

Phase No.	Phase name	Description	Output	Duration (weeks)
		refinement of configuration and refinement. Tasks 4 and 5.	and documentation.	

Tasks in support of Phases 3 and 4.

Task No.	Task name	Description	Output
1	EFO Model Verification	EFO model will be parameterized to simulate baseline operations for verification with the baseline HEC-ResSim model.	Reservoir storage levels, downstream flows, and verification statistics.
2	Perfect Forecast Operations	Develop model that uses perfect forecasts (observed hydrology) to make release decisions for scaled 1986 and 1997 events	Reservoir storage levels and downstream flows
3	EFO Risk Tolerance	Develop risk tolerance curves for exceeding max conservation and/or spillway crest. This will be developed with a daily simulation timestep.	Risk tolerance curve, objective function and optimization results
4	Alternatives simulation	Update model to support hydrologic routing and hourly time step. Simulate alternatives using the identified risk tolerance curve. This may include development of a ResSim model to incorporate EFO releases as overrides.	Reservoir storage levels and downstream flows
5	Post processing	Prepare metrics and figures to summarize model simulation results	Figures and tables
6	Documentation		slides or memo documenting framework and performance

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	Oroville
Alternative name:	IterativeForecast_1 (aka Lake Mendocino like or EFO)
Shorthand description:	Use ensemble members to determine a release for the reservoir based on an iterative process to maintain same dam risk profile as current operations. (Details being developed.)
Prepared by:	NP
Date:	7/6/2021

Provide specific descriptions below for the subject reservoir.

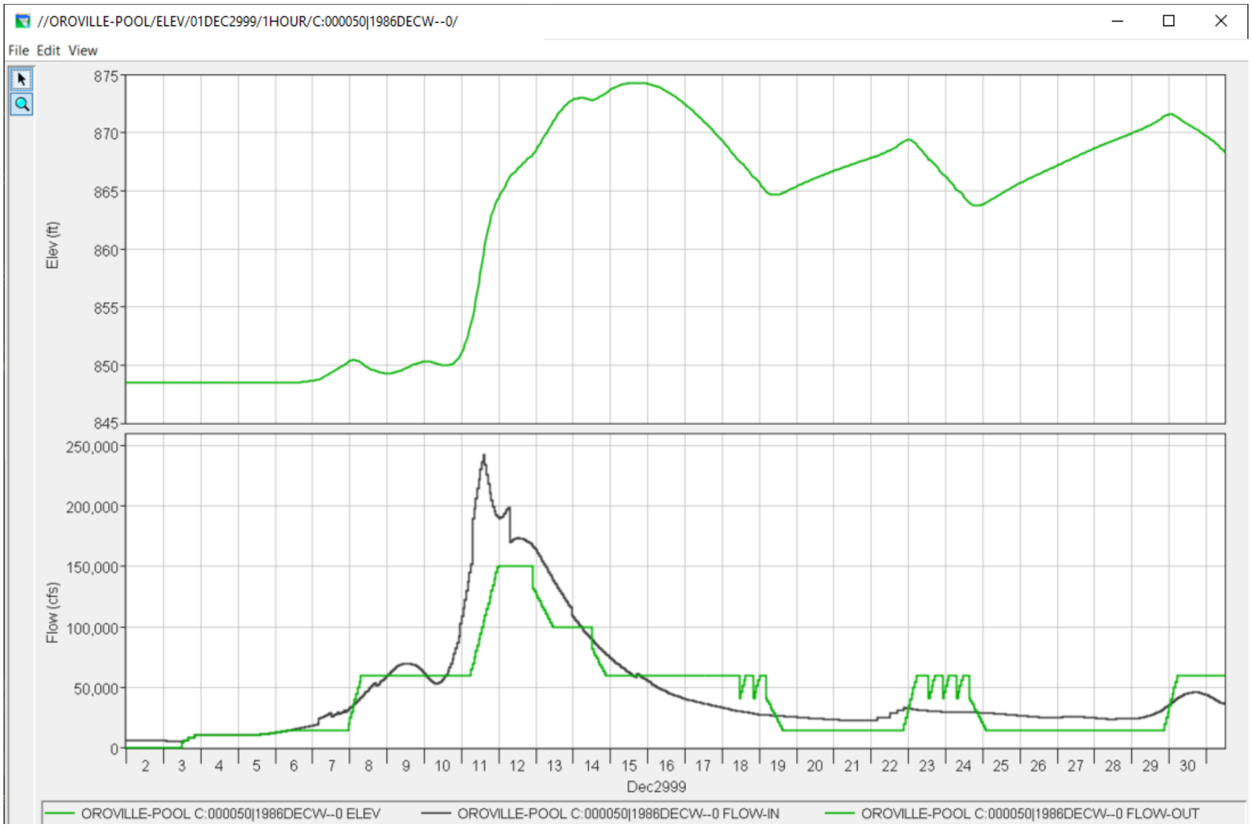
1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases? For example, evacuate flood space as quickly as possible.
- How is space used for flood management determined?
- How are forecasts used as input?
- How is release magnitude determined?
- What limits on releases are included?
- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?

Goal of this operation is to identify a "minimally-changed release" through the flood event. This release (or release pattern) is identified as the maximum release that is needed to balance the use of the flood pool but not result in adverse dam safety concerns. So, the operation seeks to answer the question, what is the release that I need to make through this event to safely pass the event. Use the forecast information, and the uncertainty of that, to identify this release.

Ideally, a release change increase would be limited to once per day during FIRO space operation.

The figure below shows the inflow and outflow, as well as pool elevation, for an event routing through Oroville Dam. This operation would conceivably result in the maximum release for an event such as this at 100k cfs and greater use of the flood pool storage.



(1986 50yr)

This alternative relies on a hazard tolerance curve based on current pool elevation-probability. (More details to be developed.) The operation targets to keep a constant 375k ac-ft of flood storage; balance between flood and water supply. Thus, the goal is to keep the pool at that storage/elevation but releasing up to the "current dam risk" (elevation-probability curve) to balance the storage vs release of flood water.

Hazard tolerance curve would be set based on pool elevation volume at elevation 890 ft (11 ft below emergency spillway crest). So, the goal would be to not exceed 890 ft at any point during the event. Initial hazard curve example:

% Chance exceedence	Future days
0	1
0	2
1	3
5	5
10	7

Variable flood space is set between 375k ac-ft of flood storage with maximum "pre-release" limit to 750k ac-ft. The variable space is defined by EFO.

Release magnitudes are determined from an iterative approach based on ensemble simulations.

Coordinated operations are informed similar to the current paradigm. (Future alternatives will use an ensemble-simulated-informed process.)

2. What are the pros to using this approach?

- Operations use full range of forecast inflows. Still sorting through the appropriate guide curve.

3. What are the cons or challenges to using this approach?

- Iterative approach may be harder to explain to stakeholders.
- May result in pre-releases greater than inflow, which may cause additional concerns to stakeholders.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

- Uses forecast information but deviates from having a defined top of conservation.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

- HEC-ResSim model, currently available and configured with WCM rules.
- Ensemble forecasts, GEFs v10 hindcasts are available and configured in HEC-ResSim model. Will need design events representing annual exceedence probabilities rarer than those historical events captured in the hindcast period. Likely to need p=0.005 (200-yr) and p=0.002 (500-yr) design event, both at site and for the system.
- Could use ensemble simulations but go through and iteratively determine release schedule with external computations or scripts.
- Need to know acceptable tolerances for exceedence thresholds at different time horizons.

6. In months, how long would it take to model and evaluate this approach for the PVA?

8 weeks for full system routings but depends on simulations needed.

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Further articulate the components of this alternative and how it would function in real-time and simulated historical events. Select an event as prototype Anticipate a pool elevation hazard curve and forecast duration.	Written description of the alternative and the parameters that would need to be defined.	2
2	Model framework	Identify to the extent this alternative could be formulated/ developed using HEC-ResSim. Identify what external processing would be needed and develop a prototype of that. Complete initial sensitivity events and runs to define the range of parameters that could be useful.	Proof of concept model and demonstrated routings.	2
3	Parameterization	Define the hazard curve and "look forward" periods.	Working model w/post processing scripts as needed.	6
4	Finalization	Simulate design events and POR.		2

For completion of phase 2 and 3:

- Simulate each ensemble member as a "true event" for large event. Use current operations. This helps to understand the variation in peak releases for the event across ensemble members.
- Assess current event operations to find where maximum channel capacity was used but not maximum flood storage. (See above.)
- Complete bookend analysis of achievable performance: Remove current variable space and set TOC at 375k ac-ft of flood storage. Repeat for TOC at 750k ac-ft. Report elevation-probability for both. From these runs, understand how aggressive the use of the current flood pool would be.

Attachment D-5: Alternative proposals – New Bullards Bar

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	New Bullards Bar
Alternative name:	FIRO Guide Curve
Shorthand description:	FIRO for flood control and water supply using a forecast-based guide curve to specify drawdown in advance of flood events and conditional storage of water in the gross pool when forecast is dry
Prepared by:	YWA, MBK Engineers
Date:	1 July 2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases?
  - Evacuate volume above FIRO guide curve over less than one day time window
  - Increases storage utilization in the reservoir to mitigate high downstream flood releases
- How is space used for flood management determined?
  - Space used for flood management spans traditional Conservation and Flood Control zones; actual bounds to be informed by study to examine required starting storages needed to pass target large events
- How are forecasts used as input?
  - Spread of ensemble forecasts are summarized as X% exceedance volume each 6 hours for 1-, 2-, 3-, 5-, 7-day volumes. These volumes are used with drawdown diagram to determine the required FIRO GC storage.
- How is release magnitude determined?
  - FIRO GC drawdown release
  - ESRD
  - Required minimum release
- What limits on releases are included?
  - Rate of change
  - Downstream constraint at Marysville
  - Downstream constraint at Feather below Yuba
  - Do not decrease releases before the event peak
  - Operational limits on outlet structures
  - Power operations

- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?
  - Balance reservoir percent encroachment OR
  - Forecasted percent encroachment OR
  - Forecasted watershed runoff volumes OR
  - Variable FIRO downstream target

2. What are the pros to using this approach?

This is a highly adaptive approach that accounts for changing forecast dynamics. FIRO space defined in this way explicitly provides for both water supply and flood control benefits. This approach can be adapted to any combination of forecast volume durations, desired lead times, and exceedance probabilities. Releases defined using the FIRO GC drawdown are simple in concept.

3. What are the cons or challenges to using this approach?

This approach requires extremely high confidence in forecasts at medium to longer lead times. This guide curve spans the traditional flood control zone and is not meant to require storage reallocation, but there will likely be sensitivity to conditionally storing water high in the pool during winter months, even with no event forecast. Care must be taken to avoid incurring additional risk of overtopping at the reservoir, though initial studies indicate, with adequate forecast lead time, this can be achieved.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

The FIRO GC is much like traditional guide curve operations specifying to evacuate the space above top of conservation as quickly as possible but is novel in the expansive definition of FIRO space. Definition of the FIRO space could also be communicated in terms of a "schedule space" for flood or water supply operations.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

Perfect forecast simulations will be evaluated to develop the initial guide curve lookup diagrams, but alternative should be refined using ensemble forecast data. MBK Yuba-Feather reservoir operations model can be leveraged to perform this initial work. Existing WCM rules will be assumed for Oroville operations and downstream control flows.

6. In months, how long would it take to model and evaluate this approach for the PVA?

1-2 months after receipt of updated forecast ensemble hydrology for analysis of appropriate forecast triggers, if isolated from Oroville and downstream performance.

7. Please break down the work execution in phases as shown in the table below.

Phase No.	Phase name	Description	Output	Duration (weeks)

1	Concept design	Develop document outlining concept	1-2 page concept description document	1
2	Model framework	Develop FIRO GC diagrams based on NBB inflow, Yuba watershed runoff and YF total runoff forecasts	Reservoir operations model with diagrams dictating FIRO GC lookup	2
3	Parameterization	Simulate operations for CVHS 1956, 1965, 1986 and 1997 scaled events with various FIRO GC alternatives and operations parameters; experiment with integration of ensembles during event simulations to stress test release decisions	regulated flow, peak elevation frequency curves; ensemble performance measures	4
4	Finalization	Simulate operations for CVHS 1956, 1965, 1986 and 1997 scaled events with selected FIRO GC alternatives with tuned operations parameters; model documentation	Regulated flow, peak elevation frequency curves; memorandum documenting performance	1

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	New Bullards Bar
Alternative name:	FIRO Release Schedule
Shorthand description:	FIRO for flood control using a forecast-based release schedule to specify drawdown in advance of flood events
Prepared by:	YWA, MBK Engineers
Date:	1 July, 2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases?
  - Evacuate conservation space to absorb forecast event, reducing peak releases and peak storage at NBB
- How is space used for flood management determined?
  - Flood Control zone is unchanged; additional drawdown into the conservation pool is allowed in advance of forecast flood event. This space is unbounded, but is limited by the combination of forecast lead-time used in FIRO release schedule and the physical capacity of the primary and secondary spillways
- How are forecasts used as input?
  - Spread of ensemble forecasts are summarized as X% exceedance volume each 6 hours for 1-, 2-, 3-, 5-, 7-day volumes. These volumes are compared to triggers for forecast-based releases in the FIRO release schedule.
- How is release magnitude determined?
  - FIRO release schedule
  - ESRD
  - Required minimum release
  - Regular drawdown release (top of conservation as guide curve)
- What limits on releases are included?
  - Rate of change
  - Downstream constraint at Marysville
  - Downstream constraint at Feather below Yuba
  - Do not decrease releases before the event peak
  - Operational limits on outlet structures
  - Power operations
- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?

  - Balance reservoir percent encroachment OR
  - Forecasted percent encroachment OR
  - Forecasted watershed runoff volumes OR
  - Variable FIRO downstream target

2. What are the pros to using this approach?

This approach is simple to implement, provides opportunity to integrate thresholds representing physical characteristics of the downstream channel, or evacuation flows and has been implemented at other reservoirs, like Folsom.

3. What are the cons or challenges to using this approach?

Typically, schedule is sized for addressing FRM and may not explicitly target water supply benefits. This method requires a long lead time to initiate releases and the stepped release pattern will almost always be limited by total NBB release capacity at the onset of the flood wave. This strategy may increase incidence of shutting down Colgate power operations in the winter.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

This approach is very similar to many existing inflow-based release schedules in USACE WCMs, and closely matches the Folsom "Table A" forecast-based release schedule.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

Key flow thresholds have been identified from the slow-rise flood plan and physical characteristics of the Yuba River channel, but other schedule flows can be included based on findings of WRE group in stakeholder consultation. Perfect forecast simulations can be evaluated to develop operation, but alternative should be refined using ensemble forecast data. MBK Yuba-Feather reservoir operations model can be leveraged to perform this initial work. Existing WCM rules will be assumed for Oroville operations and downstream control flows.

6. In months, how long would it take to model and evaluate this approach for the PVA?

1-2 months after receipt of updated forecast ensemble hydrology for analysis of appropriate forecast triggers, if isolated from Oroville and downstream performance.

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Develop document outlining concept	1-2 page concept description document	1
2	Model framework	Develop model to	reservoir operations	completed

		implement conceptual design	model with conceptual framework parameterized and implemented	
3	Parameterization	Develop FIRO RS table based on physical and regulatory characteristics of Yuba channel downstream of NBB	Tuned operational parameters and reservoir operations model results (regulated flow, peak elevation frequency curves) to justify their selection	3
4	Finalization	Simulate operations for CVHS 1956, 1965, 1986 and 1997 scaled events with various FIRO GC alternatives and tuned operations parameters; model documentation	Regulated flow, peak elevation frequency curves; memorandum documenting performance	1

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	New Bullards Bar
Alternative name:	Ensemble Forecast Operations (EFO)
Shorthand description:	FIRO for flood control using ensemble streamflow predictions to inform a risk-based operation
Prepared by:	CW3E
Date:	12 August, 2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases?
  - With Ensemble Forecast Operations flood control release decisions are formulated by managing forecasted risk of exceeding a defined storage threshold to a specified risk tolerance level. The storage threshold will be the top of the flood pool, however this may be adjusted in the design process.
  - Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
- How is space used for flood management determined?
  - The top of the flood pool would be held at 1956 ft, which is consistent with current operations. The bottom of the flood pool would be undefined however prereleases would rarely draw storage below the crest of the secondary gated spillway (1870 ft) because release capacity is greatly reduced below this elevation.
- How are forecasts used as input?
  - Each hydrologic forecast ensemble member is individually routed through a reservoir operations model to simulate reservoir storage levels and downstream flows.
- How is release magnitude determined?
  - Releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool (or lower level if modified in the design process).
  - ESRD
  - Required minimum release
- What limits on releases are included?
  - Rate of change
  - North Yuba River channel capacity
  - Downstream constraint at Marysville (180K cfs)

    - Downstream constraint at Feather below Yuba (300K cfs) assuming baseline operations for Oroville
    - Operational limits on outlet structures
- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?
    - Yet to be determined, but possibly based on evaluation of flood risk based on as modeled with the hydrologic ensemble forecast.

2. What are the pros to using this approach?

Ensemble Forecast Operations (EFO) fully incorporates forecast uncertainty through simulation of all hydrologic forecast ensemble members with a reservoir operations model. The evaluation of the forecast completed by the model is simple in concept and is easily understood by most people. Through the evaluation of forecasted risk this approach provides a recommended release schedule to an operator and also provides useful forecast metrics for situational awareness and decision support. This methodology is very adaptive to future advancements in forecast skill and reliability. Previous evaluations of this methodology at Lake Mendocino and Prado Dam have demonstrated skillful use of CNRFC ensemble forecasts to manage flood risk and increase water supply.

3. What are the cons or challenges to using this approach?

This approach requires the use of a reservoir operations model to route hydrologic forecast ensemble members and evaluate forecasted risk for recommended release decisions.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

This approach is consistent with the management goals of the reservoir for flood control and water supply, but the methods to achieve these goals differ from traditional guide curve operations that have been used in the past. A water control diagram for this approach could include a risk tolerance curve and a discussion of the evaluation and management of forecasted risk using hydrologic ensemble forecasts, and include ESRD operations, ramping rates, and downstream flow constraints in the North Yuba River and the Yuba River at Marysville.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

Evaluation of the EFO alternative will be completed with the existing Ensemble Forecast Operations (EFO) model that was developed for Lake Mendocino and further refined for Prado Dam. This model will also be used to simulate baseline operations and results will be compared to baseline ResSim simulations for model validation. Perfect forecast operations (PFO) will be developed for initial alternative refinement. When hindcasts become available PFO results will be used for development of a risk tolerance curve and full evaluation of alternatives that incorporate forecast uncertainty. A ResSim model may also be formulated to route EFO releases (defined as a release overrides) to points downstream and allow for direct comparison of other alternatives evaluated by the water resources engineering group.

6. In months, how long would it take to model and evaluate this approach for the PVA?

Approximately 2 months after receipt of hindcasts for development of alternatives for New Bullards Bar. Coordinated operations of Oroville and New Bullards Bar reservoirs would require additional time.

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Description of modeling approach	1-page document	0.1
2	Model framework	Construct modeling system software. Prepare inputs per simulation plan.	Verified working model prototype with physical representation, WCM rules, and system points.	2
3	Parameterization	Develop and refine model parameters. Tasks 1, 2, and 3.	Functioning model capable of generating informative results	4
4	Finalization	Some iterative refinement of configuration and refinement. Tasks 4 and 5.	Evaluation metrics and documentation.	2

Tasks in support of Phases 3 and 4.

Task No.	Task name	Description	Output
1	EFO Model Verification	EFO model will be parameterized to simulate baseline operations for verification with the baseline HEC-ResSim model.	Reservoir storage levels, downstream flows, and verification statistics.
2	Perfect Forecast Operations	Develop model that uses perfect forecasts (observed hydrology) to make release decisions for scaled 1986 and 1997 events	Reservoir storage levels and downstream flows
3	EFO Risk Tolerance	Develop risk tolerance curves for exceeding max conservation and/or spillway crest. This will be developed with a daily simulation timestep.	Risk tolerance curve, objective function and optimization results

Task No.	Task name	Description	Output
4	Alternatives simulation	Update model to support hydrologic routing and hourly time step. Simulate alternatives using the identified risk tolerance curve. This may include development of a ResSim model to incorporate EFO releases as overrides.	Reservoir storage levels and downstream flows
5	Post processing	Prepare metrics and figures to summarize model simulation results	Figures and tables
6	Documentation		slides or memo documenting framework and performance

Yuba-Feather FIRO Program – Alternative development proposal

Reservoir:	New Bullards Bar
Alternative name:	Hybrid Ensemble Forecast Operations (EFO)
Shorthand description:	Defines a portion of reservoir pool for FIRO using ensemble streamflow predictions to inform a risk-based operation
Prepared by:	CW3E
Date:	12 August, 2021

Provide specific descriptions below for the subject reservoir.

1. What are the proposed alternative attributes? Include description of the following.

- Operation principle: What is the general approach to use of storage and releases?
  - With Hybrid EFO the FIRO pool is defined as a portion of existing flood pool and conservation pool.
  - When storage levels are within the FIRO pool, flood control release decisions are formulated by managing forecasted risk of exceeding a defined storage threshold to a specified risk tolerance level. The storage threshold will be the top of the flood pool (1956 ft), however this may be adjusted in the design process.
  - Releases made in advance of forecasted flood events create storage space in the reservoir to accommodate high inflows.
- How is space used for flood management determined?
  - 2 possible alternatives:
    - Flood Control: FIRO Space defined as existing water conservation pool.
    - Water Supply: FIRO Space defined as water conservation pool plus 100 KAF
  - Flood releases mandatory when storage above FIRO Space
  - Flood releases calculated using the EFO approach when storage is in FIRO Space.
- How are forecasts used as input?
  - Each hydrologic forecast ensemble member is individually routed through a reservoir operations model to simulate reservoir storage levels and downstream flows.
- How is release magnitude determined?
  - FIRO pool releases are calculated to mitigate forecasted risk of exceeding the top of the flood pool (or lower level if modified in the design process).
  - A dual objective approach may be evaluated that additionally evaluates risk of exceeding the defined flood pool encroachment level (top of the FIRO pool).

    - ESRD
    - Required minimum release

- What limits on releases are included?
    - Rate of change
    - Downstream constraint at Marysville (180K cfs)
    - Downstream constraint at Feather below Yuba (300K cfs) assuming baseline operations for Oroville
    - Operational limits on outlet structures
    - Power operations

- Optional: How are coordinated releases between Oroville and New Bullards Bar determined?
    - Yet to be determined, but possibly based on evaluation of flood risk based on as modeled with the hydrologic ensemble forecast.

2. What are the pros to using this approach?

The Hybrid alternative defines a constrained portion of the pool for FIRO, and therefore limits potential impacts to flood control or water supply that could result from bad forecasts. When storage levels are within the defined FIRO pool, release are determined using the Ensemble Forecast Operations (EFO) approach that fully incorporates forecast uncertainty through simulation of all hydrologic forecast ensemble members with a reservoir operations model. The evaluation of the forecast completed by the model is simple in concept and is easily understood by most people. Through the evaluation of forecasted risk this approach provides a recommended release to an operator and also useful forecast metrics for situational awareness and decision support. This methodology is very adaptive to future advancements in forecast skill and reliability. Previous evaluations of this methodology at Lake Mendocino and Prado Dam have demonstrated skillful use of CNRFC ensemble forecasts to manage flood risk and increase water supply.

3. What are the cons or challenges to using this approach?

This approach requires the use of a reservoir operations model to route hydrologic forecast ensemble members and evaluate forecasted risk for recommended release decisions.

4. How does the approach relate to existing USACE practices, guidance, and/or policy?

The Hybrid alternative provides a storage guide curve to define the FIRO pool, and when storage levels are above or below this pool, operation will be consistent with guide curve type operations. This approach is consistent with the management goals of the reservoir for flood control and water supply, but the methods to achieve these goals differ from traditional guide curve operations that have been used in the past. A water control diagram for this approach could include the defined FIRO space and a description of the evaluation and management of forecasted risk using hydrologic ensemble forecasts when storage is within the FIRO space. A water control diagram would also include ESRD operations, ramping rates, and downstream flow constraints in the North Yuba River and the Yuba River at Marysville.

5. What data, information, and model/tools would be used for development and evaluation? Indicate availability of each.

Evaluation of the Hybrid alternative will be completed with the existing Ensemble Forecast Operations (EFO) model that was developed for Lake Mendocino and further refined for Prado Dam. This model will also be used to simulate baseline operations and results will be compared to baseline ResSim simulations for model validation. Perfect forecast operations (PFO) will be developed for initial alternative refinement. When hindcasts become available PFO results will be used for development of a risk tolerance curve and full evaluation of alternatives that incorporate forecast uncertainty. A ResSim model may also be formulated to route EFO releases (defined as a release overrides) to points downstream and allow for direct comparison of other alternatives evaluated by the water resources engineering group.

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Approximately 2 months after receipt of hindcasts for development of alternatives for New Bullards Bar. Coordinated operations of Oroville and New Bullards Bar reservoirs would require additional time.

7. Please break down the work execution in phases. Under Phase 1, what information can we gain to help decide whether to proceed to subsequent phases?

Phase No.	Phase name	Description	Output	Duration (weeks)
1	Concept design	Description of modeling approach	1-page document	0.1
2	Model framework	Construct modeling system software. Prepare inputs per simulation plan. Leverages work from NBB EFO model.	Verified working model prototype with physical representation, WCM rules, and system points.	1
3	Parameterization	Develop and refine model parameters. Tasks 1, 2, and 3. Leverages work from NBB EFO model.	Functioning model capable of generating informative results	2
4	Finalization	Some iterative refinement of configuration and refinement. Tasks 4 and 5.	Evaluation metrics and documentation.	2

Tasks in support of Phases 3 and 4.

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3	EFO Risk Tolerance	Develop risk tolerance curves for exceeding max conservation and/or spillway crest. This will be developed with a daily simulation timestep.	Risk tolerance curve, objective function and optimization results
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5	Post processing	Prepare metrics and figures to summarize model simulation results	Figures and tables
6	Documentation		slides or memo documenting framework and performance

Appendix E—NBB At-Site Alternative FIRO Guide Curve (Section 4)

MEMORANDUM

DATE: November 11, 2021

PREPARED BY: Sophie Danielsen

REVIEWED BY: Carly Narlesky, P.E.

SUBJECT: Preliminary Viability Assessment of At-Site Operations: Developing a FIRO Guide Curve for New Bullards Bar

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E.1 Purpose

The purpose of this memorandum is to outline the development of a forecast informed reservoir operations (FIRO) at-site operation with a candidate guide curve to be considered for the New Bullards Bar (NBB) reservoir water control manual (WCM) update. This was undertaken as a task in the FIRO Preliminary Viability Assessment (PVA) under the Water Resources Engineering (WRE) team at-site analysis.

A guide curve can be used by the dam operator as a tool to specify the reservoir drawdown ahead of a forecast flood event; evacuation of the flood and/or conservation space is defined by the guide curve only when necessary as indicated by forecasts. Only Folsom Reservoir has formally incorporated using a forecast-based top of conservation in this way in the past. For NBB, the current WCM instructs the operator to maintain 170 thousand acre-feet (TAF) flood reserve in the reservoir during the winter flood season. The FIRO guide curve will traverse a defined FIRO space in the reservoir. In this proposed FIRO alternative, the flood space would be emptied only when a large event is forecast.

Through coordination with FIRO program partners, Yuba Water Agency (YWA) has expressed interest in defining a flexible FIRO space that may span portions of the conservation and flood pools in order to provide both flood risk management (FRM) and water supply benefits. Drawdown in advance of flood events is aimed as a method to augment flood space by reclaiming lost Marysville Dam flood space in the Yuba Watershed, which additionally is a joint goal of WCM updates for Oroville and NBB. Notably with this proposed operation is that the reservoir can be drawn down into the conservation space when an event is forecast, as is shown in Figure E-1, and thus farther than with current operations, to create additional protection. The proposed guide curve enhances water supply operations by specifying conditional storage in the flood pool. As such, an updated guide curve drawdown paradigm can result in both flood management and water supply benefits.

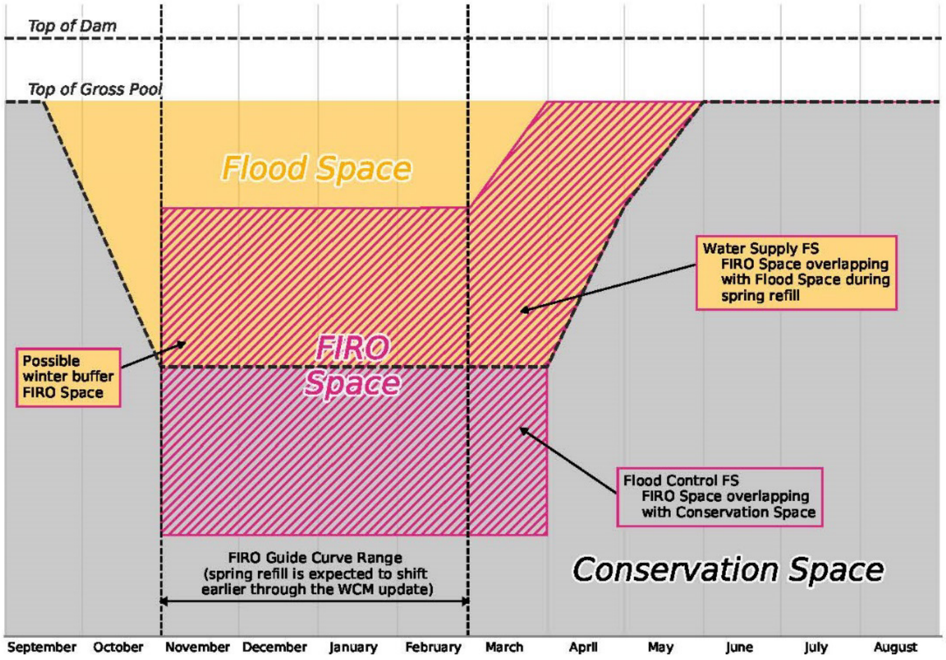


Figure E-1. *Conceptual Illustration of FIRO Space*

A range of goals were set to guide the development of the FIRO at-site operation to adhere to pre- existing operational constraints and incorporates the proposed ARC spillway. These goals include developing an operation that:

- allows drawdown with a release pattern that only increases during the onset of the flood event
- is compatible with other system constraints (such as Yuba downstream flow limits and joint constraints on the Feather mainstem)
- can seamlessly transition from flood pool to conservation zone
- prioritizes flood operations but also supports water supply benefits
- has a framework that can adapt to future improvements in forecast abilities
- enhances functional flood space to make up for lost Marysville Dam storage

E.2 Methods for Developing the Guide Curve Diagram

NBB operations were simulated using the MBK reservoir operations model configured in Python. This model represents the Yuba-Feather watershed with boundary conditions and hydrologic inputs adopted from the Central Valley Hydrology Study (CVHS) for flood events in water years 1956, 1965, 1986, and 1997. The method detailed herein for designing the updated NBB guide curve follows a similar paradigm to that of Folsom reservoir's multiple forecast duration forecast-based top of conservation lookup as detailed in the Folsom Flood Control Diagram (FCD) (USACE-SPK, 2019). One of the most significant differences between developing the Folsom FCD compared to this new NBB guide curve is that the Folsom variable top of conservation was defined within a range bounded by the existing 400/600 TAF variable winter flood space, whereas the implementation of the NBB guide curve required defining the top and bottom of a new FIRO space, to be layered over the existing seasonal top of conservation.

The method for obtaining a guide curve from the lookup starts with reading the corresponding storage value for a timestep in the NBB reservoir inflow forecast for each forecast duration. Then the minimum of the correlated storage values for each forecast duration determines the guide curve storage at that timestep. This is repeated for all timesteps and results in a continuous guide curve timeseries.

The guide curve lookup can be altered by changing any of the parameters that correspond to the coordinates (A) through (E) on Figure E-2. Part of the purpose of this project is to determine the variation or variations of those parameters that would result in the most appropriate drawdown pattern for NBB, or the "candidate guide curve". This was accomplished by evaluating how different guide curve designs performed for an extensive range of simulated historical flood events. Each parameter was varied in isolation to observe the impacts of every parameter on at-site FRM performance.

Description of each guide curve coordinate:

- **A =** minimum inflow forecast volume (this parameter is always set to zero)
- **B =** top of FIRO space bound
- **C =** drawdown trigger (minimum inflow forecast volume that triggers start of drawdown)
- **E =** bottom of FIRO space bound
- **D_{24}, D_{48}, D_{72}, D_{96}, D_{120}, D_{168} =** inflow volume at the bottom of FIRO space for the shortest (D_{24}) to longest (D_{168}) forecast durations

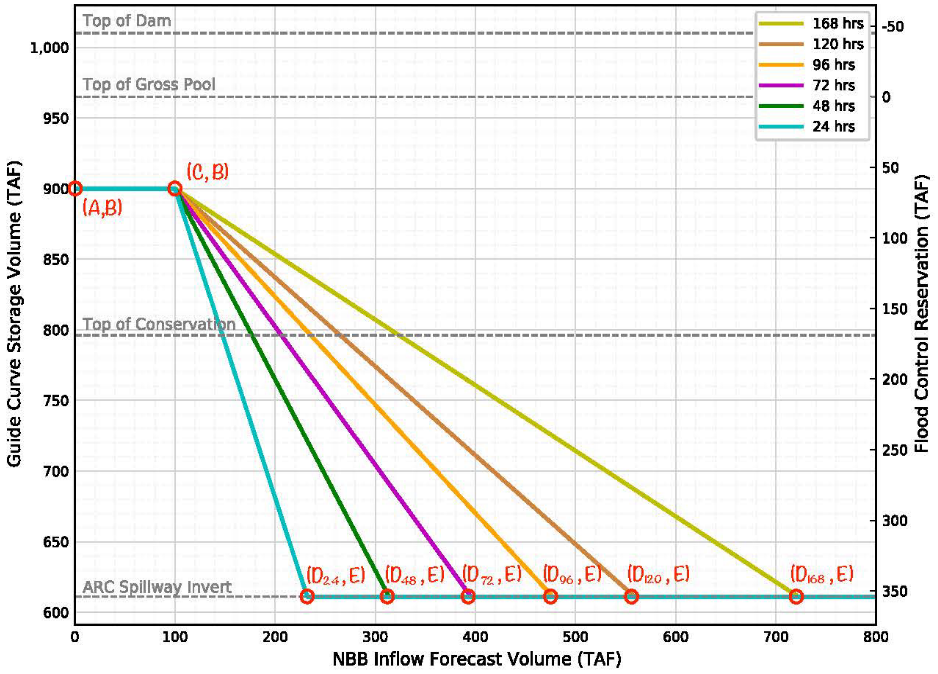


Figure E-2. *NBB Guide Curve Lookup with Input Parameter Coordinates*

E.3 Release Computation

The algorithm for the release pattern was constructed to simultaneously match the drawdown of the guide curve and follow reasonable operating patterns leading up to a flood event. These operating patterns include:

- steadily increasing releases during onset of the event (not altering between increasing and decreasing releases) apart from changes due to physical release capacity constraints or down- stream flow constraints,
- changing releases with a time interval that is consistent with expected gate change capability of the ARC spillway gate house and respecting the WCM rate of increase limitation, minimizing outflow oscillations, and
- respecting more imminent constraints such as the maximum release capacity of NBB's existing outlets and proposed ARC spillway, emergency spillway release diagram (ESRD) rules, and downstream flow constraints.

E.4 Methods for Evaluating the Alternative Performance

E.4.1 Developing the "Candidate Guide Curve"

Preliminary results based on models that were run with perfect forecasts were used as an indication of the sensitivity of performance to each of the guide curve parameters indicated in Figure E-2. Here, performance is measured as change in peak elevation and peak outflow at New Bullards Bar.

E.4.2 Max Release Capacity Limitations

Reservoir drawdown ahead of flood events can be restricted by the maximum physical release capacity due to the pressure head of the water in the reservoir. For larger events, changes in drawdown trigger (Figure E-2 coordinate C) and inflow volume at the bottom of FIRO space (coordinates D24 through D168) did not result in significant changes to performance. Insensitivity to guide curve parameters is due to maximum release capacity limiting drawdown ahead of an event when the guide curve bottom of FIRO space (coordinate E) is set low in the pool. In the large events tested, where release capacity was the determining factor for drawdown capability, storage diverged from the guide curve early in the drawdown operation. This resulted in peak flow and peak elevation reaching similar magnitudes regardless of how most of the parameters were changed.

E.4.3 FIRO Space Bounds

Part of this project includes defining the allowable bounds of the FIRO space. In order to meet FRM and water supply objectives, the FIRO space was allowed to span portions of the flood pool and conservation space. For preliminary testing, the FIRO space bounds were set as the entire range between the top of gross pool and the atmospheric river control (ARC) spillway invert. From this, it was clear that even for large events, minimum drawdown elevation never approached the bottom of FIRO space at the ARC spillway invert, as the example in Figure E-3 demonstrates. The bottom of FIRO space parameter was changed to better represent the actual bottom of drawdown. Instead of setting the bottom of FIRO space at the ARC spillway invert, it was set to a guide curve storage volume of 700 TAF. Comparisons between the two bottom of

FIRO space bounds indicated that little to no change in performance occurred with a bottom if FIRO space set higher in the pool.

It is important to note that drawdown never reached close to the bottom of FIRO space at the ARC spillway invert for a 7-day forecast, which was the longest forecast duration used for the simulation. This is because the release capacity decreases drastically leading up to the event, and with a 7-day forecast there is not enough lead time to draw down towards the ARC spillway invert. However, with a longer forecast it might be possible to increase drawdown ability. The bottom of drawdown seen in this modeling is therefore not an absolute minimum, but rather a minimum for the boundaries of the current simulation.

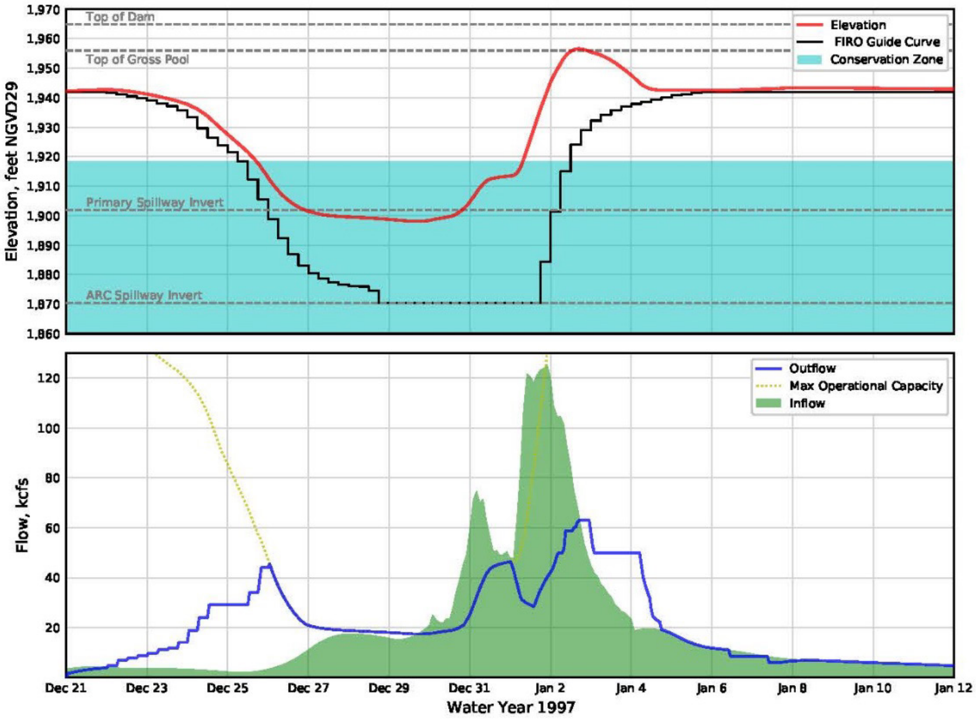
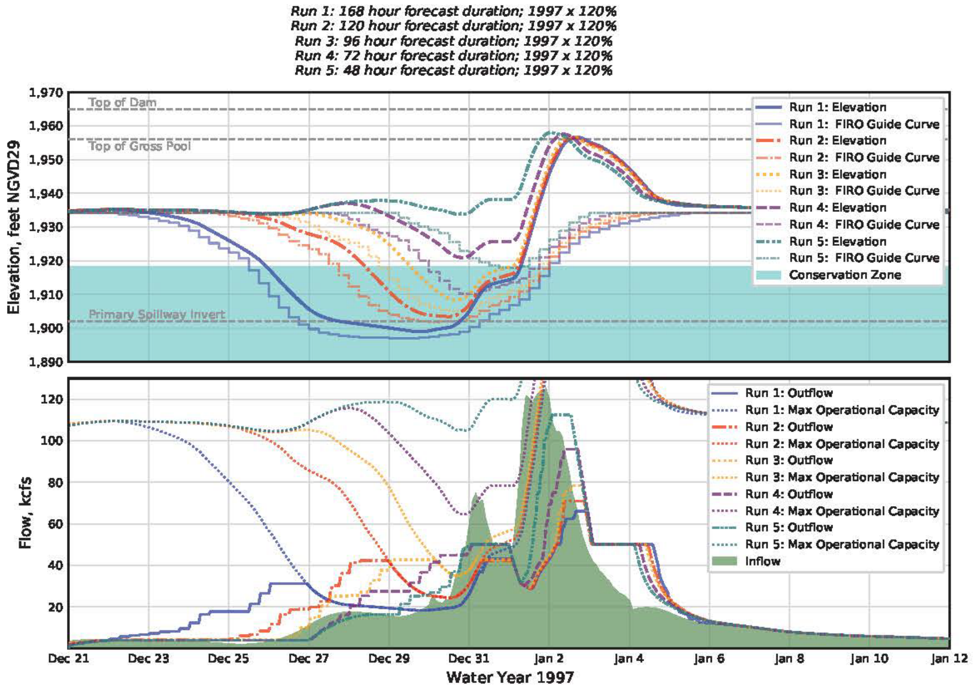


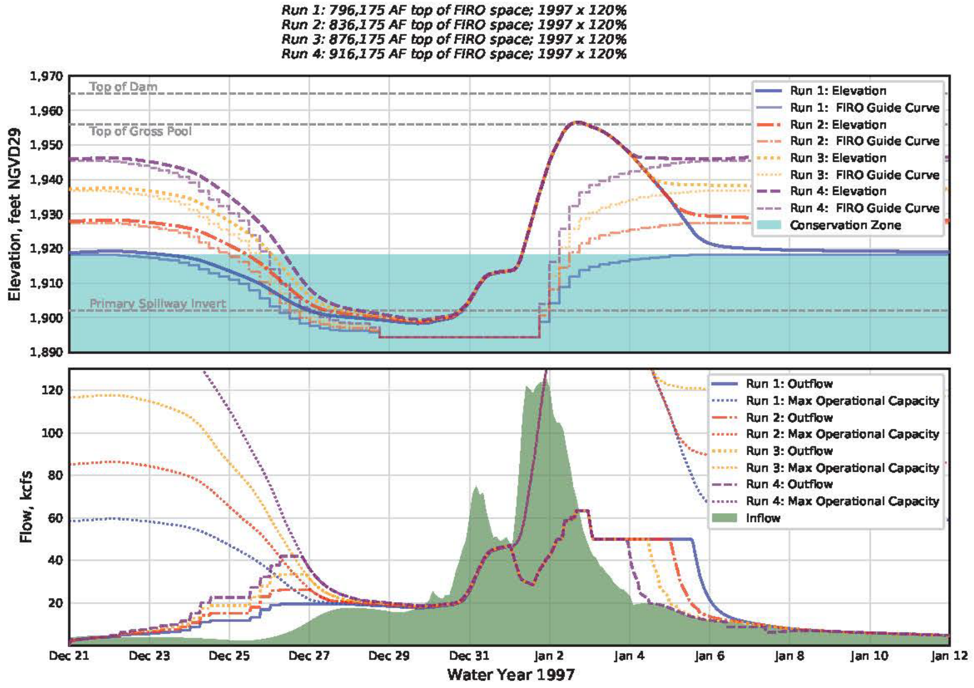
Figure E-3. *Guide Curve Operations with Bottom of FIRO Space at ARC Spillway In- vert; 1997 120%*

E.4.4 Parameter Sensitivity

A comparison was conducted to evaluate sensitivity to changes in forecast durations and top of FIRO space. Here, each run for the forecast duration comparison included only one forecast duration, from a 2-day to a 7-day duration, to test the sensitivity of each in isolation. The top of FIRO space was set in the model as the starting storage at the first simulation timestep. The top of FIRO space alternatives for comparison were chosen in intervals between top of gross pool and top of conservation. Note that each FIRO guide curve simulation was initialized with a starting storage matching the guide curve value. The results, as seen in Figure E-4, demonstrate that the peak elevation and outflow were more sensitive to changes in forecast durations than to changes in top of FIRO space. When the top of FIRO space is high in the pool the release capacity is large enough to evacuate the excess water if the forecast duration is long enough to allow this. For the top of FIRO space comparison all alternatives were simulated with up to a 7-day forecast, giving the reservoir enough time to sufficiently empty ahead of an event. When comparing forecast durations, however, there is a more significant difference in performance because the reservoir does not have time to draw down ahead of the event to an equal degree for the shorter forecast durations.



(a) Forecast Duration Comparison



(b) Starting Storage and Top of FIRO Space Comparison

Figure E-4. *Compare Top of FIRO Space and Forecast Duration Parameters*

E.5 Results

A candidate guide curve was developed from the preliminary modeling results. This guide curve was informed by physical limitations and shaped with consideration for four major historical flood patterns: 1956, 1965, 1986, and 1997.

E.6 The Candidate Guide Curve

The candidate guide curve has the following input parameters and the lookup diagram can be seen in Figure E-5.

- **Forecast Durations:** range of 1-day to 7-day forecast durations
- **Bottom of FIRO space:** 700 TAF
- **Top of FIRO space:** between top of gross pool and top of conservation
- **Drawdown trigger:** 100 TAF inflow forecast volume
- **Inflow volume at the bottom of FIRO space:**
  - – D_{24} = 231,982 AF
  - – D_{48} = 313,706 AF
  - – D_{72} = 395,430 AF
  - – D_{96} = 477,154 AF
  - – D_{120} = 558,878 AF
  - – D_{168} = 722,330 AF

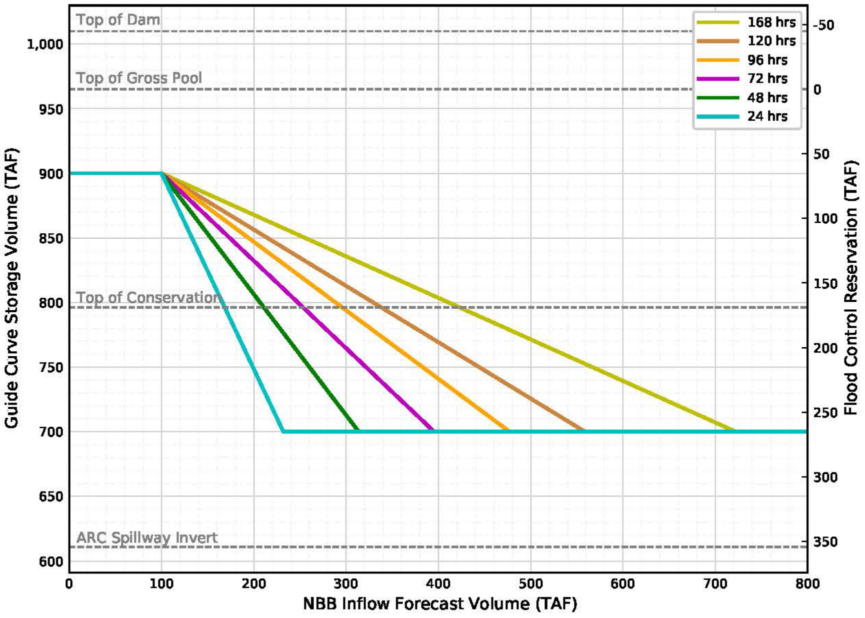


Figure E-5. *Candidate Guide Curve Example*

It is important to note that with the top of FIRO space, (B), set between the top of gross pool and the top of conservation, the performance and suitability of the candidate guide curve is contingent on having a long enough maximum forecast duration to allow enough time to draw down sufficiently, even when top of FIRO space is set as high as the top of gross pool. Thus, for the use of a flexible top of FIRO space, the maximum lead time must be set so that the reservoir has time to adequately draw down ahead of the flood event peak.

E.7 Preliminary Performance

The following list outlines the metrics used to evaluate the performance of the proposed NBB guide curve drawdown logic when compared to baseline operations (operations according to current WCM).

- **Improved flood protection:**
  - achieve lower peak elevations and peak outflow when compared to WCM operations.
  - ability to successfully route larger event without exceeding the top of gross pool compared to the baseline WCM operations.
- **Improved water supply:**
  - ability to store more water through winter and into spring without sacrificing FRM performance.
  - ability to refill after event when the forecast is dry.
- **Pre-release operations:**
  - only allowing reservoir outflow to increase ahead of event (unless maximum operational capacity or operating constraints limit this).
  - change outflow in manageable timesteps and avoid release oscillations.
  - change outflow in a manner that is consistent with expected gate change capability of the ARC spillway gate house.

When comparing the baseline alternative operation with the proposed guide curve operations, as in Figure E-6, a trend of lower peak elevations and peak outflows were observed across all tested large events and scale factors.

Refinements to this operation will also extensively leverage the forecast skill and verification analysis under the scope of the FIRO PVA teams to ensure an appropriate representation of NBB inflow forecast distribution is used operationally.

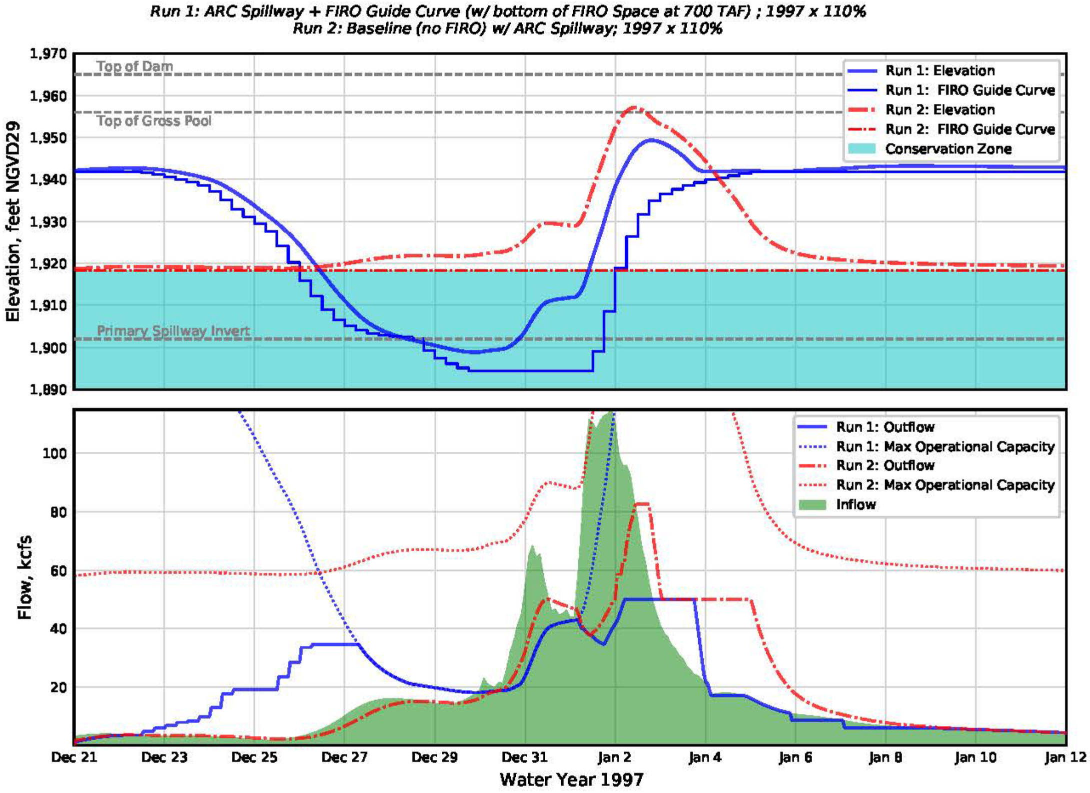


Figure E-6. *Comparison between Operations with Baseline (no FIRO) and Candidate Guide Curve; 1997 110%*

To measure the performance of the candidate guide curve in terms of the change in the largest event the reservoir can operate without exceeding the top of gross pool, a comparison was conducted as demonstrated in Table E-1. Table E-1 shows that for all events tested, the operations with the candidate guide curve can manage events with scale factors between 15% and 30% larger than for baseline operations without FIRO.

Table E-1. *Scaled Event at Which Top of Gross Pool is First Exceeded*

CVHS Event	Baseline (no FIRO operations)	With "candidate guide curve" drawdown
1956	155%	180%
1965	135%	165%
1986	125%	145%
1997	105%	120%

From the parameter sensitivity analysis (Figure E-4), it is clear that, when using perfect forecasts, storing water higher in the pool during the flood season would not impact flood protection performance when using a sufficient forecast duration. Figure E-4 also demonstrates the ability to refill after the event for runs using different starting storages. This indicates that improved water supply ability is possible with this new operation.

The candidate guide curve drawdown trigger was set to 100 TAF as a measure to preserve a gradual drawdown shape. Since changes to the drawdown trigger resulted in little to no impact on performance in terms of peak elevation and outflow during the event, the drawdown trigger was determined by how it shaped the outflow pattern at the onset of the event. A drawdown trigger of 100 TAF allowed for the outflow to adhere to the pre-release operation goals, such that the reservoir outflow only increased ahead of event and outflow changed in manageable timesteps. Similarly, changes to the inflow volume at the bottom of FIRO space for each forecast duration did not majorly impact performance in terms of peak elevation and outflow. The selected inflow volumes at the bottom of FIRO space coordinates were chosen such that the guide curve would account for varying lead times for different forecast durations. These D_x coordinates are candidates for further refinement in guide curve development, depending on the final selection of operational forecast durations.

E.8 Preliminary Robustness Testing

The analysis and performance seen in previous sections was conducted using perfect forecasts. Comparison between models run with perfect forecast hydrology and hindcast hydrology was used to evaluate the robustness of the candidate guide curve algorithm.

E.9 Testing with 2015 Scaled Runoff Hindcast Hydrology

The imperfect forecast simulations leveraged a hydrologic dataset of ensemble runoff hindcasts produced by the California-Nevada River Forecast Center in 2015. Analysis of various forecast duration volumes at the time revealed a dry bias in larger flood events: the observed runoff volumes more closely matched the 25% to 10% exceedance values than the median. To develop a single- value forecast timeseries for each forecast duration, a specified exceedance volumes was computed for each hindcast ensemble issued in during the 1986 and 1997 flood events. These were resampled to simulate a 6-hour forecast issuance period, and matched to the 100% CVHS scaled events as in MBK (2020). These runoff hindcasts were scaled by the same CVHS unregulated flow scale factors, to provide associated imperfect forecasts for each simulation.

A comparison between simulations with guide curves based on the runoff-scaled hindcasts and perfect forecasts can be seen in Figure E-7. There was little to no difference in peak elevation and peak outflow between the two alternatives, indicating that the guide curve paradigm is flexible enough to meet the performance metrics when used with varied hydrology. This trend was observed for a range of events and scale factors.

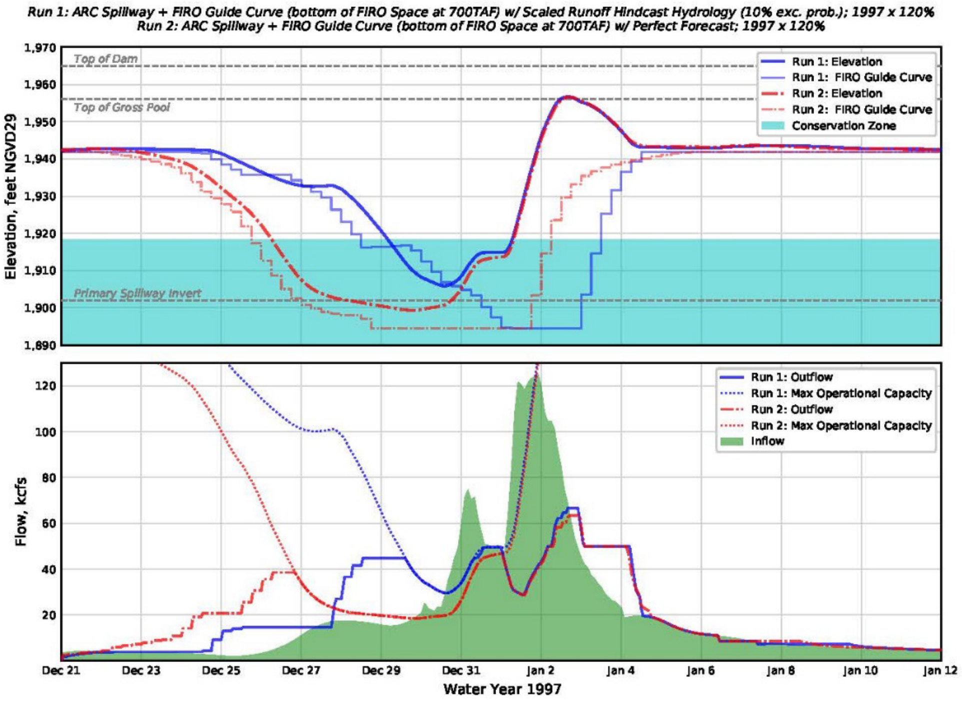


Figure E-7. *Perfect Forecast and Scaled Runoff Hindcast Hydrology Comparison*

The guide curve framework currently relies on a statistically derived single-value forecast for an exceedance probability of 10% to summarize ensemble forecasts. However, as forecast skill improves in the future, the best-estimate of observed runoff may fall closer to the median. Because the guide curve relies on a summary of the ensemble, the target exceedance value can be updated, thus meeting the goal of creating a FIRO alternative that can adapt to future improvements in forecast abilities.

E.10 Conclusion

The FIRO at-site operation and guide curve methodology outlined in this report provide improved FRM and water supply benefits at NBB. The guide curve paradigm was evaluated with an extensive range of event magnitudes, and demonstrated the flexibility to manage to a range of hydrologic patterns while meeting the goals of providing improved flood protection and increased end of flood season water supply and also operating according to the pre-release operations goals.

E.11 Next Steps

The following steps will be taken in the future to continue to develop and test the NBB guide curve paradigm:

- integrate the variable guide curve operation with Yuba-Feather system operations
- continue robustness testing with the 2021 Scaled Precipitation Hindcast Hydrology produced by the FIRO PVA Hydrology team
- adjust top of FIRO space for YWA and United States Army Corps of Engineers (USACE) comfort levels

- adjustment to the number of forecast durations used

The FIRO guide curve framework is expected to provide an adaptive flood operation that incorporates the proposed ARC spillway and leverages forecast technology to improve regional flood protection in the Yuba watershed.

E.12 References

MBK Engineers (2020). New Bullards Bar Secondary Spillway: Evaluation of Flood Management Performance for Candidate Secondary Spillway Outlets. Final Technical Report dated August 24, 2020.

United States Army Corps of Engineers, Sacramento District (SPK) (2019). *Folsom Dam and Lake, American River, California: Water Control Manual*.

Appendix F—ORO At-Site Alternative EF008 (Section 4)

MEMORANDUM

DATE: Wednesday, November 03, 2021

PROJECT: Forecast-Informed Reservoir Operations Program Support for Lake Oroville Water Control Manual Update

TO: Dustin Jones, PE

FROM: Hongyu Deng, PE (CA Lic. #90802); Nathan Pingel, PE, D.WRE, PMP; Donna Lee, PMP; and Michael Konieczki, PE, D.WRE

SUBJECT: Development of Oroville Dam Forecast-informed Reservoir Operation Alternatives – At-site Alternative EF008

F.1 Situation

The California Department of Water Resources (DWR) is participating in the Yuba-Feather Forecast- Informed Reservoir Operations (FIRO) Program, a multi-agency partnership focused on evaluating the viability of FIRO at Oroville and New Bullards Bar dams and identifying opportunities for forecast enhancement. Oroville Dam on the Feather River is owned and operated by DWR, and New Bullards Bar on the Yuba River is owned and operated by Yuba Water Agency (YWA). For flood control, the dams are operated separately and as a system to avoid exceeding the maximum objective flow at the Yuba-Feather confluence and downstream. Flood operation rules for the dams are prescribed in each dam's water control manual (WCM) developed by the U.S. Army Corps of Engineers Sacramento District (SPK).

In parallel with the FIRO Program, SPK is updating the WCMs for each dam. Flood operation alternatives developed by the FIRO Program will inform the WCM updates.

DWR began developing Oroville FIRO alternatives under the Oroville Comprehensive Needs Assessment (CNA) (DWR 2020). These alternatives were similar to the forecast-based alternative developed for the Folsom Dam WCM update, where inflow forecast ensembles are used as input to a prescriptive operation that specifies the top of conservation (TOC) pool elevation and magnitude of release depending on the forecasted inflows.

For the FIRO Program, DWR is refining the CNA alternatives as well as examining other FIRO methods.

F.2 Task

HDR is refining CNA alternative EF004 as part of the FIRO Program alternative development. This was a promising alternative developed by HDR under the CNA that was built around the existing variable flood space within Lake Oroville and showed enhanced performance relative to 1970 WCM operation. EF004 was designed to use the full variable space to pass the standard project flood (SPF). The refinement described herein focuses on modifying EF004 so that it passes the 1986 and 1997 historical events, which are of magnitude more frequent than the SPF, leveraging the full variable flood space. In other words, under the refined alternative, the full variable flood space would be used more often. The 1986 and 1997 events are the largest in the historical record, and it is assumed that the full flood space would be used to pass events of this magnitude to effectively attenuate peak flows downstream.

F.3 Actions

To complete this task, HDR:

1. Reviewed the candidate FIRO WCP alternative routings and identified candidate alternative Operation EF004 developed previously as the most appropriate starting point for additional analysis and refinement.

2. Identified the 2 main components of the FIRO alternative for which potential refinements could be made. Specifically: (1) the computation of the forecast-based TOC, or drawdown curves, and (2) the forecast-based maximum release triggers.

3. Developed 11 different forecast-based TOC scenarios in which the use of the flood management volume is based on specific forecast inflow volume-duration annual exceedance probability (AEP) quantiles.

4. Configured each TOC scenario and simulated the 1986 and 1997 events using HEC-ResSim version 3.3.

5. Reviewed these simulations and identified the scenario with the most desirable operation based on the following criteria:

    a. Maximum release from Oroville Dam.

    b. Maximum reservoir pool elevation.

    c. Use of dedicated flood management volume.

6. Reviewed the reservoir routings and identified further refinements that could be made to the forecast-based TOC drawdown curves and new refinements to the forecast-based maximum release triggers concurrently.

7. Configured each TOC and release trigger scenario and simulated the 1986 and 1997 events using HEC-ResSim.

8. Reviewed these simulations and identified the scenario with the most desirable operation based on the above criteria.

9. Configured the identified scenario and simulated the SPF routings using HEC-ResSim.

10. Reviewed the SPF routing and confirmed appropriate operation based on the above criteria.

F.3.1 Starting Model and Candidate WCP Alternative

For this analysis, HDR used the Scenario 4 HEC-ResSim model developed for the YWA ARC Spillway benefit analysis as the starting model, in which alternative EF004 for Oroville is configured. This model considers the existing physical condition at Oroville, proposed ARC spillway in place at New Bullards Bar, and Marysville Dam not in place. The configuration of that model is detailed in (DWR 2020 & YWA 2021).

EF004 computes a variable TOC elevation based on the AEP of the forecast inflows averaged for 1-, 3-, and 7-day durations, as follows:

- For forecast average inflows of any duration less than or equal to the $p = 0.1$ (1/10-year) AEP quantile, the prescribed flood storage would be 375,000 ac-ft (TOC elevation 875.4 ft).
- For forecast average inflows of any duration greater than or equal to the $p = 0.005$ (1/200-year) AEP quantile, the prescribed flood storage would be 750,000 ac-ft (TOC elevation 848.5 ft).
- For forecast average inflows between the $p = 0.1$ and $p = 0.005$ AEP quantiles, the prescribed flood storage (variable TOC) would be read from Figure F-1. The lowest TOC read from the 3 duration curves would be used.

Forecast-based releases would occur when the TOC drops below the current storage and the minimum flood storage (TOC elevation 875.4 ft). Maximum releases would be a function of 1-, 3-, and 7-day forecast average inflows and stepped as follows:

- If the forecast average inflow of any duration is greater than or equal to the $p = 0.1$ AEP quantile, release up to 60,000 cfs.
- If the 3-day or 1-day forecast average inflow is greater than or equal to the $p = 0.04$ AEP quantile, release up to 100,000 cfs.
- If the 1-day forecast average inflow is greater than or equal to the $p = 0.01$ AEP quantile, release up to 150,000 cfs.

Figure F-2 shows a plot of the forecast-based thresholds. Release decisions would be dictated by the duration curve from Figure F-2 that shows the highest average inflow.

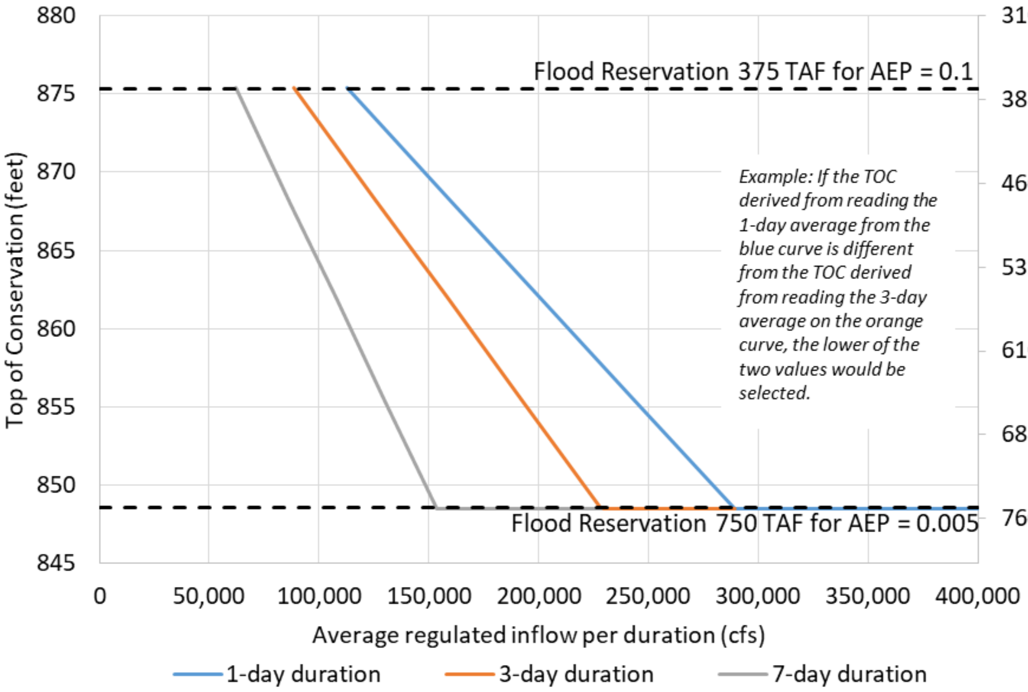


Figure F-1. *Drawdown Curves for Operation EF004 Variable TOC Computation*

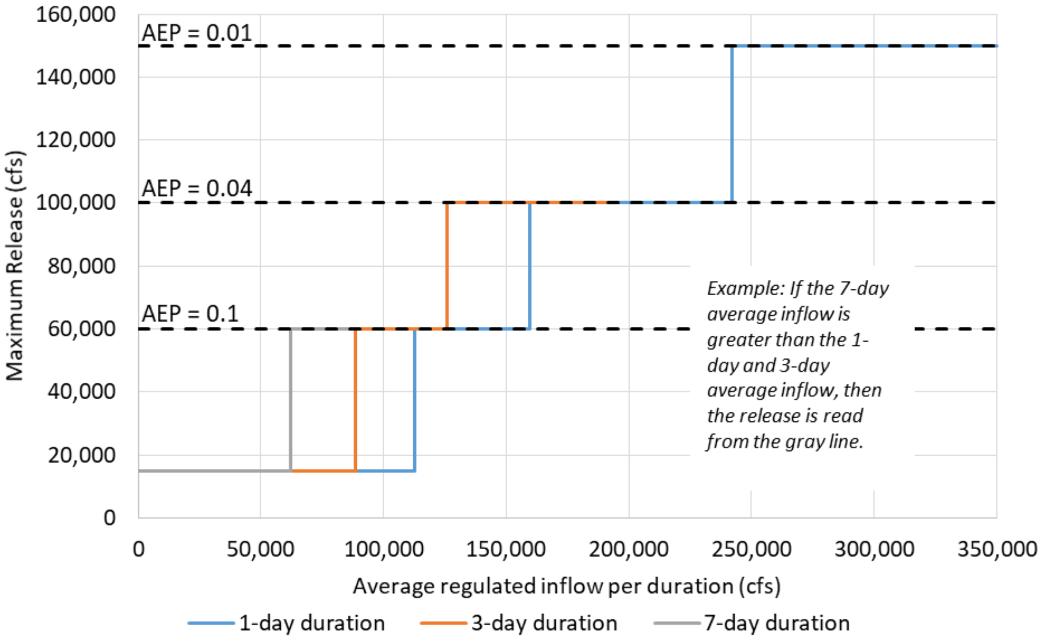


Figure F-2. *Forecast-Based Releases for Operation Set EF004*

F.4 Refinements to Forecast-Based TOC

As illustrated earlier, EF004 computes the variable TOC elevation based on the AEP of the forecast inflows averaged for 1-, 3-, and 7-day duration as follows:

- The variable TOC would be at 375,000 ac-ft of flood management storage (875.4 ft) for forecast average inflows of any duration less than or equal to the p = 0.1 (1/10-year) AEP quantile (1-day average inflow ≤ 112,524 cfs, 3-day average inflow ≤ 88,737 cfs, and 7-day average inflow ≤ 61,907 cfs).
- The variable TOC would be at 750,000 ac-ft of flood management storage (848.4 ft) for forecast average inflows of any duration greater than or equal to the p = 0.005 (1/200-year) AEP quantile (1-day average inflow ≥ 289,156 cfs, 3-day average inflow ≥ 228,710 cfs, or 7-day average inflow
- ≥ 153,470 cfs).
- For forecast average inflows between the p = 0.1 and p = 0.005 AEP quantiles, the variable TOC would be interpolated from TOC curves determined from TOC elevations (875.4 ft and 848.5 ft) and the corresponding (p = 0.1 and p = 0.005) average inflow thresholds; the lowest TOC of the three durations would be used.

For CNA Task 2, EF004 was developed using simulation of design events in reservoir operations and starting storage sensitivity analyses. These analyses suggested that further refinements could be made to the AEP thresholds (more frequent or rarer) which would eventually result in more or less aggressive use of the variable TOC.

HDR reviewed the CNA Task 2 routings and identified the 11 TOC elevation alternatives listed in Table F-1 to evaluate and inform refinement of the TOC elevation alternatives. Each alternative uses a combination of volume-duration quantiles to define the required storage available for flood management from a minimum 375,000 ac-ft (elevation 875.4 ft) to a maximum 750,000 ac-ft (elevation 848.5 ft) similar to the EF004 alternative and consistent with the 1970 WCM. Table F-2 lists select headwater-regulated inflow volume-frequency quantiles at Oroville used for the TOC alternatives.

Table F-1. *TOC Alternative Matrix*

		Quantile associated with 750,000 ac-ft of flood management storage (pool elevation 848.5ft)			
		p = 0.04 (1/25-year)	**p = 0.02 (1/50-year)**	**p = 0.01 (1/100-year)**	**p = 0.005 (1/200-year)**
Quantile associated with 375,000 ac-ft of flood management storage (pool elevation 875.4 ft)	p = 0.2 (1/5-year)	X	X	X	X
	p = 0.1 (1/10-year)	X	X	X	X
	p = 0.04 (1/25-year)	N/A	X	X	X

Table F-2. *Lake Oroville Headwater-Regulated Inflow Volume-Frequency Quantiles*

AEP		Average Inflows (cfs) by Duration		
		1-Day	**3-Day**	**7-Day**
p = 0.5	**1/2-year**	45,459	35,676	24,881
p = 0.2	**1/5-year**	94,009	73,098	50,047
p = 0.1	**1/10-year**	112,524	88,737	61,907
p = 0.04	**1/25-year**	159,720	125,934	87,093
p = 0.02	**1/50-year**	198,875	157,836	107,854
p = 0.01	**1/100-year**	242,164	192,157	130,010
p = 0.005	**1/200-year**	289,156	228,710	153,470

HDR evaluated alternative performance of each alternative for the 1986 and 1997 events. Here, each TOC alternative was configured in the existing HEC-ResSim model and the CVHS 1986 and 1997 100% scaled inflows were routed through the system. Forecast-based release rules were kept the same as those in the EF004 alternate shown in Figure F-2. Simulation results were evaluated using engineering judgement to identify a candidate refinement to the prescriptive FIRO alternative considering: (1) maximum release and duration thereof, and (2) maximum reservoir elevation at Lake Oroville. The complete set of routing results are shown in Appendix A. Drawdown Curve Alternatives Results (11 scenarios).

HDR identified the candidate forecast-based variable TOC elevation alternative where the minimum 375,000 ac-ft (elevation 875.4 ft) and maximum 750,000 ac-ft (elevation 848.5 ft) flood management requirements are defined by the p = 0.1 (1/10-year) and p = 0.04 (1/25-year) AEP quantiles respectively. This alternative, hereafter referred to as EF006, computes the variable TOC elevation based on the AEP of the forecast inflows averaged for 1-, 3-, and 7-day duration, as follows:

- The variable TOC would be at 375,000 ac-ft of flood management storage (875.4 ft) for forecast average inflows of any duration less than or equal to the p = 0.1 (1/10-year) AEP quantile (1-day average inflow ≤ 112,524 cfs, 3-day average inflow ≤ 88,737 cfs, and 7-day average inflow ≤ 61,907 cfs).
- The variable TOC would be at 750,000 ac-ft of flood management storage (848.5 ft) for forecast average inflows of any duration greater than or equal to the p = 0.04 (1/25-year) AEP quantile (1- day average inflow ≥ 159,720 cfs, 3-day average inflow ≥ 125,934 cfs, or 7-day average inflow ≥ 87,093 cfs).
- For forecast average inflows between the p = 0.1 and p = 0.04 AEP quantiles, the variable TOC would be interpolated from TOC curves determined from TOC elevations (875.4 ft and 848.5 ft) and the corresponding (p = 0.1 and p = 0.04) average inflow thresholds. The lowest TOC of the three durations would be used.

Figure F-3 shows the EF006 forecast-based inflow TOC requirements, and Table F-3 provides a comparison summary of EF004, EF006 and 1970 WCM operations. Figure F-4 and Figure F-5 compare EF004 and EF006 routings for 1986 and 1997 events. The pre-releases under EF006 could reduce pool elevations for both events.

In general, HDR found that the peak pool elevations for the EF006 routings were less than those of EF004, and maximum releases were the same. For both event routings, there were small increases in pre-releases resulting from the decreased TOC of EF006. However, the pool elevation did not drawdown along the decreasing TOC. In addition, the 1986 event routing did not drawdown to the maximum flood management storage (750,000 ac-ft, elevation 848.5 ft). These routings suggest additional refinements may be made to the forecast-based TOC and releases rules to allow for greater pre-release volumes.

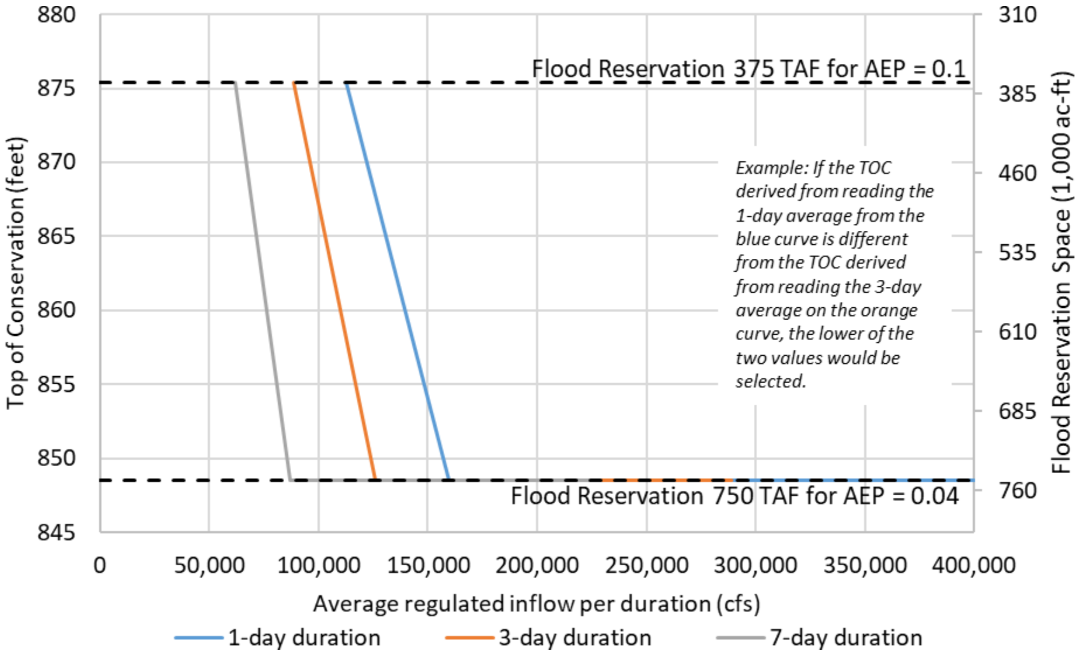


Figure F-3. *Drawdown Curves for Operation EF006 Variable TOC Computation*

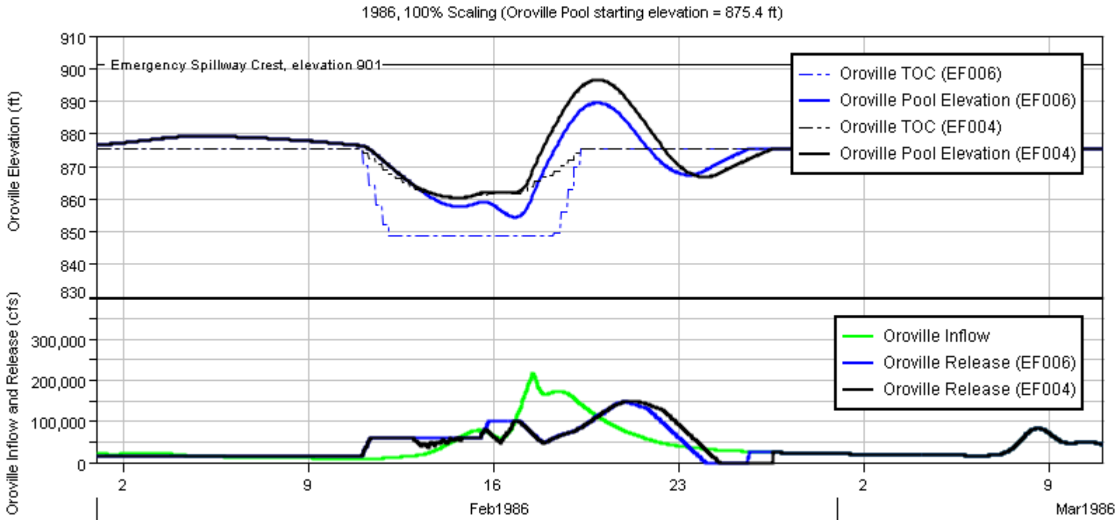


Figure F-4. *Comparison of Operations EF004 and EF006 at Oroville (1986, 100% Scaling)*

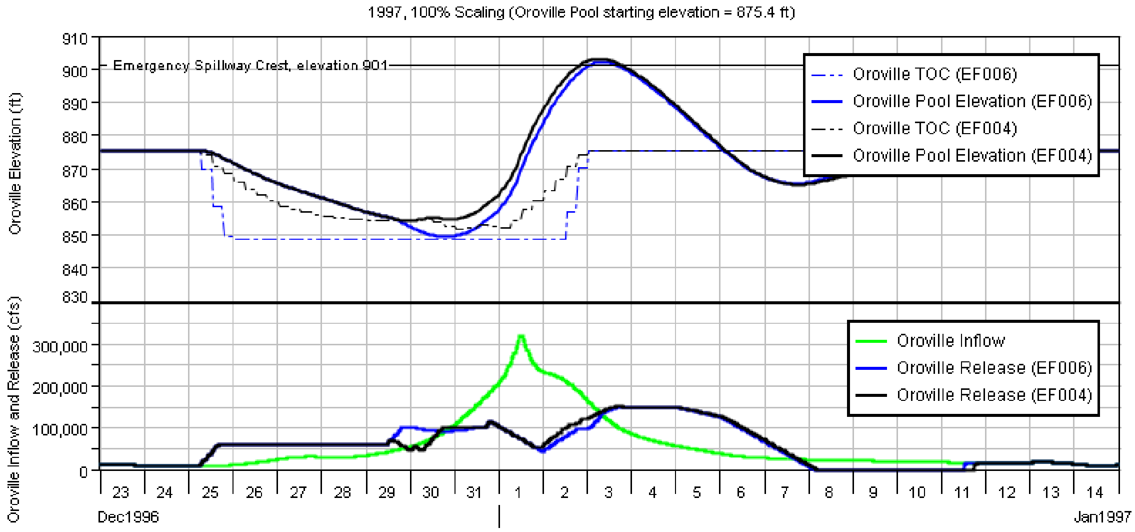


Figure F-5. *Comparison of Operations EF004 and EF006 at Oroville (1997, 100% Scaling)*

Table F-3. *Comparison of Alternative EF004, EF006, and 1970 WCM*

	1970 WCM	Alternative EF004	Alternative EF006
Variable Space	Minimum 375,000 ac-ft to maximum 750,000 ac-ft (elevation 848.5 ft)	Minimum 375,000 ac-ft (elevation 875.4 ft) to maximum 750,000 ac-ft (elevation 848.5 ft)	Minimum 375,000 ac-ft (elevation 875.4 ft) to maximum 750,000 ac-ft (elevation848.5 ft)
Use of Variable Space	Required space varies based on precipitation indices ranging from 3.5 (minimum flood reservation required) to 11 (maximum flood reservation required)	Required space varies based on forecast average regulated inflows. If forecast average regulated inflows > p=0.1 (1/10-year) AEP quantile (for any duration), flood reservation increases and TOC decreases. Maximum flood reservation of 750,000 ac-ft would be required for forecast average regulated inflows ≥ p=0.005 (1/200-year) AEP quantile (for any duration)	Required space varies based on forecast average regulated inflows. If forecast average regulated inflows > p=0.1 (1/10-year) AEP quantile (for any duration), flood reservation increases and TOC decreases. Maximum flood reservation of 750,000 ac-ft would be required for forecast average regulated inflows ≥ p=0.04 (1/25-year) AEP quantile (for any duration)
Maximum Release Limits	Based on current inflow	Based on duration showing greatest forecast average inflow.	Based on duration showing greatest forecast average inflow.

	1970 WCM	Alternative EF004	Alternative EF006
Release Steps	If current inflow > 0 cfs, release up to 15,000 cfs 30,000 cfs, release up to 60,000 cfs 120,000 cfs, release up to 100,000 cfs 175,000 cfs, release up to 150,000 cfs	If forecast average regulated inflow all durations ≤ p=0.1 (1/10-year) AEP quantile: 15,000 cfs if current inflow ≤ 30,000 60,000 cfs if current inflow > 30,000 7-day or less > 10-year: 60,000 cfs 3-day or less > 25-year: 100,000 cfs 1-day or less > 100-year: 150,000 cfs	If forecast average regulated inflow all durations ≤ p=0.1 (1/10-year) AEP quantile: 15,000 cfs if current inflow ≤ 30,000 60,000 cfs if current inflow > 30,000 7-day or less > 10-year: 60,000 cfs 3-day or less > 25-year: 100,000 cfs 1-day or less > 100-year: 150,000 cfs
ESRD	Prescribes releases > 150,000 cfs	No change	No change

F.5 Refinements to Forecast-Based Maximum Release

HDR developed two additional alternatives by modifying the Operation EF006 forecast-based TOC and release rules: (1) Operation EF007, and (2) Operation EF008. These new alternatives allow earlier drawdown of the TOC and a more aggressive pre-release based on the forecasted 7-day averaged inflows. Table F-4 provides a comparison between operation alternatives EF006, EF007 and EF008.

EF007 computes the variable TOC elevation based on the AEP of the forecast inflows averaged for 1-, 3-, and 7-day duration, as follows:

- The variable TOC would be at 375,000 ac-ft of flood management storage (875.4 ft) for forecast average inflows of 1-day or 3-day duration less than or equal to the p = 0.1 (1/10-year) AEP quantile and 7-day duration less than or equal to the p = 0.5 (1/2-year) AEP quantile (1-day average inflow ≤ 112,524 cfs, 3-day average inflow ≤ 88,737 cfs, and 7-day average inflow ≤ 24,881 cfs).
- The variable TOC would be at 750,000 ac-ft of flood management storage (848.5 ft) for forecast average inflows of any duration greater than or equal to the p = 0.04 (1/25-year) AEP quantile (1- day average inflow ≥ 159,720 cfs, 3-day average inflow ≥ 125,934 cfs, or 7-day average inflow ≥ 87,093 cfs).
- For forecast 1-day and 3-day average inflows between the p = 0.1 and p = 0.04 AEP quantiles and 7-day average inflows between the p = 0.5 and p = 0.04 AEP quantiles, the variable TOC would be interpolated from TOC curves determined from TOC elevations (875.4 ft and 848.5 ft) and the corresponding (p = 0.1 and p = 0.04 for 1-day and 3-day, and p = 0.5 and p = 0.04 for 7- day) average inflow thresholds using Figure F-6; the lowest TOC of the three durations would be used.

Forecast-based releases would occur when the TOC drops below the current storage and the minimum flood storage (TOC elevation 875.4 ft). Maximum releases would be a function of 1-, 3-, and 7-day forecast average inflows and stepped as follows:

- If the 3-day or 1-day forecast average inflow is greater than or equal to the p = 0.1 AEP quantile, or the 7-day forecast average inflow is greater or equal to the p = 0.5 AEP quantile, release up to 60,000 cfs.

- If the 3-day or 1-day forecast average inflow is greater than or equal to the p = 0.04 AEP quantile, release up to 100,000 cfs.
- If the 1-day forecast average inflow is greater than or equal to the p = 0.01 AEP quantile, release up to 150,000 cfs.

Forecast average inflows would be evaluated based on 1-, 3-, and 7-day averaging durations. Release decisions would be dictated by reading from Figure F-7 for the duration which shows the highest average inflow. Figure F-7 shows a plot of the forecast-based thresholds.

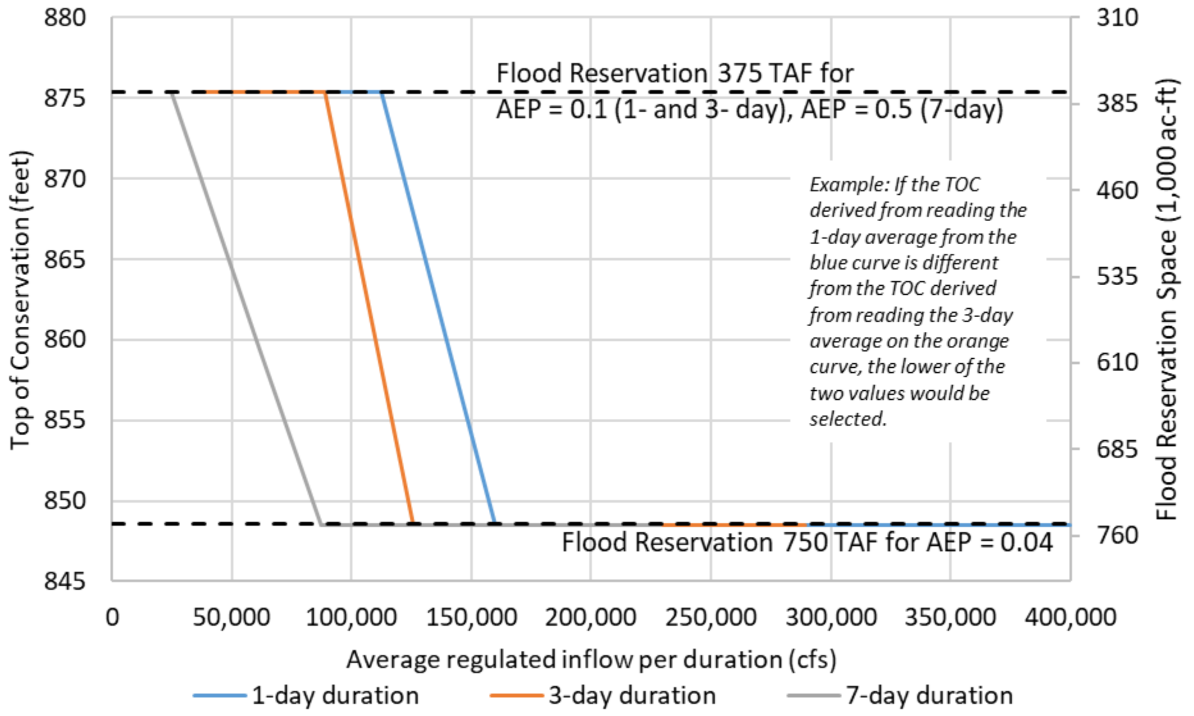


Figure F-6. *Drawdown Curves for Operation EF007 Variable TOC Computation*

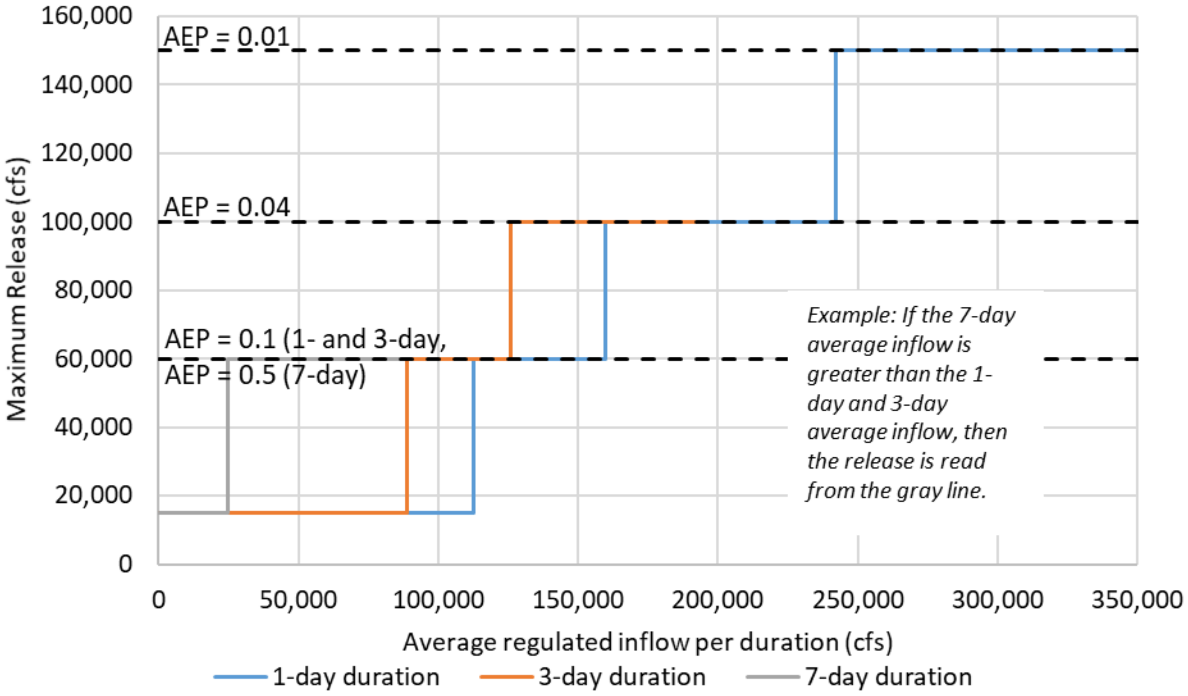


Figure F-7. *Forecast Based Releases for Operation EF007*

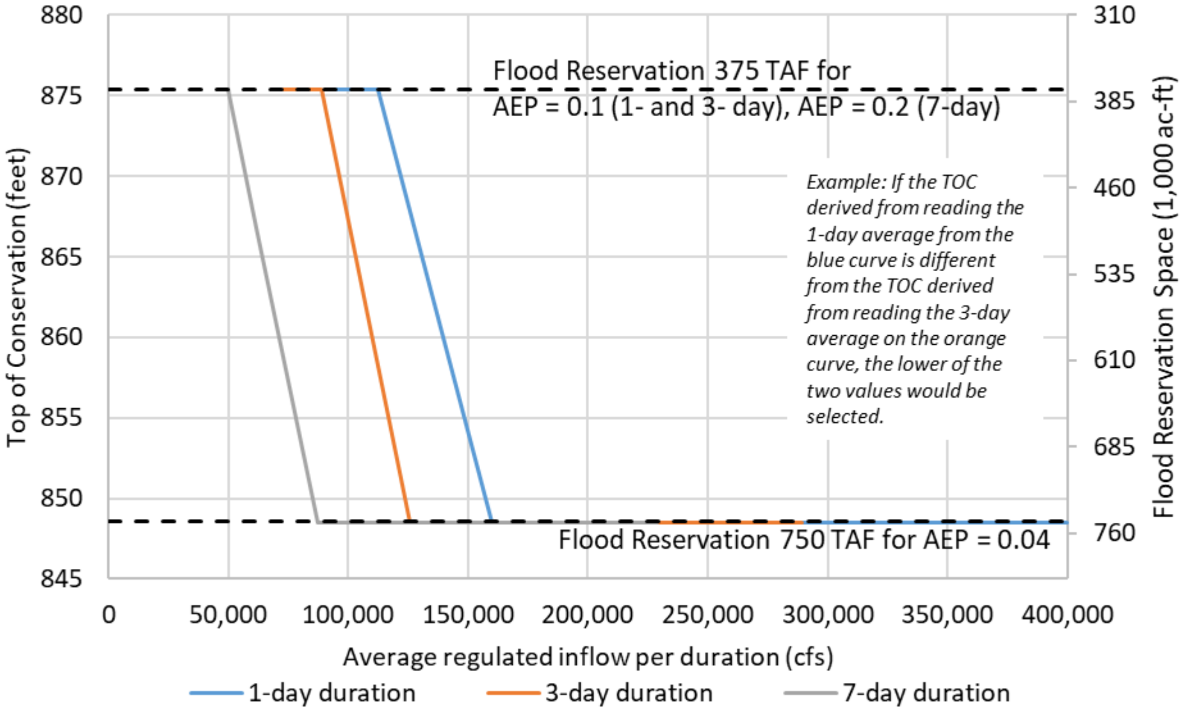
Similar to EF007, EF008 computes the variable TOC elevation based on the AEP of the forecast inflows averaged for 1-, 3-, and 7-day duration, as follows:

- The variable TOC would be at 375,000 ac-ft of flood management storage (875.4) for forecast average inflows of 1-day or 3-day duration less than or equal to the p = 0.1 (1/10-year) AEP quantile and 7-day duration less than or equal to the p = 0.2 (1/5-year) AEP quantile (1-day average inflow ≤ 112,524 cfs, 3-day average inflow ≤ 88,737 cfs, and 7-day average inflow ≤ 50,047 cfs).
- The variable TOC would be at 750,000 ac-ft of flood management storage (848.5 ft) for forecast average inflows of any duration greater than or equal to the p = 0.04 (1/25-year) AEP quantile (1- day average inflow ≥ 159,720 cfs, 3-day average inflow ≥ 125,934 cfs, or 7-day average inflow ≥ 87,093 cfs).
- For forecast 1-day and 3-day average inflows between the p = 0.1 and p = 0.04 AEP quantiles and 7-day average inflows between the p = 0.2 and p = 0.04 AEP quantiles, the variable TOC would be interpolated from TOC curves determined from TOC elevations (875.4 ft and 848.5 ft) and the corresponding (p = 0.1 and p = 0.04 for 1-day and 3-day, and p = 0.2 and p = 0.04 for 7- day) average inflow thresholds using Figure F-8; the lowest TOC of the three durations would be used.

Forecast-based releases would occur when the TOC drops below the current storage and the minimum flood storage (TOC elevation 875.4 ft). Maximum releases would be a function of 1-, 3-, and 7-day forecast average inflows and stepped as follows:

- If the 3-day or 1-day forecast average inflow is greater than or equal to the p = 0.1 AEP quantile, or the 7-day forecast average inflow is greater or equal to the p = 0.2 AEP quantile, release up to 60,000 cfs.
- If the 3-day or 1-day forecast average inflow is greater than or equal to the p = 0.04 AEP quantile, release up to 100,000 cfs.
- If the 1-day forecast average inflow is greater than or equal to the p = 0.01 AEP quantile, release up to 150,000 cfs.

Forecast average inflows would be evaluated based on 1-, 3-, and 7-day averaging durations. Release decisions would be dictated by reading from Figure F-9 for the duration which shows the highest average inflow. Figure F-9 shows a plot of the forecast-based thresholds.



Example: If the TOC derived from reading the 1-day average from the blue curve is different from the TOC derived from reading the 3-day average on the orange curve, the lower of the two values would be selected.

Figure F-8. *Drawdown Curves for Operation EF008 Variable TOC Computation*

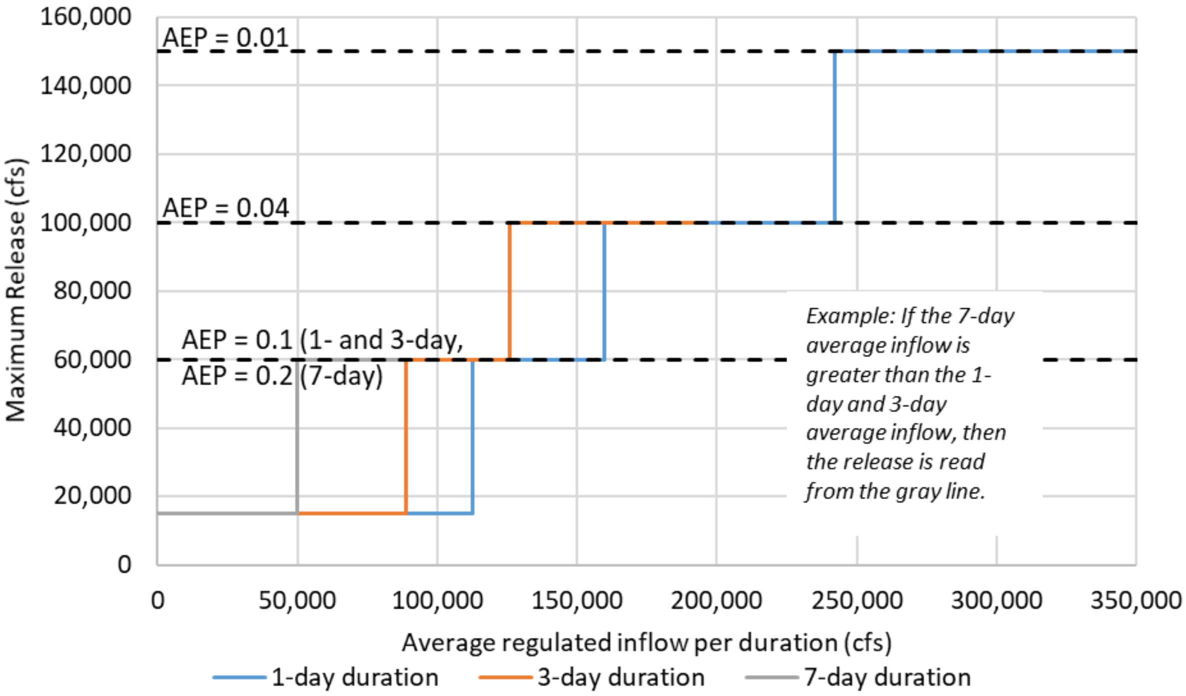


Figure F-9. *Forecast Based Releases for Operation EF008*

Table F-4. *Comparison of Alternative EF006, EF007, and EF008*

	Alternative EF006	Alternative EF007	Alternative EF008
Variable Space	Minimum 375,000 ac-ft (elevation 875.4 ft) to maximum 750,000 ac-ft (elevation 848.5 ft)	Minimum 375,000 ac-ft (elevation 875.4 ft) to maximum 750,000 ac-ft (elevation 848.5 ft)	Minimum 375,000 ac-ft (elevation 875.4 ft) to maximum 750,000 ac-ft (elevation 848.5 ft)
Use of Variable Space	Required space varies based on forecast average regulated inflows. If forecast average regulated inflows ≥ p=0.1 (1/10-year) AEP quantile (for any duration), flood reservation increases and TOC decreases. Maximum flood reservation of 750,000 ac-ft would be required for forecast average regulated inflows ≥ p=0.04 (1/25-year) AEP quantile (for any duration)	Required space varies based on forecast average regulated inflows. If forecast average regulated inflows > p=0.1 (1/10-year) AEP quantile for 1- day and 3-day durations, or ≥ p=0.5 (1/2-year) AEP quantile for 7-day duration, flood reservation increases and TOC decreases. Maximum flood reservation of 750,000 ac-ft would be required for forecast average regulated inflows ≥ p=0.04 (1/25-year) AEP quantile (for any duration)	Required space varies based on forecast average regulated inflows. If forecast average regulated inflows > p=0.1 (1/10-year) AEP quantile for 1- day and 3-day durations, or ≥ p=0.2 (1/5-year) AEP quantile for 7-day duration, flood reservation increases and TOC decreases. Maximum flood reservation of 750,000 ac-ft would be required for forecast average regulated inflows ≥ p=0.04 (1/25-year) AEP quantile (for any duration)

	Alternative EF006	Alternative EF007	Alternative EF008
Maximum Release Limits	Based on duration showing greatest forecast average inflow.	Based on duration showing greatest forecast average inflow.	Based on duration showing greatest forecast average inflow.
Release Steps	If forecast average regulated inflow all durations ≤ p=0.1 (1/10-year) AEP quantile: 15,000 cfs if current inflow ≤ 30,000 60,000 cfs if current inflow > 30,000 7-day or less > 10-year: 60,000 cfs 3-day or less > 25-year: 100,000 cfs 1-day or less > 100-year: 150,000 cfs	If forecast average regulated inflow for 1-day and 3-day durations ≤ p=0.1 (1/10-year) AEP quantile, and for 7-day duration ≤ p=0.5 (1/2-year) AEP quantile: 15,000 cfs if current inflow ≤ 30,000 60,000 cfs if current inflow > 30,000 3-day or less > 10-year, or 7-day > 2- year: 60,000 cfs 3-day or less > 25-year: 100,000 cfs 1-day or less > 100-year: 150,000 cfs	If forecast average regulated inflow for 1-day and 3-day durations ≤ p=0.1 (1/10-year) AEP quantile, and for 7-day duration ≤ p=0.2 (1/5-year) AEP quantile: 15,000 cfs if current inflow ≤ 30,000 60,000 cfs if current inflow > 30,000 3-day or less > 10-year, or 7-day > 5- year: 60,000 cfs 3-day or less > 25-year: 100,000 cfs 1-day or less > 100-year: 150,000 cfs
ESRD	No change	No change	No change

HDR assessed the performance of candidate alternatives (EF007 and EF008) by routing the 100% scaled 1986 and 1997 inflows from the CVHS (DWR 2015) through the configured Yuba-Feather River system reservoirs. The routing results are shown in Figure F-10 and Figure F-11. EF008 did not pre-release as aggressively as EF007 while it reduced the pool elevation similar to EF007 as compared to EF006. EF008 was identified as the best candidate alternative at this time.

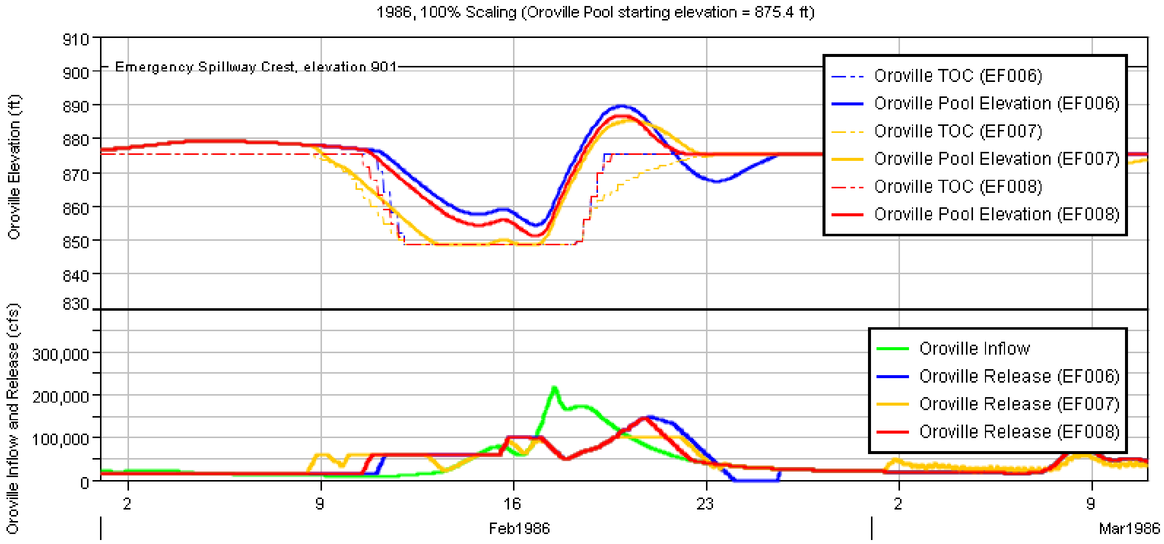


Figure F-10. *Comparison of Operations EF006, EF007 and EF008 at Oroville (1986, 100% Scaling)*

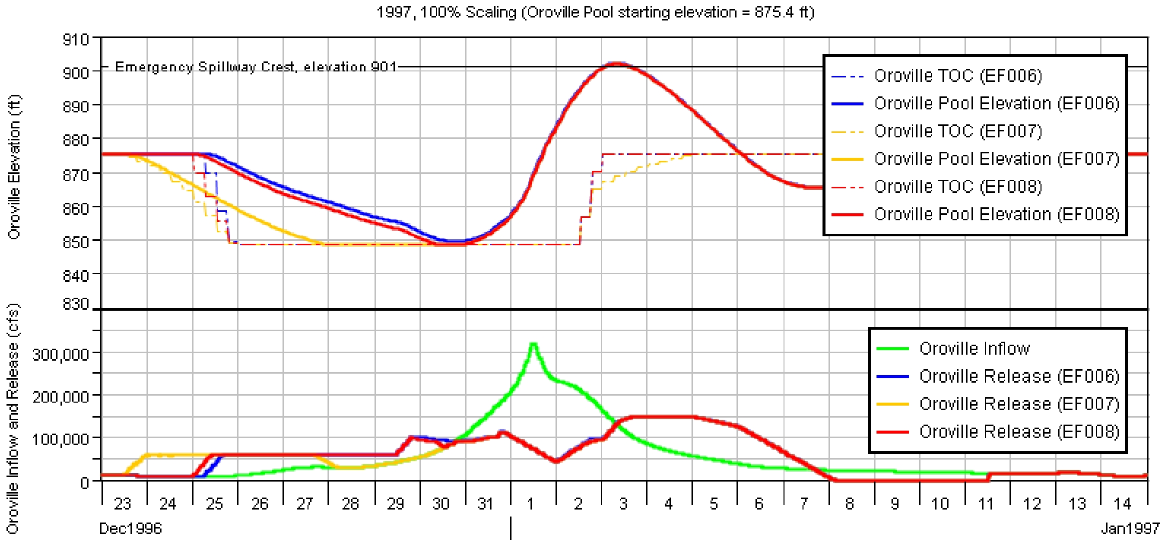


__Figure F-11.__ Comparison of Operations EF006, EF007 and EF008 at Oroville (1997, 100% Scaling)

HDR confirmed the appropriateness of EF008 by comparing routings of the 1986, 1997, and SPFs (SPF1, wet, centered on Feather River; SFP2, wet, centered on Yuba River) and confirming that peak reservoir elevations and releases were either reduced or not increased. Figure F-12 through Figure F-15 show these comparisons.

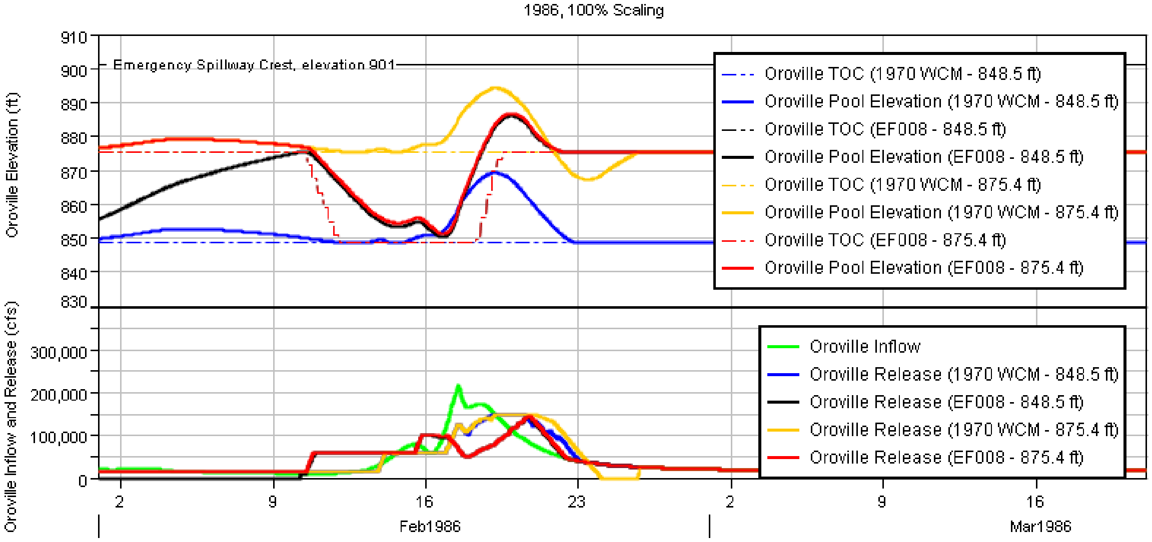


__Figure F-12.__ Comparison of Operation EF008 and WCM operations at Oroville (1986, 100% Scaling)

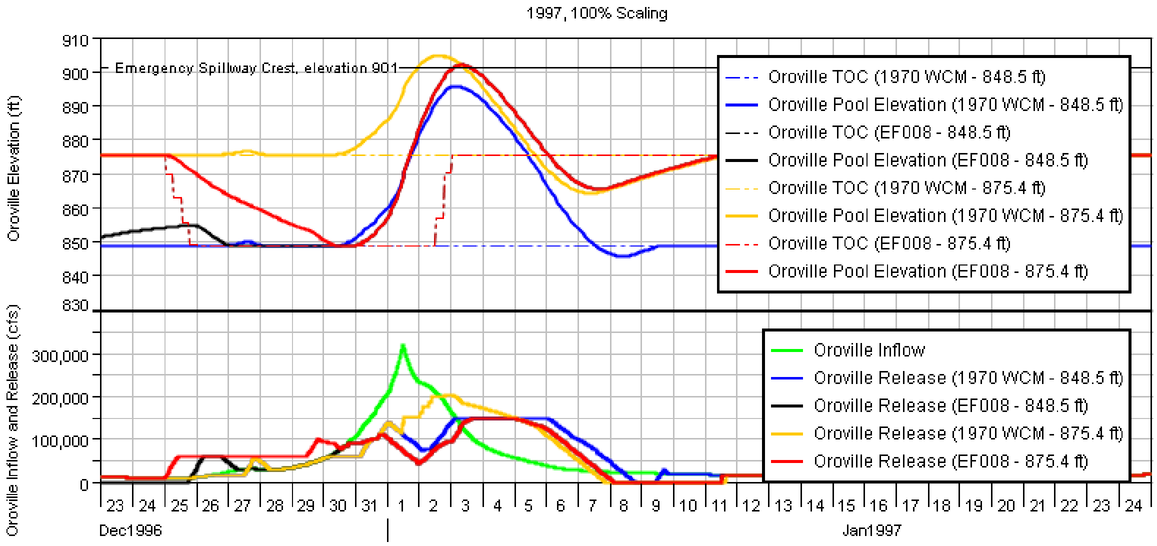


Figure F-13. *Comparison of Operation EF008 and WCM operations at Oroville (1997, 100% Scaling)*

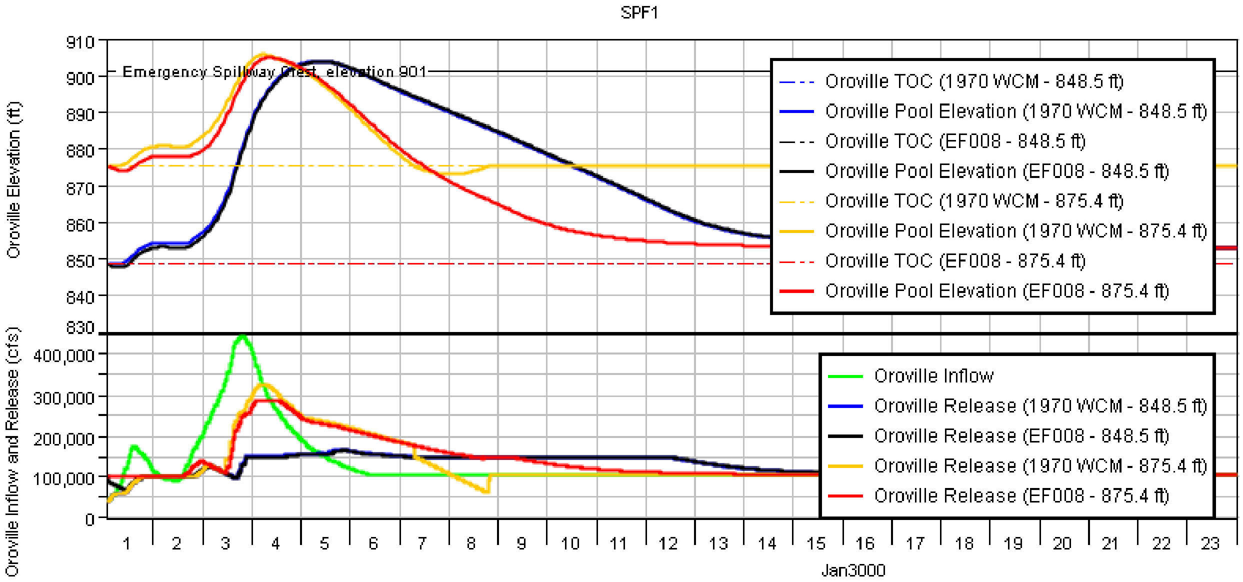


Figure F-14. *Comparison of Operation EF008 and WCM operations at Oroville (SPF1, wet SPF centered on Feather River above Oroville Dam from Oroville 1970 WCM, Chart 32)*

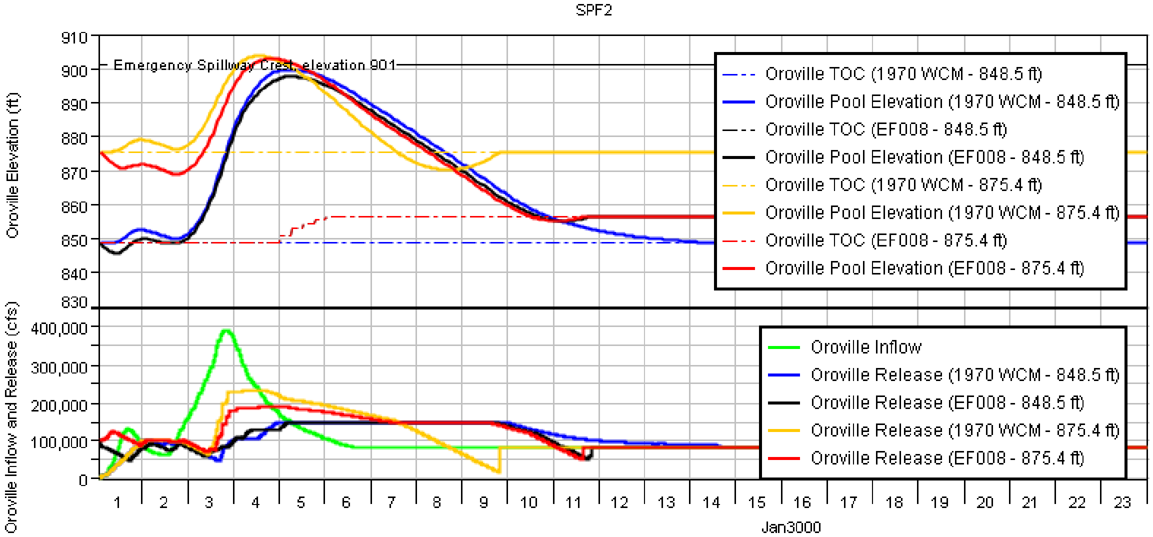


Figure F-15. *Comparison of Operation EF008 and WCM operations at Oroville (SPF2, wet SPF centered on Yuba River below New Bullards Bar Dam from Oroville 1970 WCM, Chart 32)*

F.6 Results

In summary, compared to the 1970 WCM operations:

- EF008 increases pre-release and reduces pool elevation at Oroville for the events simulated.
- EF008 decreases the maximum release or reduces the duration of outflow at 150,000 cfs.
- EF008 allows the TOC to return to the minimum flood management storage requirement and thus increases storage at the end of flood events.

F.7 Reference

DWR (2020). Oroville Dam Comprehensive Needs Assessment – Task 2 – Operations. Prepared by HDR. May.

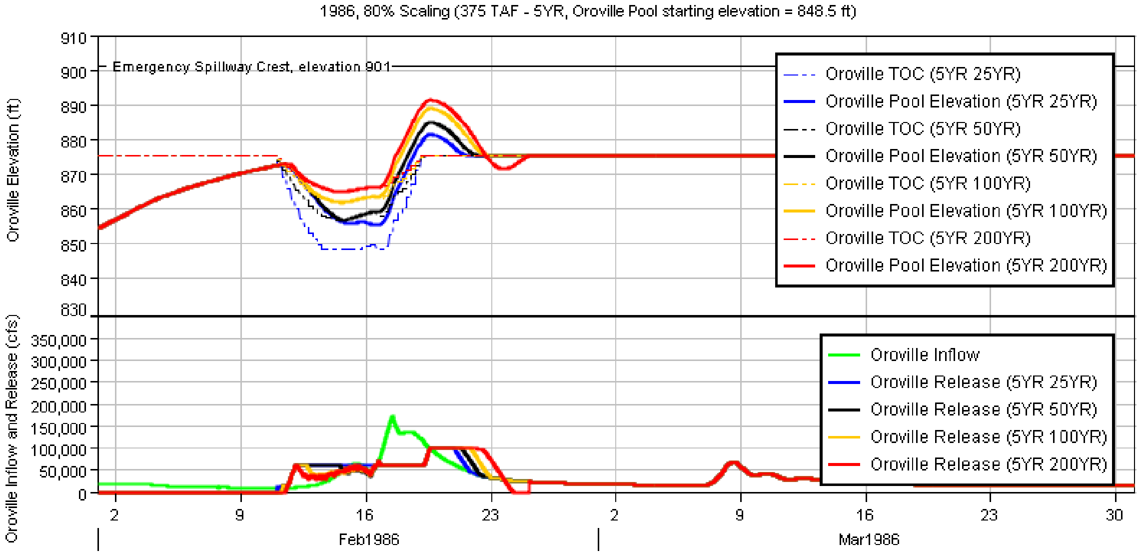
YWA (2021). “Task 5: Assess Inundation-Reduction Benefits.” Technical Memorandum. Prepared by HDR. August 13.

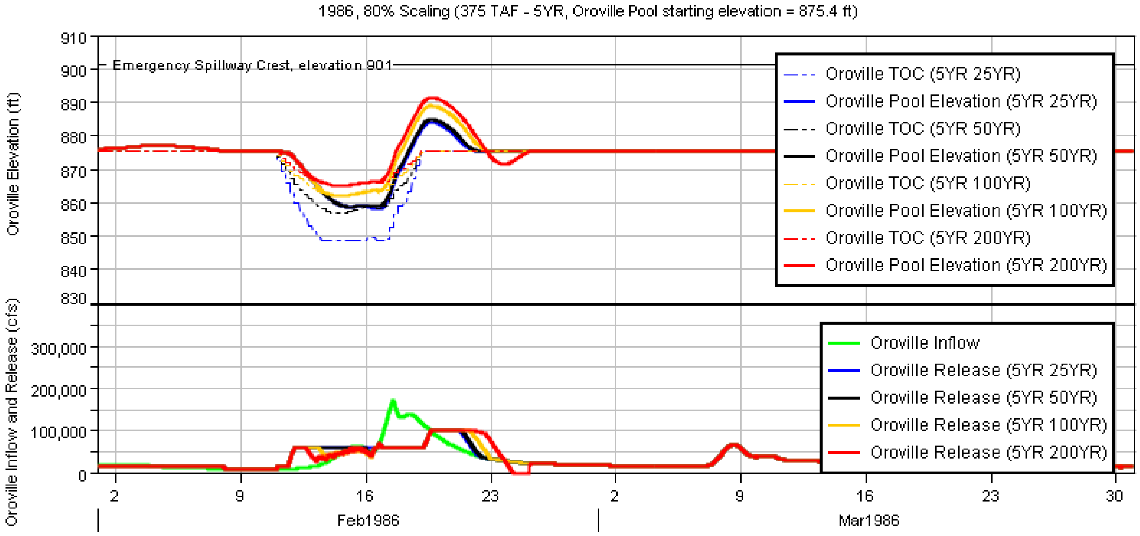
Attachment F-1: Drawdown Curve Alternatives Results (11 scenarios)

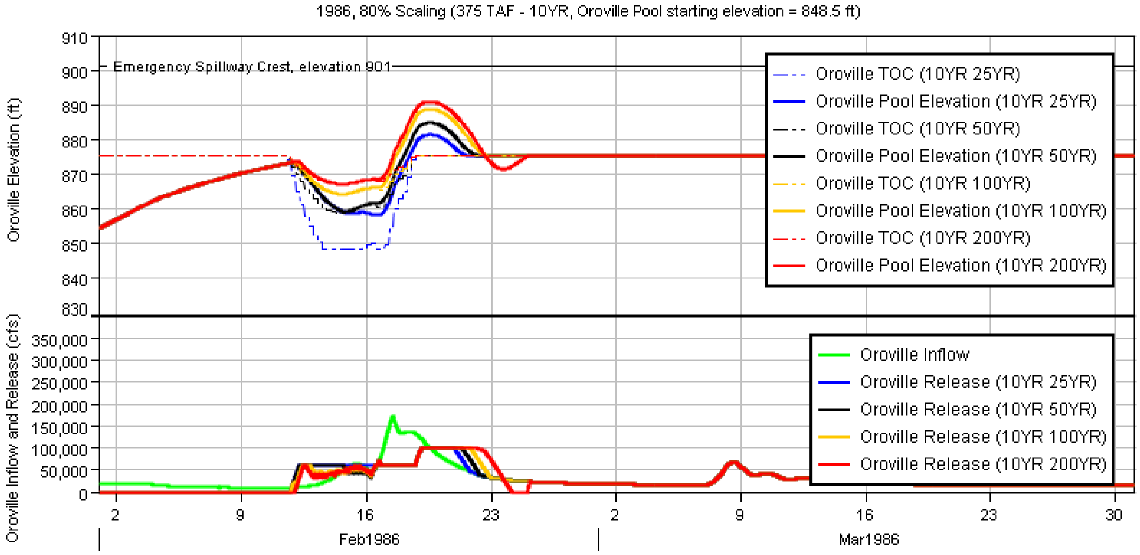
This appendix shows the routing results of the reservoir simulations completed to refine EF004.

(A YR B YR) in the legend indicates that the routing results are based on a variable TOC elevation based on the AEP of forecast inflows averaged for 1-, 3-, and 7-day durations, as follows:

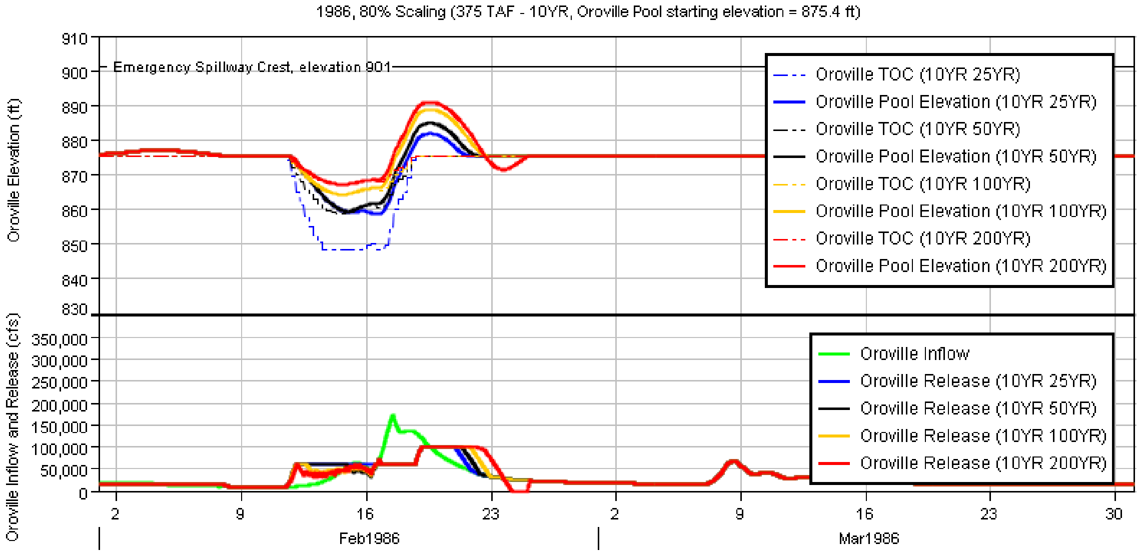
- The variable TOC would be at 375,000 ac-ft of flood management storage (875.4 ft) for forecast average inflows of any duration less than or equal to the p = 1/A (1/A-year) AEP quantile.
- The variable TOC would be at 750,000 ac-ft of flood management storage (848.5 ft) for forecast average inflows of any duration greater than or equal to the p = 1/B (1/B-year) AEP quantile.
- For forecast average inflows between the p = 1/A and p = 1/B AEP quantiles, the variable TOC would be interpolated from TOC curves determined from TOC elevations (875.4 ft and 848.5 ft) and the corresponding (p = 1/A and p = 1/B) average inflow thresholds. The lowest TOC of the three durations would be used.


1986, 80% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 848.5 ft)


1986, 80% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 875.4 ft)



1986, 80% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 848.5 ft)
Oroville Elevation (ft)
910
900
890
880
870
860
850
840
830
Emergency Spillway Crest, elevation 901
Oroville TOC (10YR 25YR)
Oroville Pool Elevation (10YR 25YR)
Oroville TOC (10YR 50YR)
Oroville Pool Elevation (10YR 50YR)
Oroville TOC (10YR 100YR)
Oroville Pool Elevation (10YR 100YR)
Oroville TOC (10YR 200YR)
Oroville Pool Elevation (10YR 200YR)
Oroville Inflow and Release (cfs)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Oroville Inflow
Oroville Release (10YR 25YR)
Oroville Release (10YR 50YR)
Oroville Release (10YR 100YR)
Oroville Release (10YR 200YR)
2
9
16
23
2
9
16
23
30
Feb1986
Mar1986



1986, 80% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 875.4 ft)
Oroville Elevation (ft)
910
900
890
880
870
860
850
840
830
Emergency Spillway Crest, elevation 901
Oroville TOC (10YR 25YR)
Oroville Pool Elevation (10YR 25YR)
Oroville TOC (10YR 50YR)
Oroville Pool Elevation (10YR 50YR)
Oroville TOC (10YR 100YR)
Oroville Pool Elevation (10YR 100YR)
Oroville TOC (10YR 200YR)
Oroville Pool Elevation (10YR 200YR)
Oroville Inflow and Release (cfs)
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Oroville Inflow
Oroville Release (10YR 25YR)
Oroville Release (10YR 50YR)
Oroville Release (10YR 100YR)
Oroville Release (10YR 200YR)
2
9
16
23
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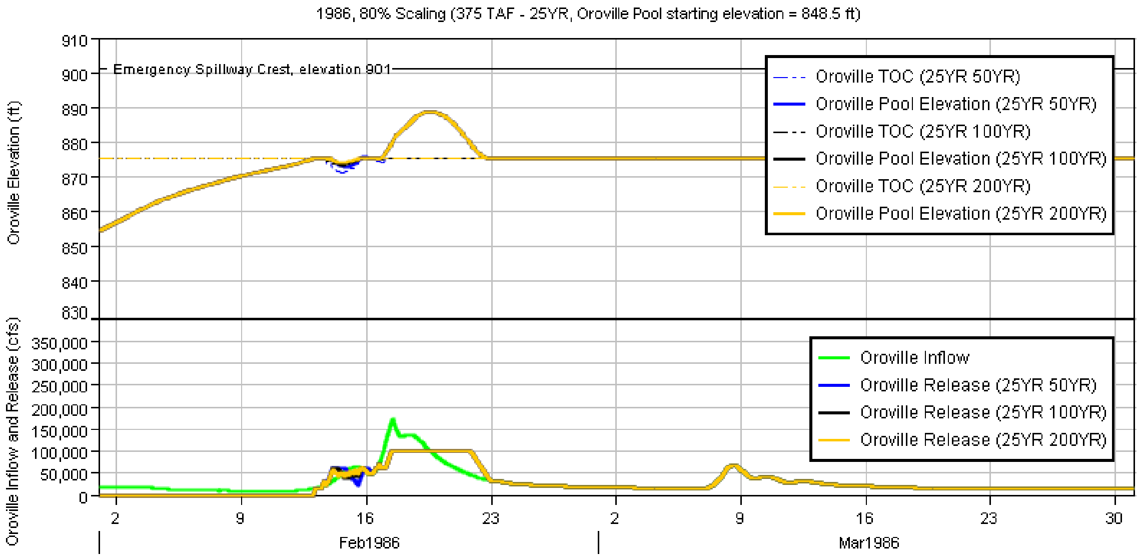
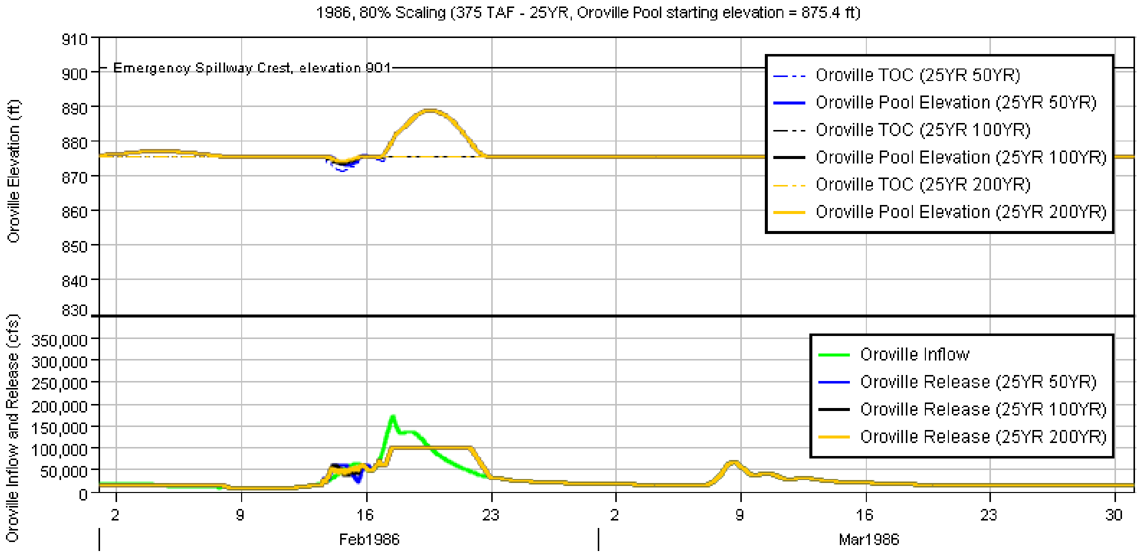
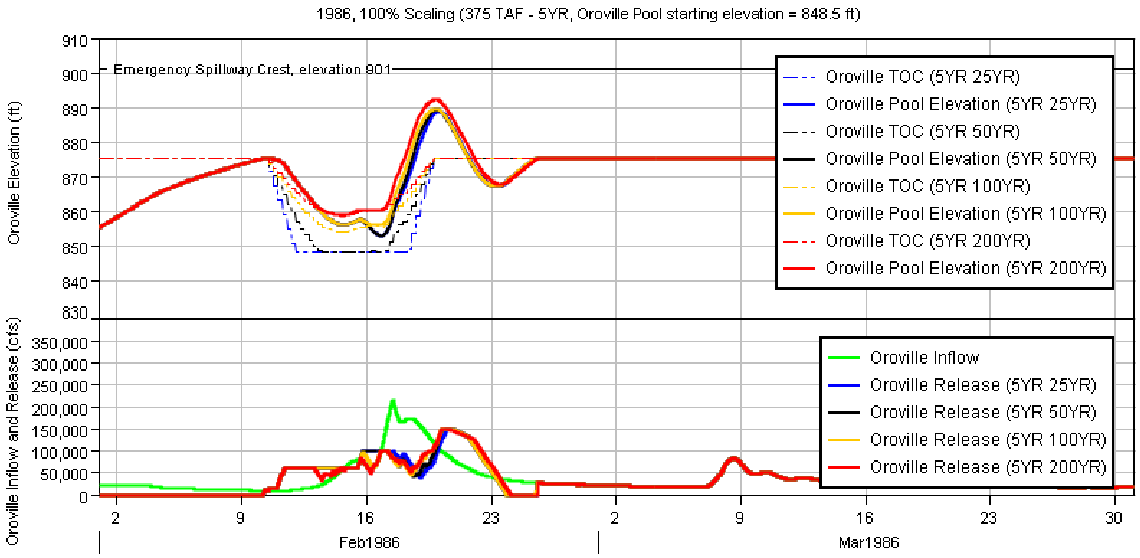
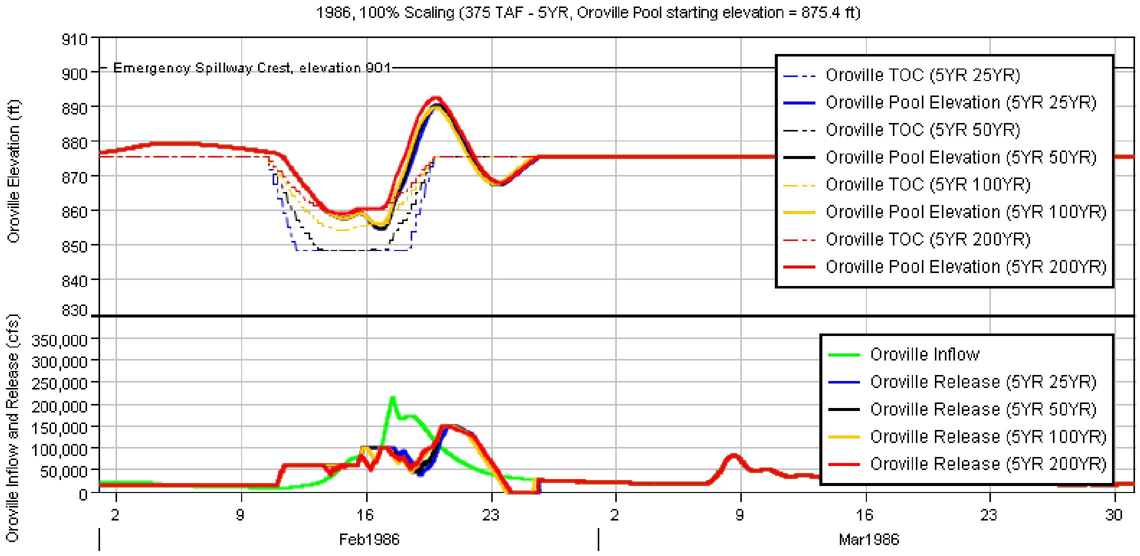
9
16
23
30
Feb1986
Mar1986


1986, 80% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 848.5 ft)


1986, 80% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 875.4 ft)


1986, 100% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 848.5 ft)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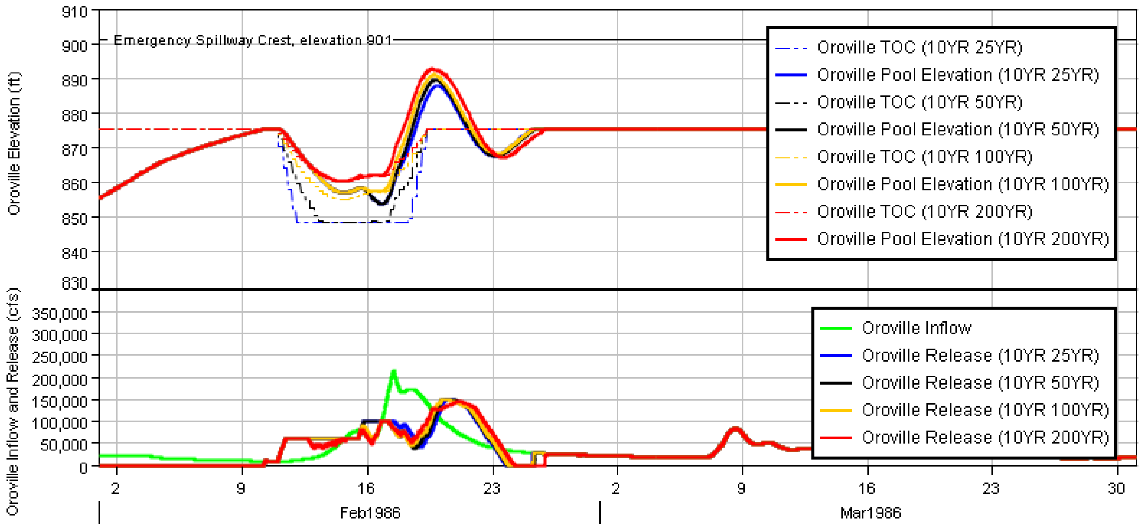

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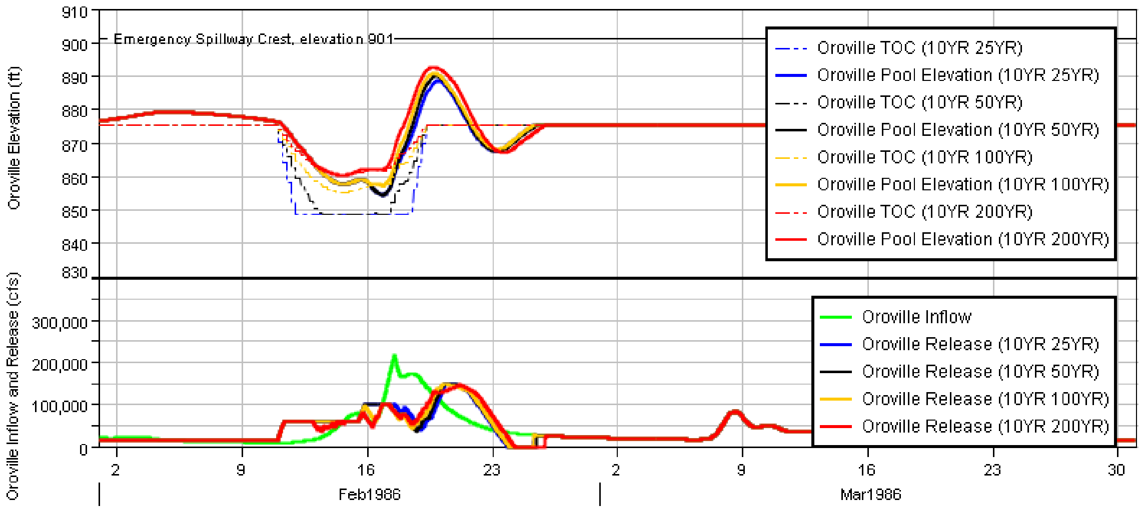

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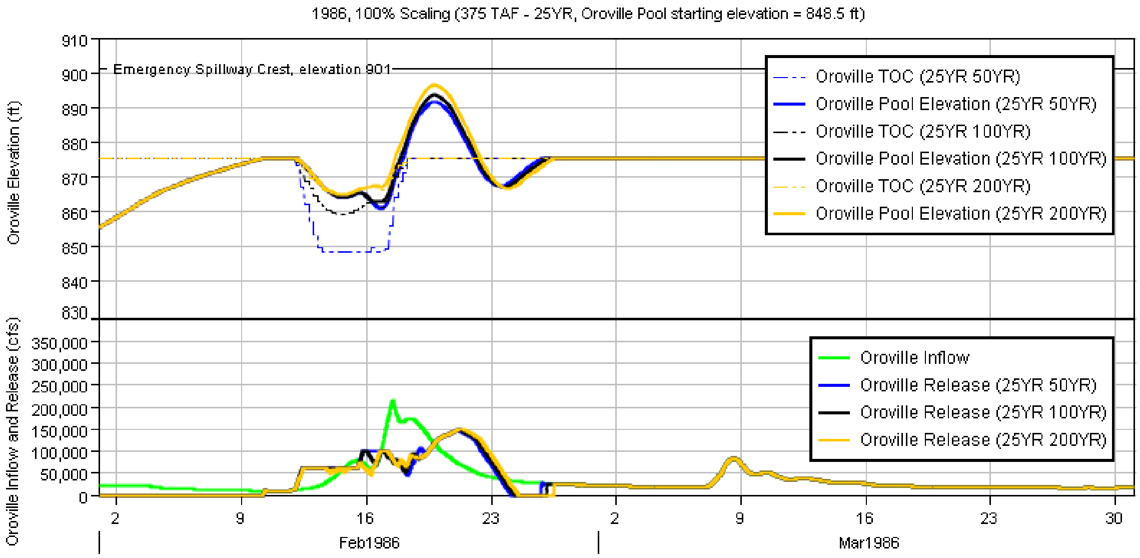
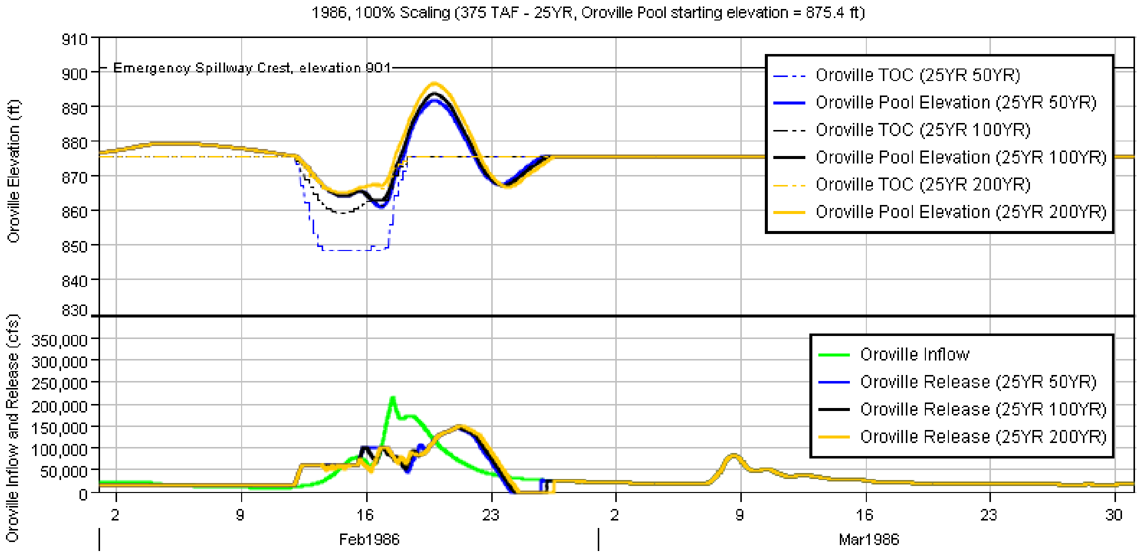
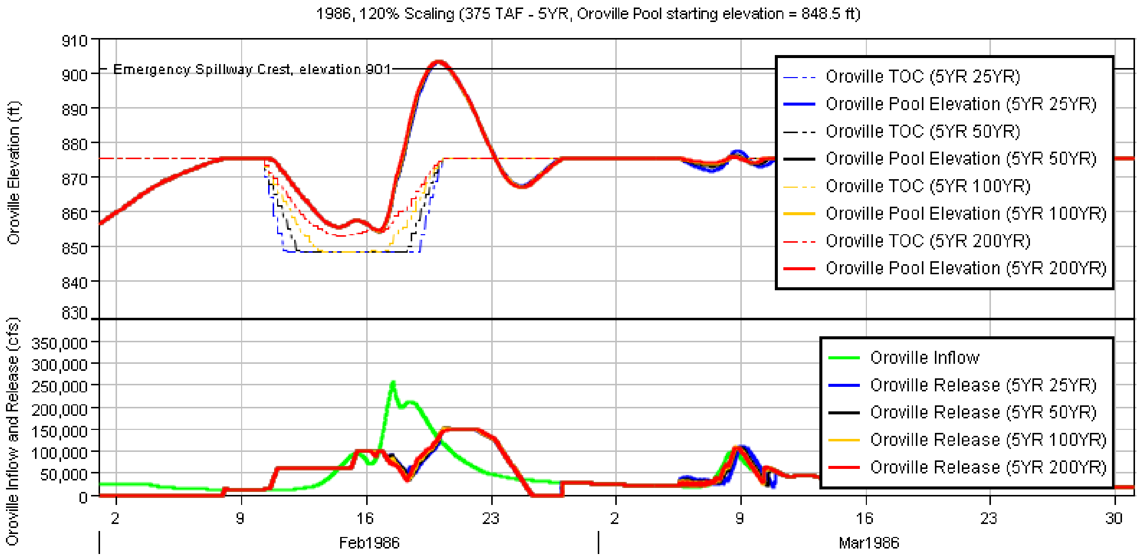


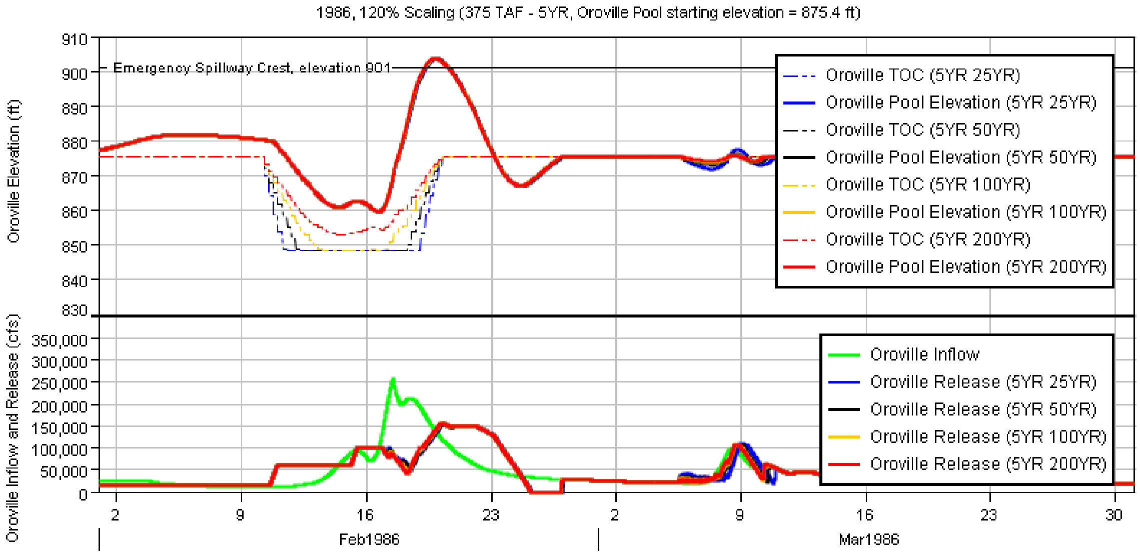
1986, 100% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 848.5 ft)



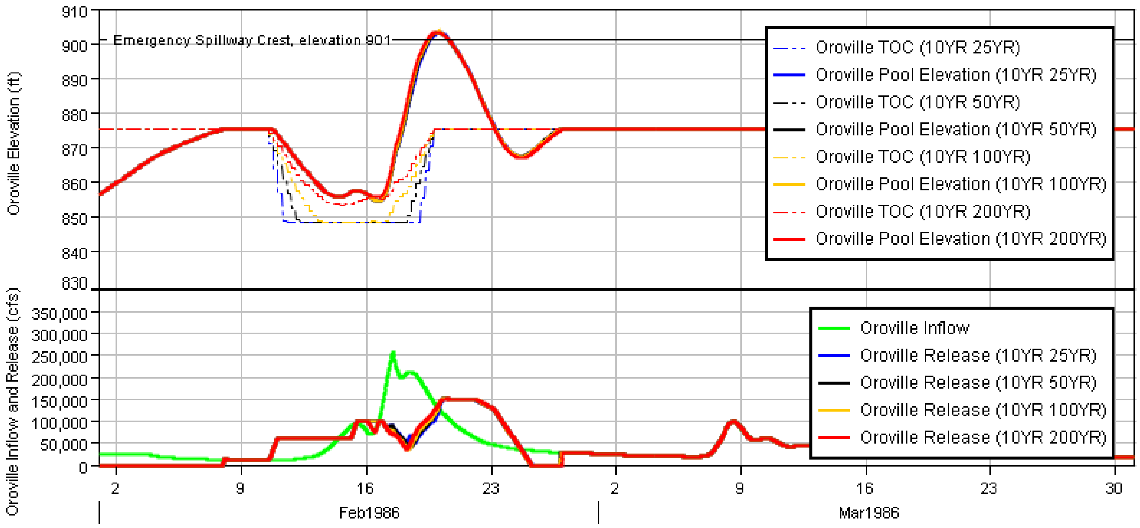
1986, 100% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 875.4 ft)

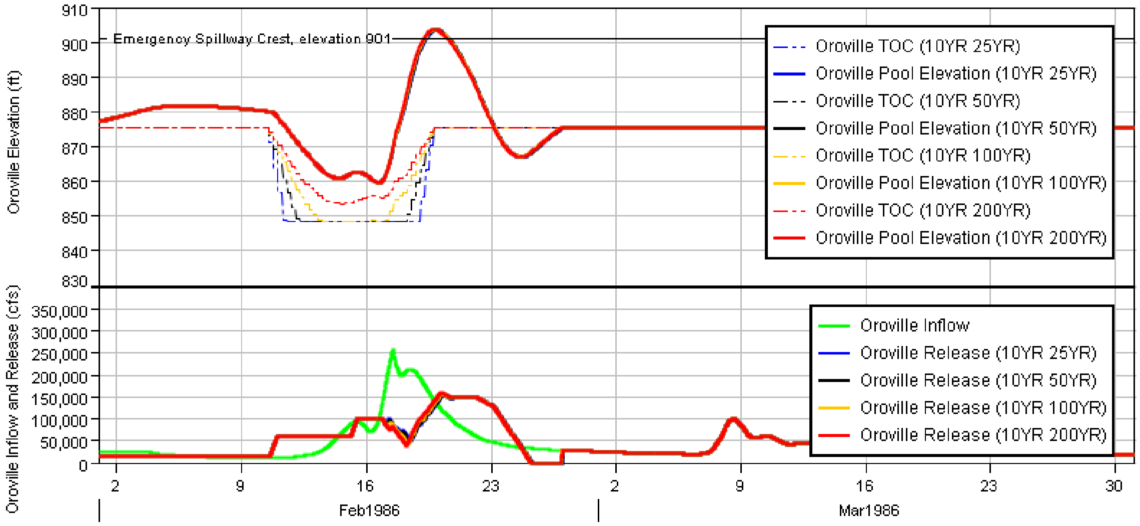


1986, 120% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 848.5 ft)



1986, 120% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 875.4 ft)


1986, 120% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 848.5 ft)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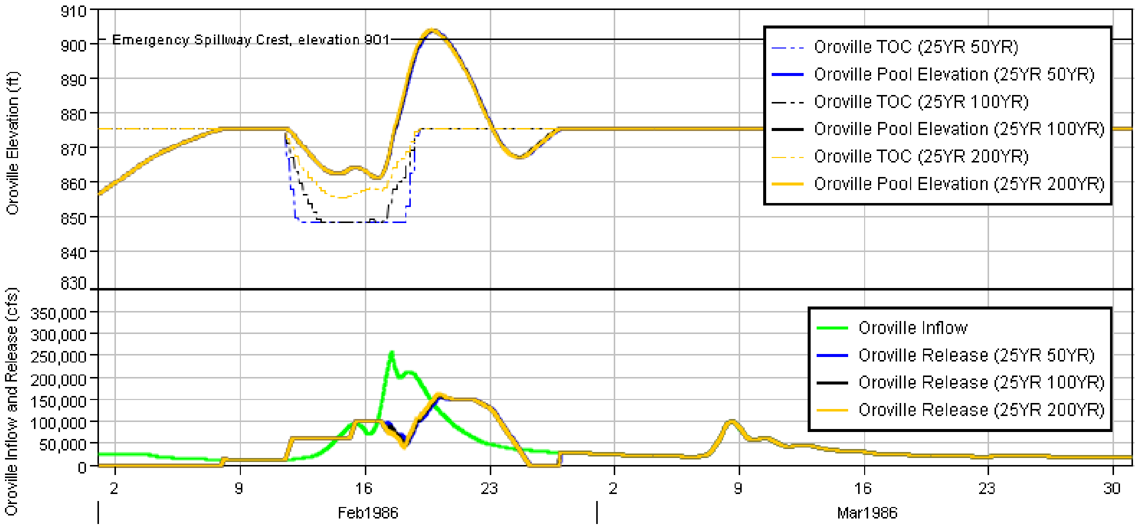
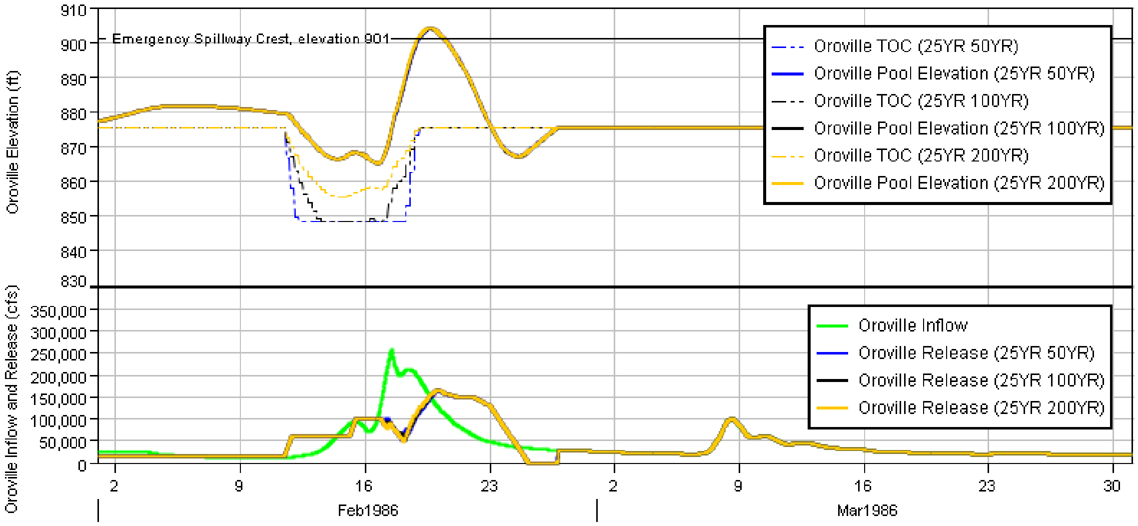
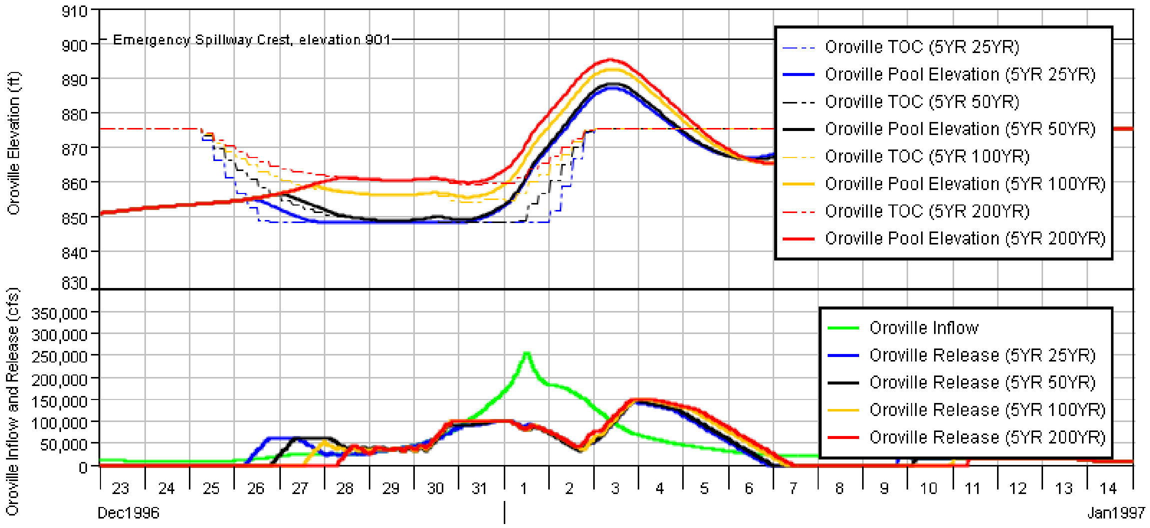
1986, 120% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 848.5 ft)



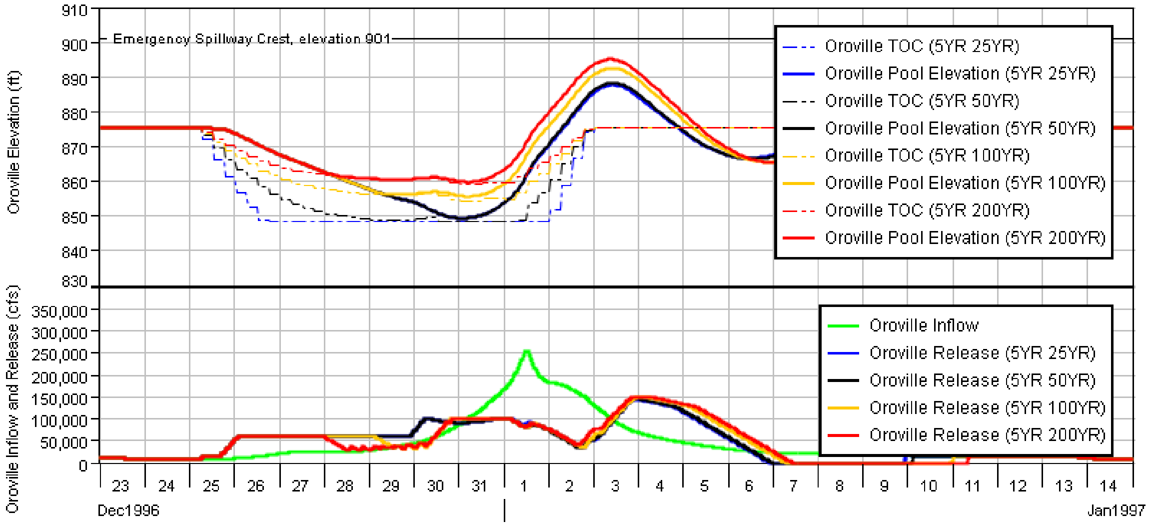
1986, 120% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 875.4 ft)

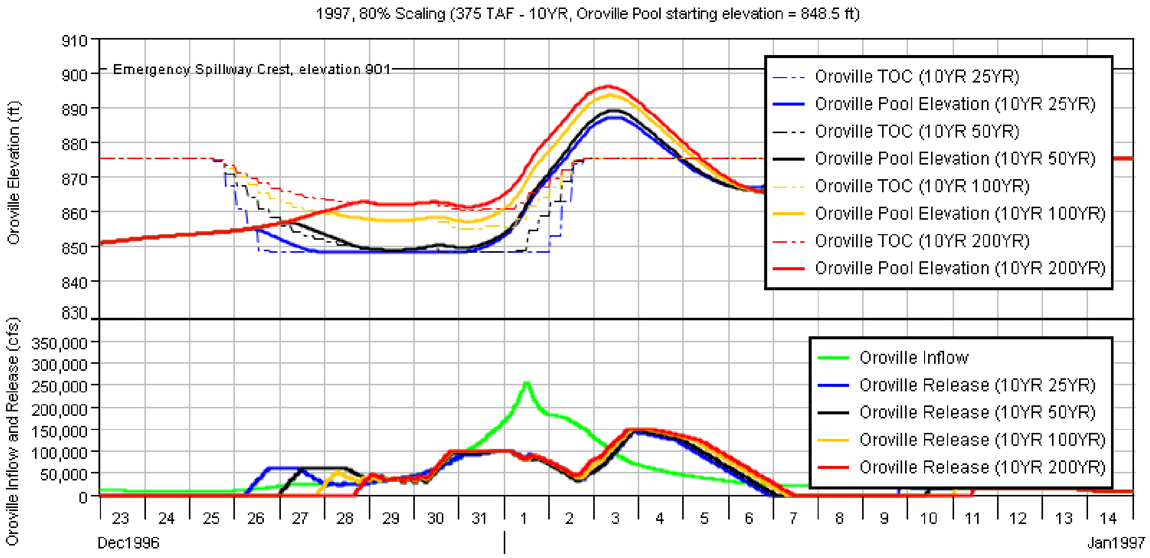


1997, 80% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 848.5 ft)

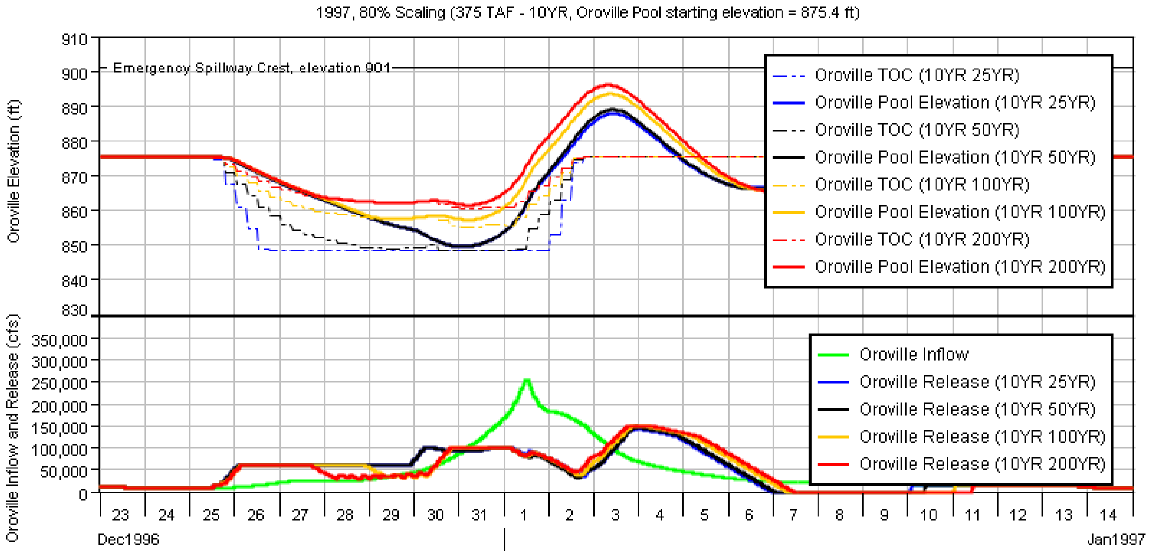


1997, 80% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 875.4 ft)





1997, 80% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 848.5 ft)



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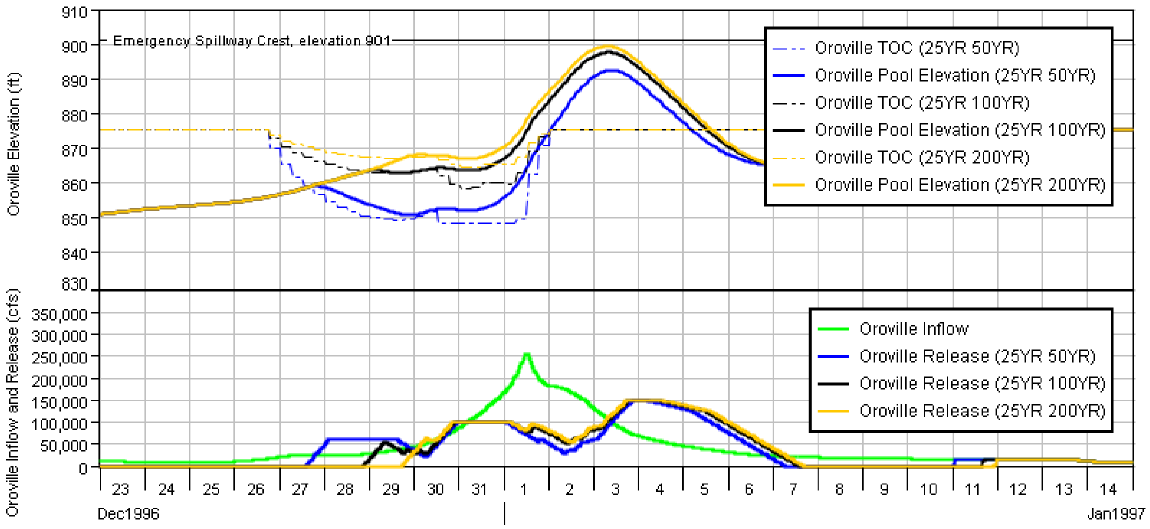
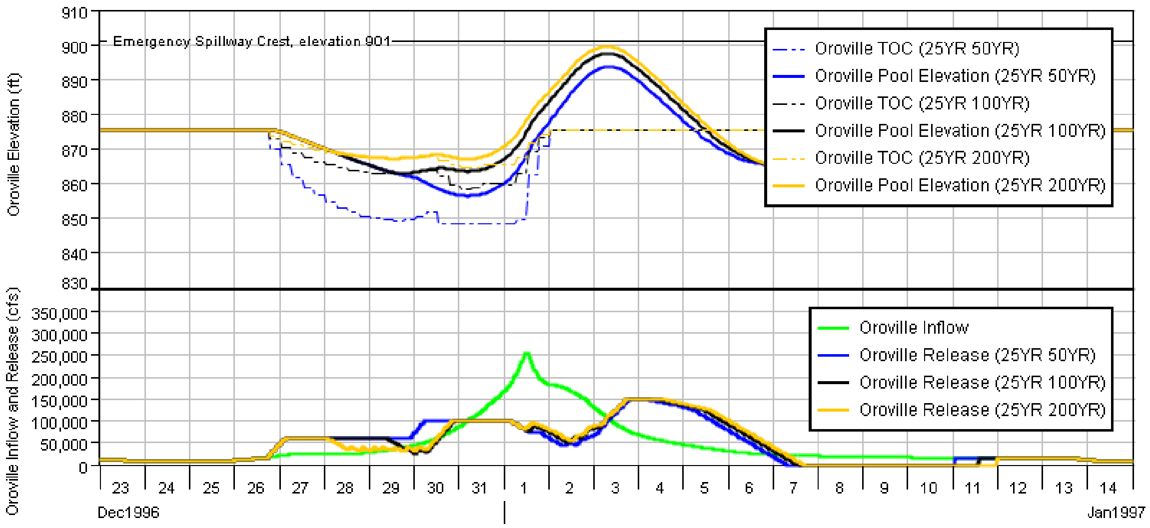
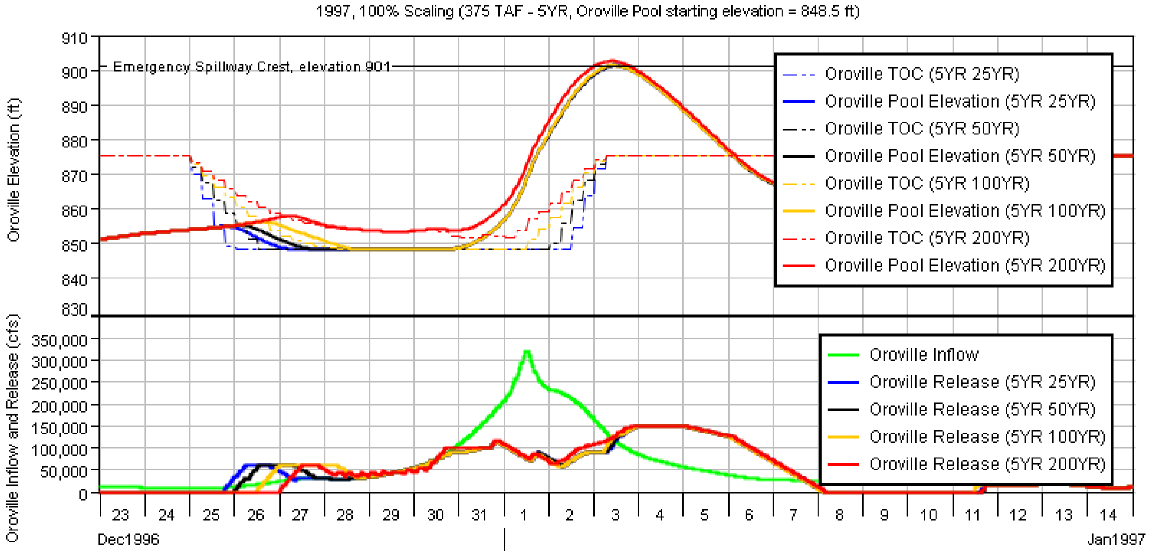
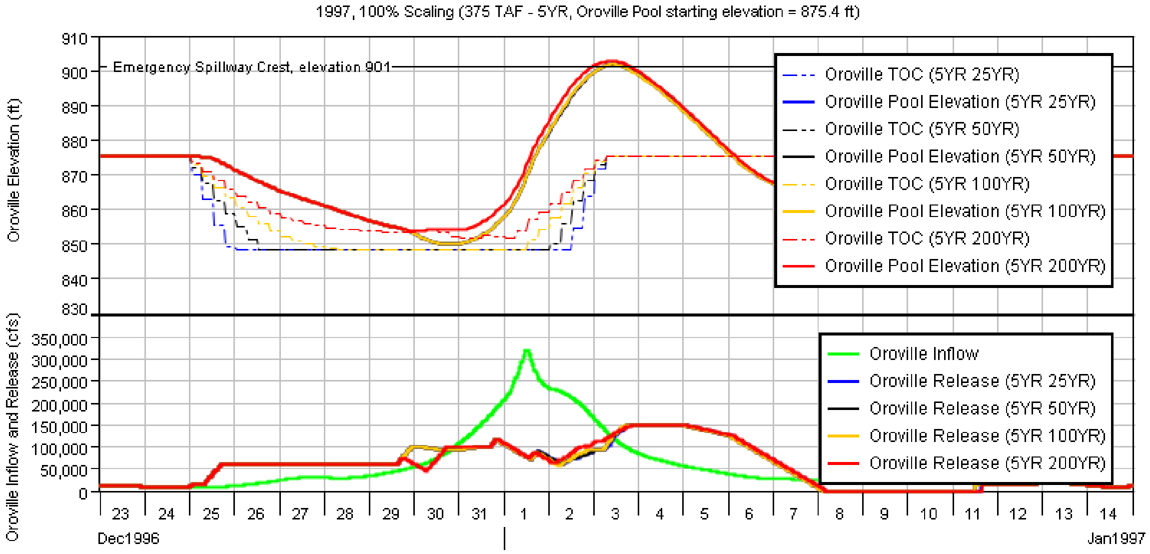


1997, 80% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 848.5 ft)



1997, 80% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 875.4 ft)


1997, 100% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 848.5 ft)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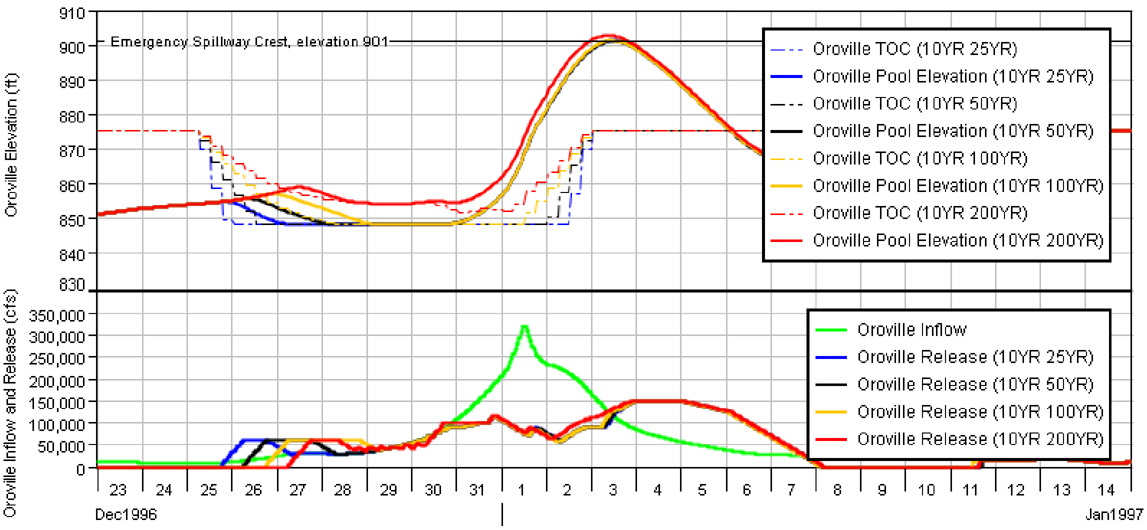
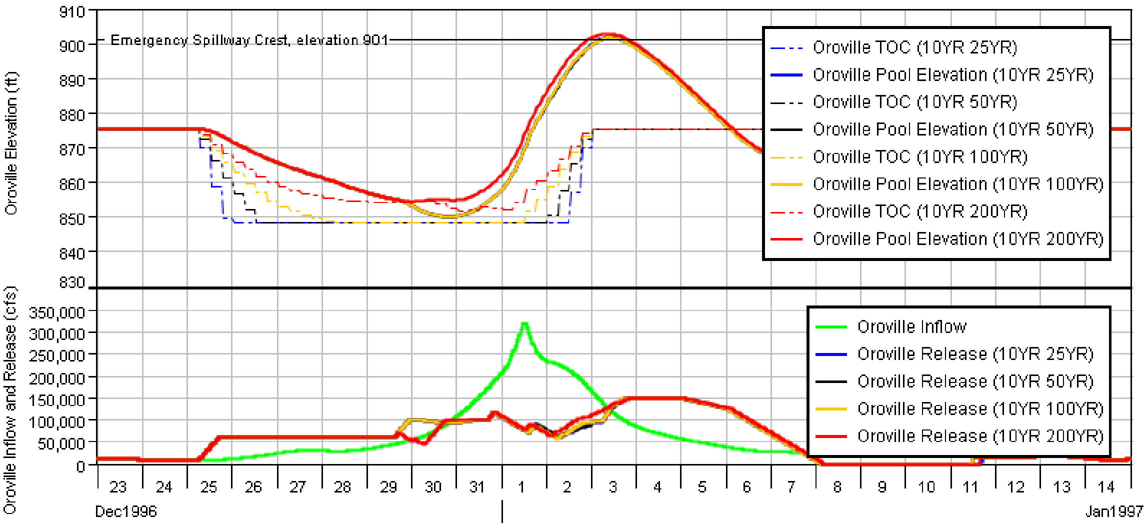
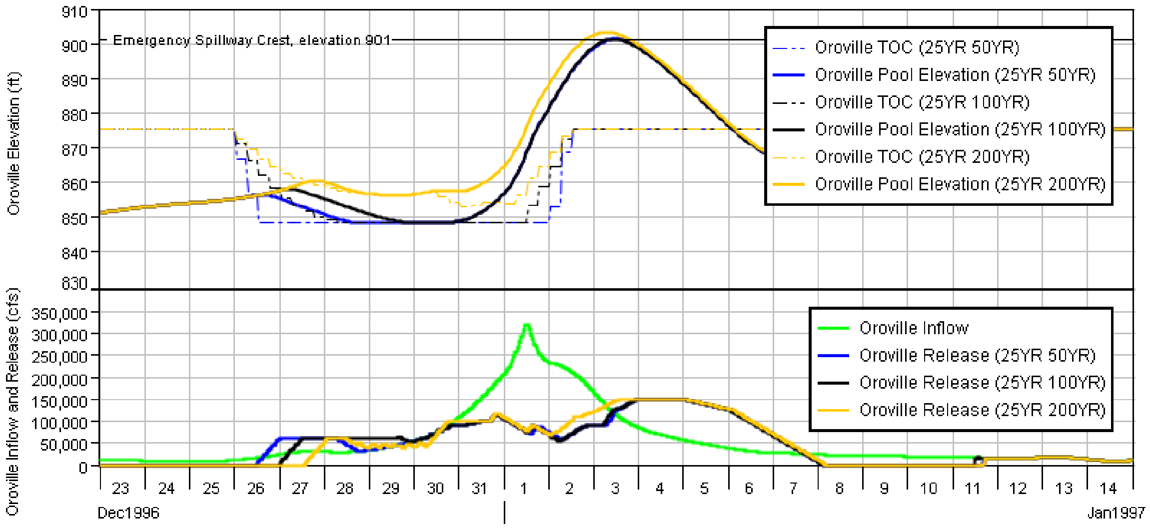


1997, 100% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 848.5 ft)

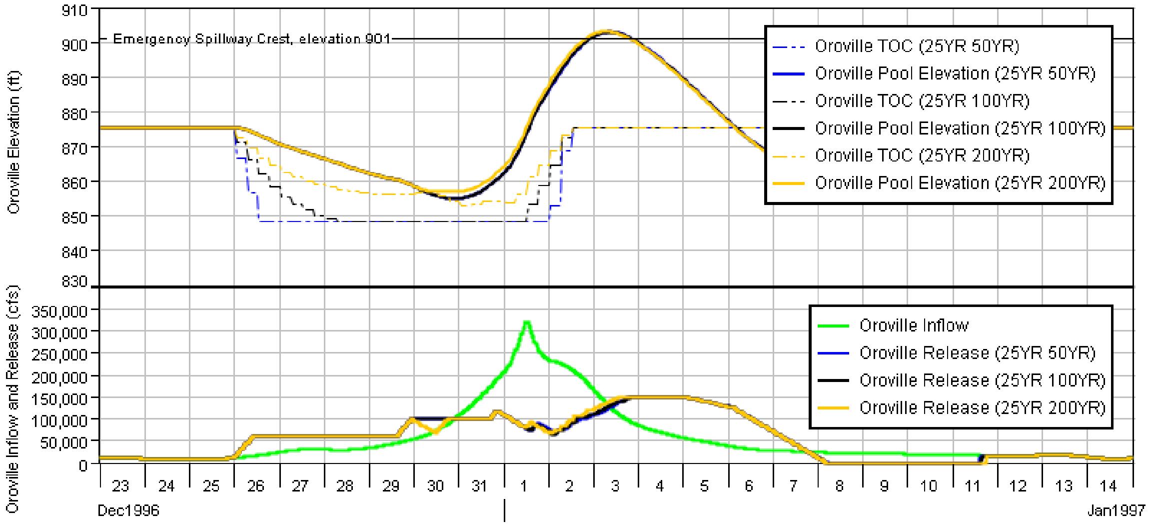


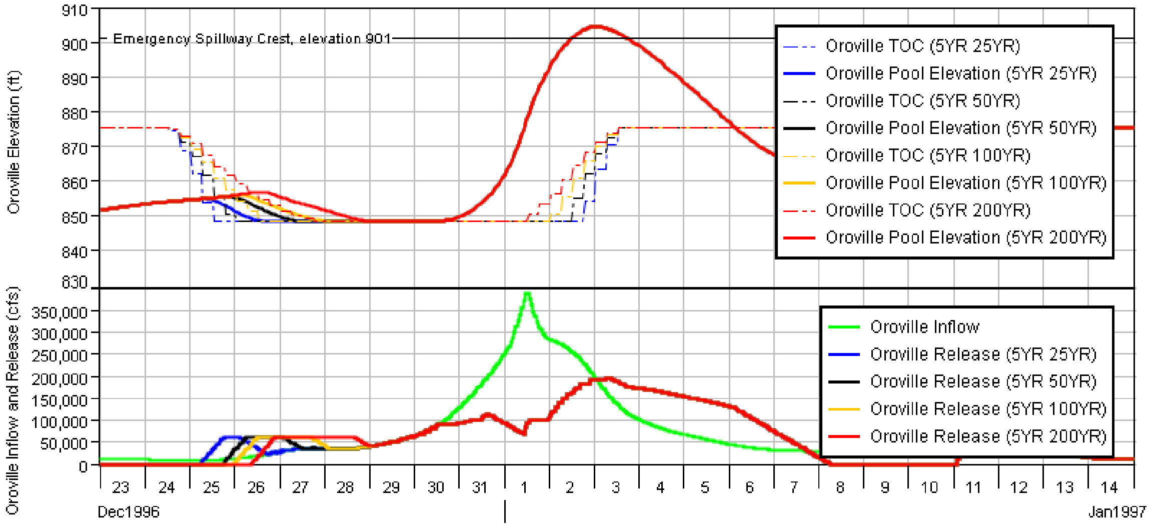
1997, 100% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 875.4 ft)

1997, 100% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 848.5 ft)

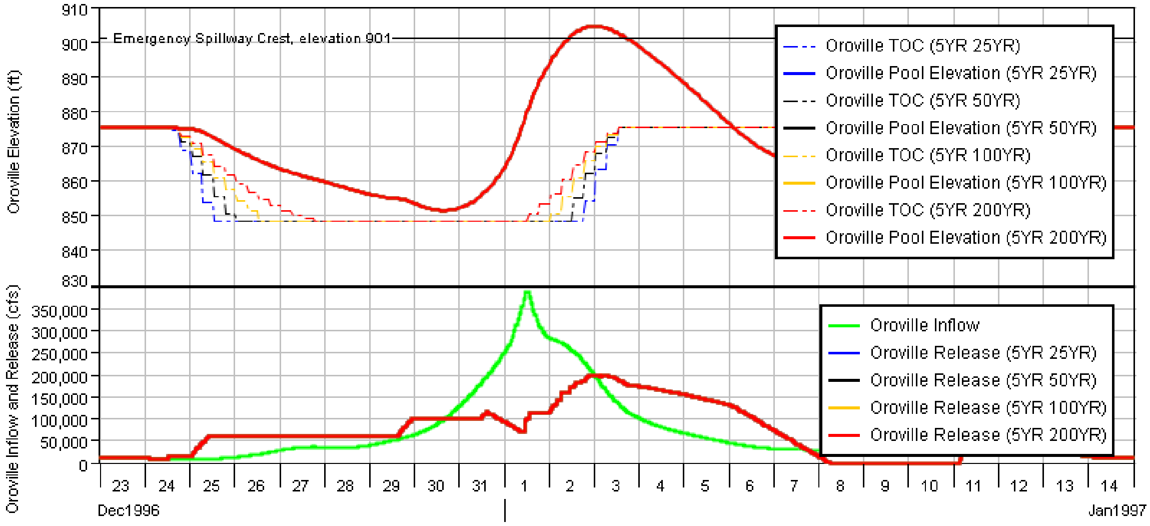


1997, 100% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 875.4 ft)



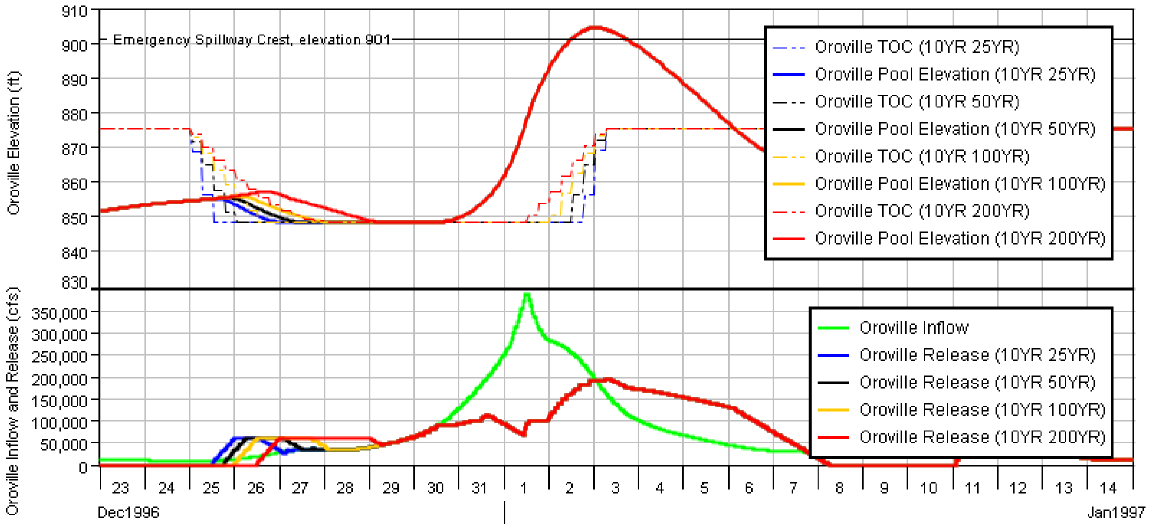


1997, 120% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 848.5 ft)

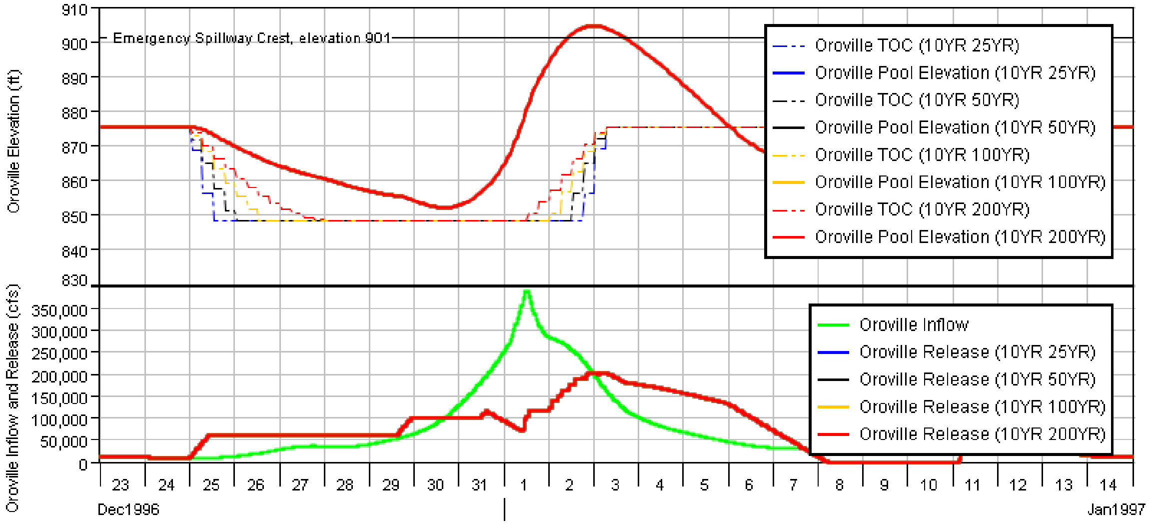


1997, 120% Scaling (375 TAF - 5YR, Oroville Pool starting elevation = 875.4 ft)

1997, 120% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 848.5 ft)



1997, 120% Scaling (375 TAF - 10YR, Oroville Pool starting elevation = 875.4 ft)



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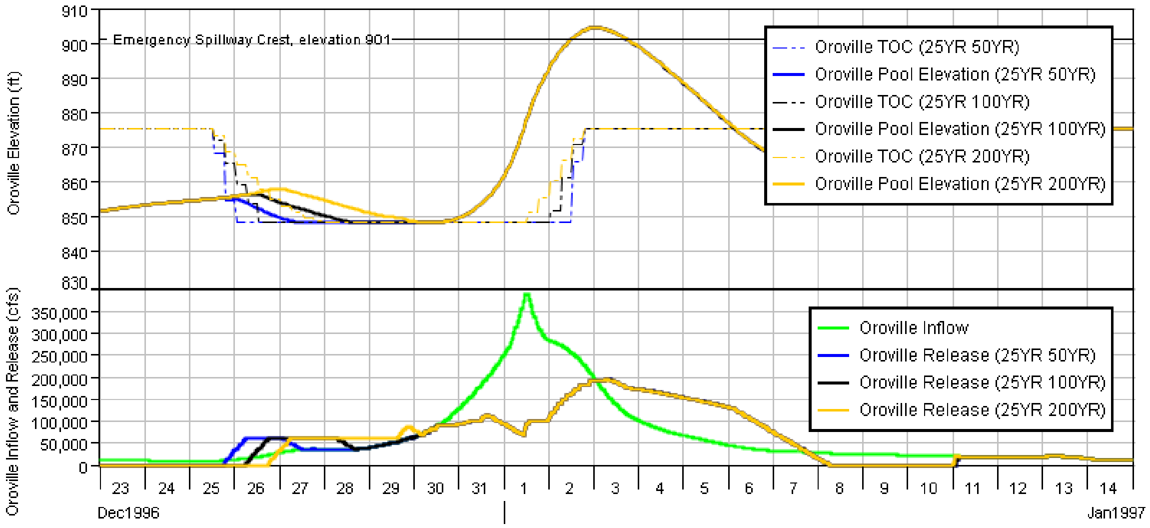
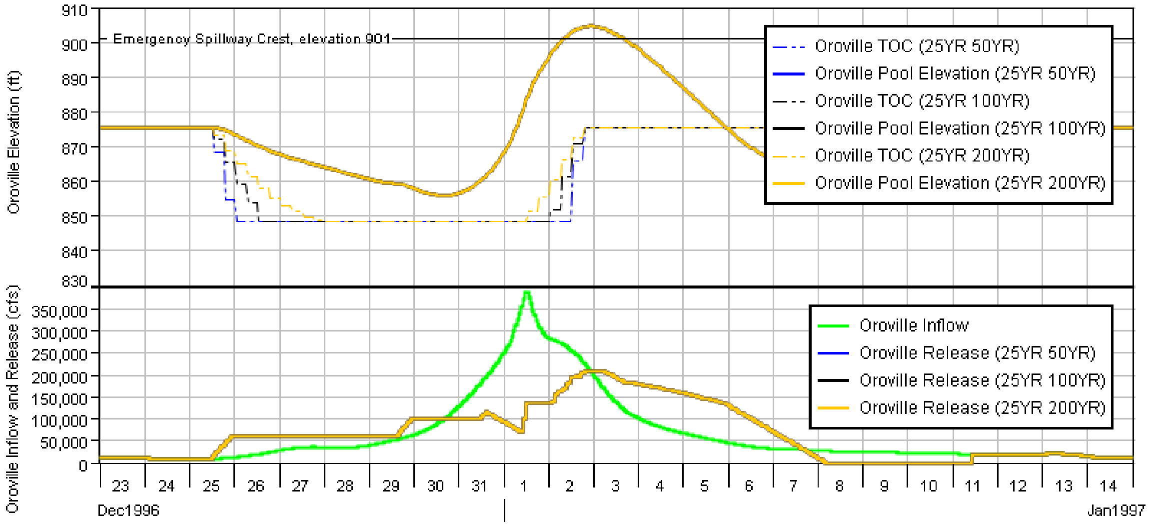


1997, 120% Scaling (375 TAF - 25YR, Oroville Pool starting elevation = 875.4 ft)



Appendix G—ORO-NBB At-Site Alternative FIRO Guide Curve (Section 4)

G.1 Yuba-Feather Forecast Informed Reservoir Operations

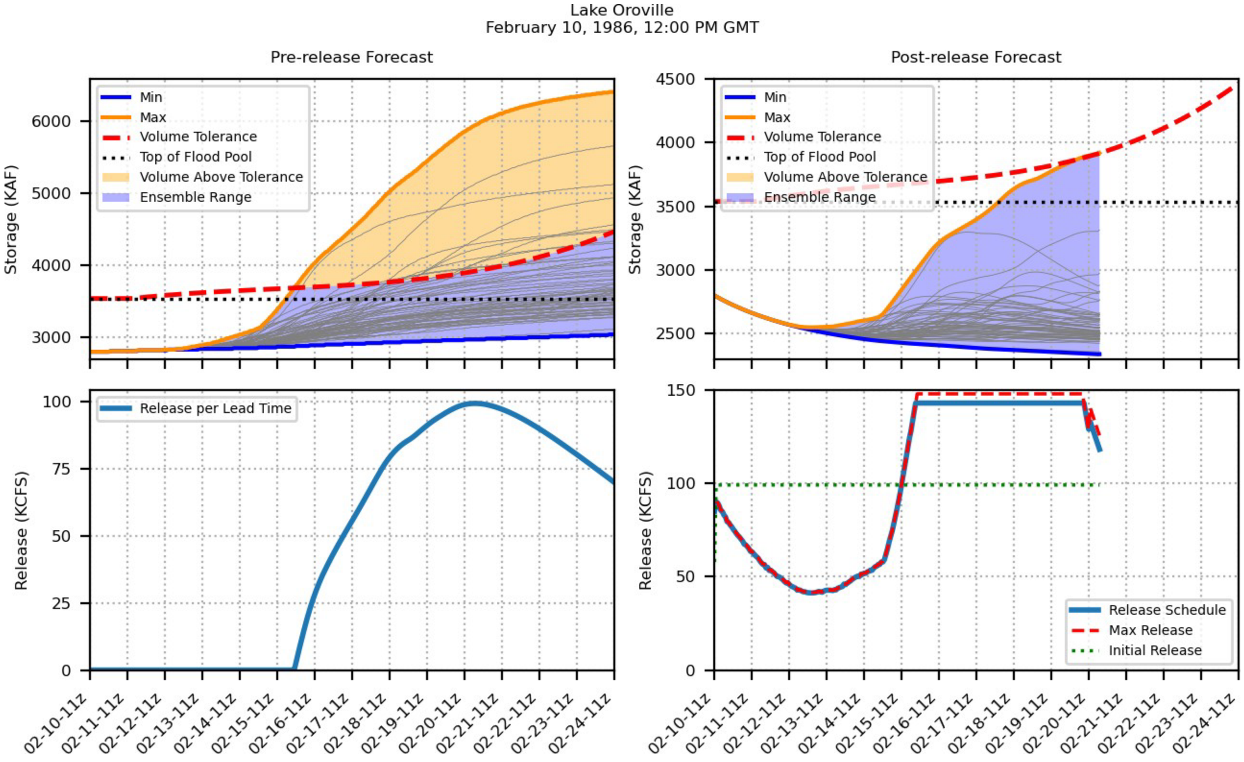


Figure G-1. *Development of Ensemble Forecast Operations Alternatives for Lake Oroville and New Bullards Bar Reservoir*

G.2 Background

The Yuba and Feather River (Y-F) system, located within the Sacramento River Flood Control Project, is an integrated system of levees, dams, and bypass channels. The Y-F system contains 2 primary reservoirs, Lake Oroville and New Bullards Bar Reservoir, that are operated for flood control, water supply and hydro power generation (Yuba-Feather Forecast-Coordinated Operations Program, 2017).

Lake Oroville (Oroville), located on the Feather River, was constructed by the U.S. Army Corps of Engineers (USACE) and is operated by the California Department of Water Resources (DWR) and has a total capacity of 3,870 thousand acre-feet (KAF). The flood control and conservation storage capacity of the reservoir are established by a series of seasonally varying guide curves defined in the Water Control Manual (WCM) (U.S. Army Corps of Engineers, 1970), where a single curve from the series is activated based on established thresholds of accumulated basin precipitation. The dam at Oroville consists of a series of outlet structures, where the primary flood control outlet structure is a gated spillway at elevation 813.6-feet above mean sea level (ft msl) with a maximum release capacity of 308 thousand cubic feet per second (KCFS). Oroville also has an ungated spillway at 922-ft msl. During heavy winter storms, storage levels and releases from Oroville are managed to minimize flooding downstream on the Feather River at Yuba City.

New Bullards Bar Reservoir (NBB), located on the Yuba River, was constructed by the USACE and is operated by the Yuba County Water Agency (Yuba Water) and has a total capacity of 1,010 KAF. The flood control and conservation capacity of the reservoir are established by a seasonally varying guide curve defined in the WCM (U.S. Army Corps of Engineers, 1972), which establishes a conservation capacity of 796 KAF during the wet season (September 15 to March 30) and 965 KAF during the dry season (June 1 to September 15). The dam at NBB consists of a series of outlet structures, where the primary flood control outlet structure is a gated spillway at elevation 1910-ft msl with a maximum release capacity of 172 KCFS. The USACE and Yuba Water are currently evaluating the construction of an additional gated spillway, called the Atmospheric River Control (ARC) spillway. A number of design options have been evaluated, but the current preferred design includes an invert elevation of 1874.5-ft msl and a max release capacity of 63 KCFS. During heavy winter storms, storage levels and releases from NBB are managed to minimize flooding downstream on the Yuba River at Marysville.

The Yuba and Feather River Basins present unique operational challenges to managing flows downstream of the reservoirs. Oroville and NBB are operated by different agencies, and there is a shared responsibility for both projects to keep flows from exceeding channel capacities. The coordination of reservoir releases is critical to achieving this and to meet maximum downstream objective flows as prescribed by the current Water Control Manuals for Oroville and NBB. The Forecast Coordinated Operations (F-CO) program is a multi-agency partnership between DWR, Yuba Water, NOAA and the USACE that seeks to reduce peak flood flows through improved river flow forecasting and improved coordination of flood control operations between both reservoirs (Yuba-Feather Forecast- Coordinated Operations Program, 2017).

This report describes the development and evaluation of Forecast Informed Reservoir Operations (FIRO) alternatives for Oroville and NBB to support the Y-F FIRO Preliminary Viability Assessment (PVA). The objective of the Y-F FIRO is to reduce flood risk for the regions downstream of Oroville and NBB, while not impacting the water supply reliability of these reservoirs.

This report focuses on alternatives that incorporate the Ensemble Forecast Operations (EFO) methodology, which is a type of FIRO that utilizes ensemble streamflow predictions to evaluate forecast uncertainty to help inform release decisions. This methodology was originally developed for Lake Mendocino (Delaney, et al., 2020) located on the Russian River in Mendocino County, California and was critical in demonstrating the viability of FIRO for Lake Mendocino through evaluations completed in both the Preliminary Viability Assessment (PVA) (FIRO Steering Committee, 2017) and Final Viability Assessment (FVA) (FIRO Steering Committee, 2020). EFO was later evaluated for the Prado Dam PVA (Ralph, et al., 2020) and was critical to demonstrating viability of FIRO for that system as well. The methodologies evaluated for Lake Mendocino and Prado Dam incorporated forecasts of risk or probabilities of exceeding defined critical storage thresholds. These evaluations both demonstrated that implementation of EFO would improve water supply reliability without increasing flood risk to downstream communities.

Like the methodologies developed for Lake Mendocino and Prado Dam, the methodologies developed for Oroville and NBB utilize the ensemble range to evaluate inflow forecast uncertainty to inform operations, however in place of evaluating forecasted risk above a storage threshold, the methodologies developed for Oroville and NBB evaluate forecasted storage volumes that exceed a defined storage threshold. This methodology is described in further detail below and design of alternatives, model formulation, model results and discussion are presented in subsequent sections.

G.3 Ensemble Forecast Operations Methodology

The EFO methodology developed for Oroville and NBB evaluates storage volumes above the top of the flood pool, elevations 900 feet above mean sea level (msl) (3,538 KAF) at Oroville and 1956 feet msl (965 KAF) at NBB. This mu

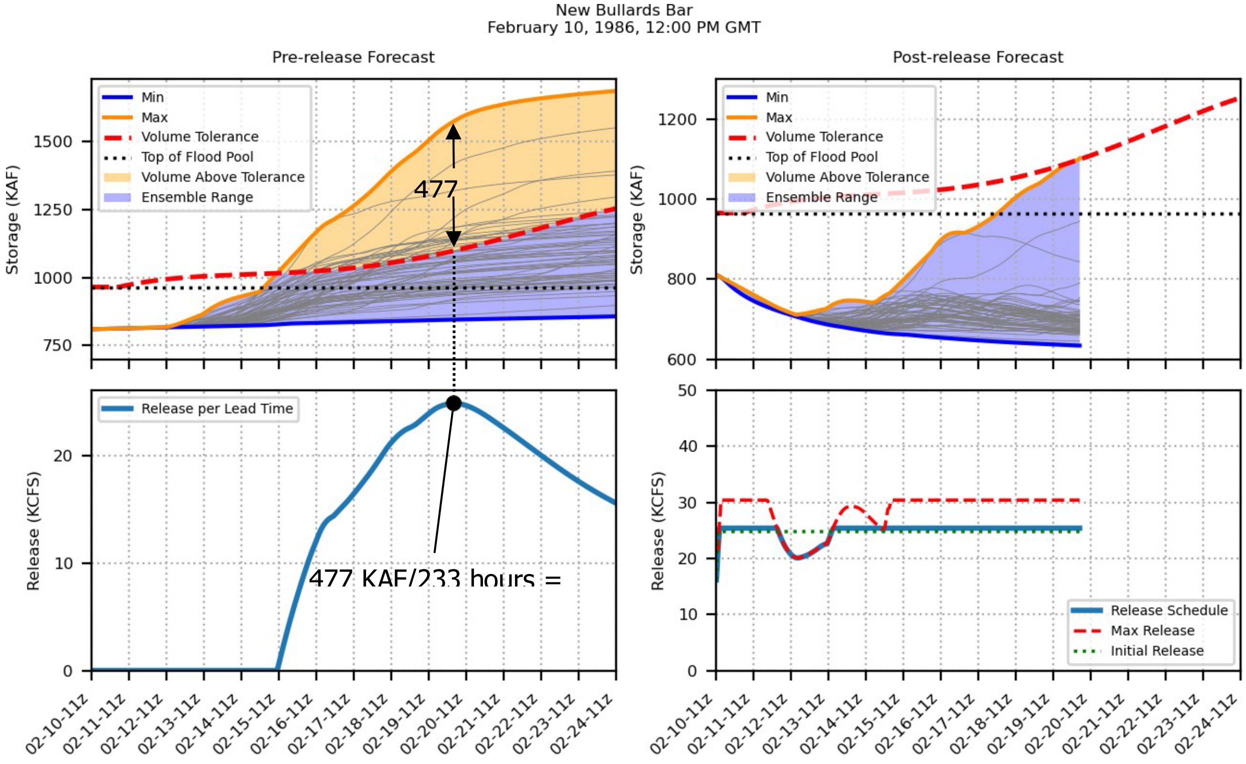


Figure G-2. *February 10, 1986 New Bullards Bar example of EFO methodology.*

Storage levels of the maximum ensemble range that exceed the volume tolerance curve over the duration of the forecast, shown as the orange shaded region in Figure G-2, are used to calculate release schedules. Exceedance volumes are divided by lead time to calculate release rates for each lead time, which is shown in the lower left panel of Figure G-2 for the February 10, 1986 example. This figure shows that at a lead time of 233-hours the volume exceeds the tolerance curve by 477 KAF, and this volume divided by 233 hours of lead time (applying necessary unit conversions) yields in a release of 24.8 thousand cubic feet per second (KCFS), which (as can be seen in the lower left panel of Figure G-2) is the maximum lead time release.

To generate a release schedule, the maximum lead time release is evaluated against the forecasted release constraints. For NBB these release constraints include outlet release capacity, release rate of change limits, and the maximum downstream objective flow for the Feather River at Marysville of 180 KCFS. The formulation of release schedules for the February 10, 1986 example is summarized in the lower right panel of Figure G-2 where the initial release schedule of 24.8 KCFS is shown as the green dotted line. For this example, the forecasted maximum release constraint (shown as the red dashed line in the lower right panel) is mostly determined by the increasing release rate of change limit of 5 KCFS, however, between days 2 and 5 of the forecast horizon, the maximum release is constrained by the release outlet capacity caused by a reduction of forecasted storage (as shown in the upper right panel) and reduced surcharge on the gated spillway structures (current primary spillway and proposed ARC spillway). The initial release schedule is redistributed based on the calculated maximum release such that the total volume of the release is retained if feasible. The final release schedule is shown as the solid blue line in the lower right panel. For this example, it can be seen that the initial release exceeds max release constraint between days 2 and 3 of the forecast, therefore the release schedule is increased for the remaining days so that the total release volume is retained. Note that this release schedule is only adhered to until the forecast is updated the next day (or next forecast issuance) when the process will be repeated.

A similar example for Oroville is provided in Figure G-3 for February 10, 1986 using the 120% scaled hindcast. The top left panel of Figure G-3 shows that at a lead time of 247-hours, the forecasted storage exceeds volume tolerance by 2,024 KAF, and this volume divided by 247-hours of lead time (applying necessary unit conversions) yields in a release of 99.2 KCFS, which (as can be seen in the lower left panel of Figure G-3) is the maximum lead time release.

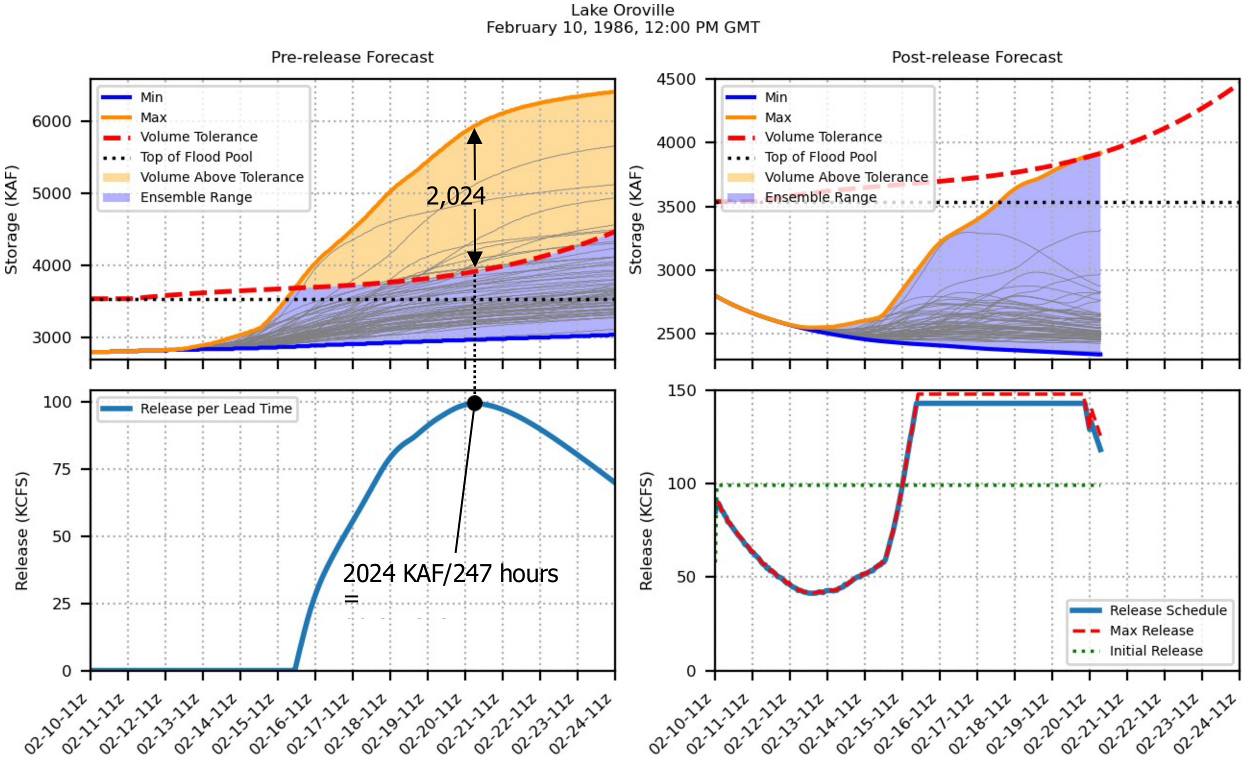


Figure G-3. *February 10, 1986 Lake Oroville example of EFO methodology.*

For the Oroville example, the initial release per lead time of 99.2 KCFS (shown as the dotted green line in the lower right panel of Figure G-3) is evaluated against the release constraints of Oroville which include the outlet release capacity, a maximum release of 150 KCFS, release rate of change limits and the maximum downstream objective flow of 180 KCFS at Yuba City. The forecasted maximum release based on the release constraints is provided as the red dashed line in the lower right panel of Figure G-3. For this example, the first 5 days of the forecast horizon show the maximum release is constrained by the release outlet capacity caused by a reduction of forecasted storage (as shown in the upper right panel) and reduced surcharge on the gated spillway. The final release schedule (shown as the solid blue line in the lower right panel) in this example is constrained by the forecasted maximum release for the first 5 days, therefore, in order to retain the total volume of the initial release, the release schedule is increased for the remaining days of the forecast horizon. Note that, as with the previous example for NBB, this release schedule is only adhered to until the forecast is updated the next day (or next forecast issuance) when the process will be repeated.

G.4 Configuration of EFO Model for Application at Oroville and NBB

This study involved running a reservoir system simulation model for Oroville and NBB reservoirs and evaluating operational outcomes for different management alternatives. The computer model used in this study, called the EFO model, was developed with the Python programming language and was originally developed for the Prado Dam PVA study. For this study that model was expanded to simulate the EFO alternatives developed for Oroville and NBB. The EFO model was developed using an object- oriented programming structure, and provides the basic building blocks common to most reservoir systems through a framework of object classes and sub-classes. A summary of the primary object classes of the EFO model are provided below:

- Junctions: Define locations in a reservoir system where inflows are defined and water balance calculations are performed to compute an outflow. Junction types include reservoirs and flow junctions. Rules can be added to junctions to provide logic for reservoir releases and diversions.
- Inflows: Data inputs for junctions, which can include natural inflows, reach losses (negative inflows) and routed flows from an upstream junction.
- Reach: Define links to route flows from an upstream model junction to a downstream junction.
- Rules: Define logic for setting releases and diversions from model junctions.

Each of the primary class types listed above has an abstract base class (with the keyword “Base” at the end of the class name), and multiple subclasses which inherit and expand from the properties and methods of the base class. A unified modeling language (UML) diagram of the EFO model class structure is provided in Figure G-4.

The model applies reservoir operation rules of Oroville and NBB and water balance calculations to simulate reservoir releases and storage levels. Releases through the controlled outlet are simulated by evaluating a series of rules (called the rule stack), which are evaluated in successive order that is defined in the rules stack.

The primary purpose of the EFO model is to simulate forecast based reservoir rules, and the model has a series of classes for that purpose. These include time classes that define time steps both as a continuous array of monotonically increasing time steps, and a forecast time class that define forecast lead times for each forecast cycle. These time classes allow model objects, such as junctions, reaches, rules, and inflows, to be defined for either a continuous time model or a forecast-based model. The primary forecast based class is the EFO class that allows parallel simulation of a model for each member of an ensemble streamflow forecast.

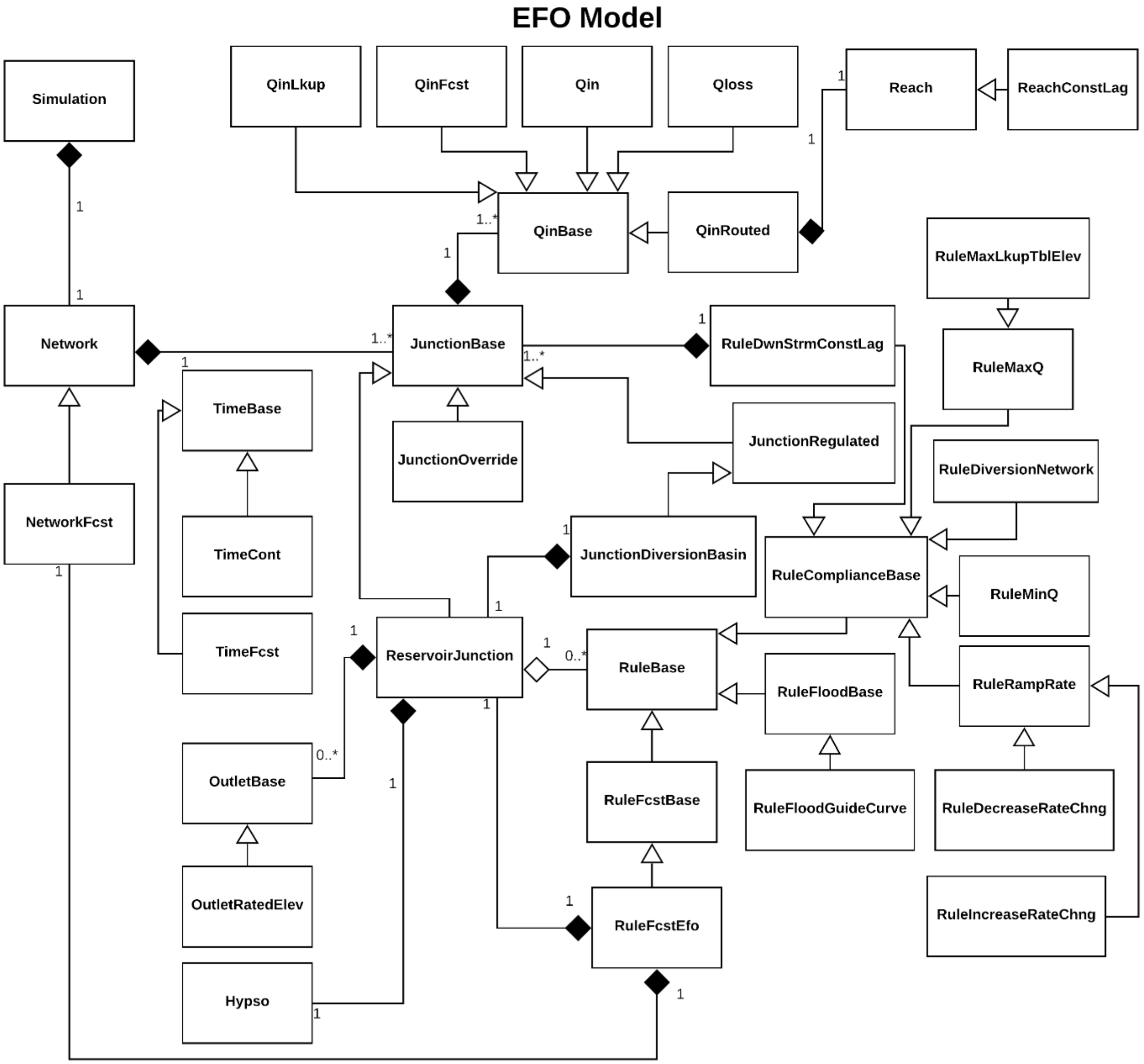


Figure G-4. *Unified modeling language diagram of the EFO model.*

Using the object classes of the EFO model code, a model was developed for the Y-F system, called the Yuba Feather EFO model (Y-F EFO), to simulate and evaluate FIRO alternatives at Oroville and NBB reservoirs. The majority of the parameters used to define the Y-F EFO model were sourced from a HEC- ResSim model (Y-F ResSim) provided by HDR Engineering (California Department of Water Resources, 2021).

Oroville and NBB contain multiple control outlets to support flood control operations, hydropower generation, and water conservation releases. Controlled outlet rating curves were defined in the Y-F EFO model for both reservoirs as total release capacity which were provided in the Y-F ResSim model. The total Oroville controlled release capacity rating curve is shown in Figure G-5. The simulation of NBB alternatives incorporated two different release capacities: 1) current release capacity of the existing controlled outlets, and 2) incorporation of the proposed ARC spillway to increase total release capacity for flood control operations. Rating curves for the additional spillway were provided by MBK Engineers. The release capacity rating curves for NBB are shown in Figure G-6.

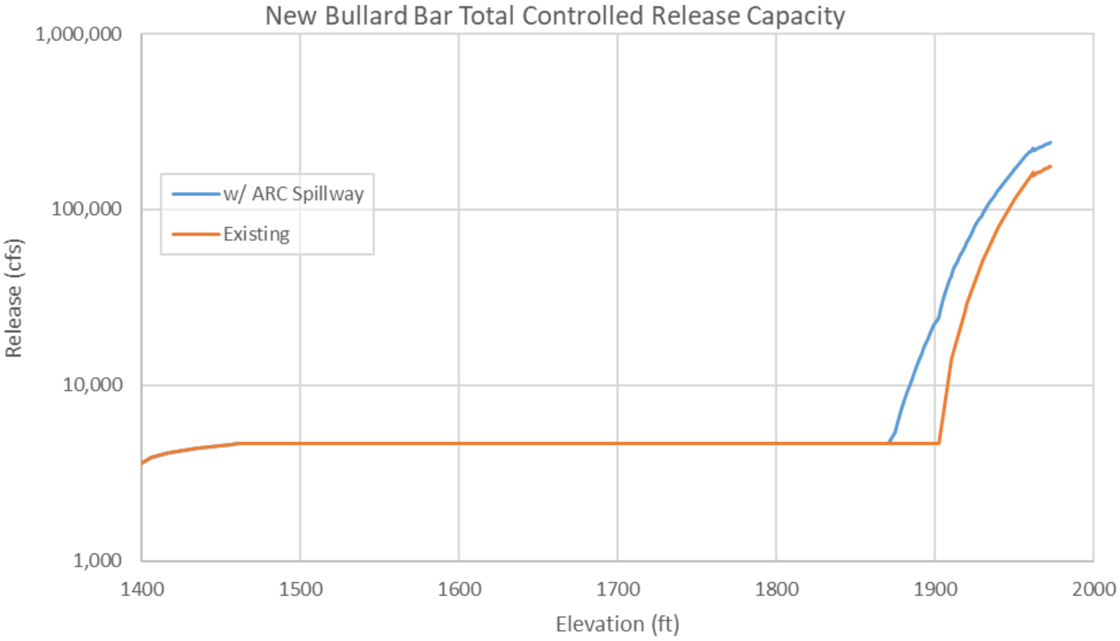


Figure G-5. *Lake Oroville controlled outlet rating curve.*

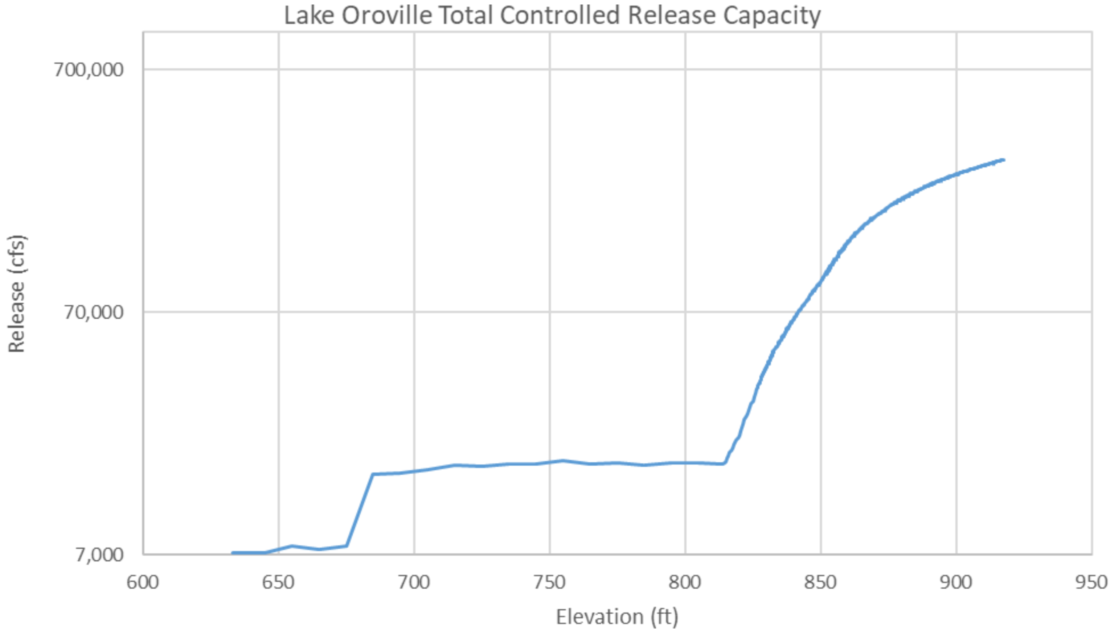


Figure G-6. *New Bullards Bar controlled outlet rating curve with proposed ARC spillway and existing release capacity (without proposed ARC spillway).*

The release rating curve for the spillway at Oroville used in the Y-F EFO model was provided in the Y-F ResSim model and is shown in Figure G-7. NBB does not have an uncontrolled spillway, because under very extreme events uncontrolled releases are designed to flow over the top of dam. The rating curve for releases over the top of NBB dam were also provided in the Y-F Resim model and is shown in Figure G-8.

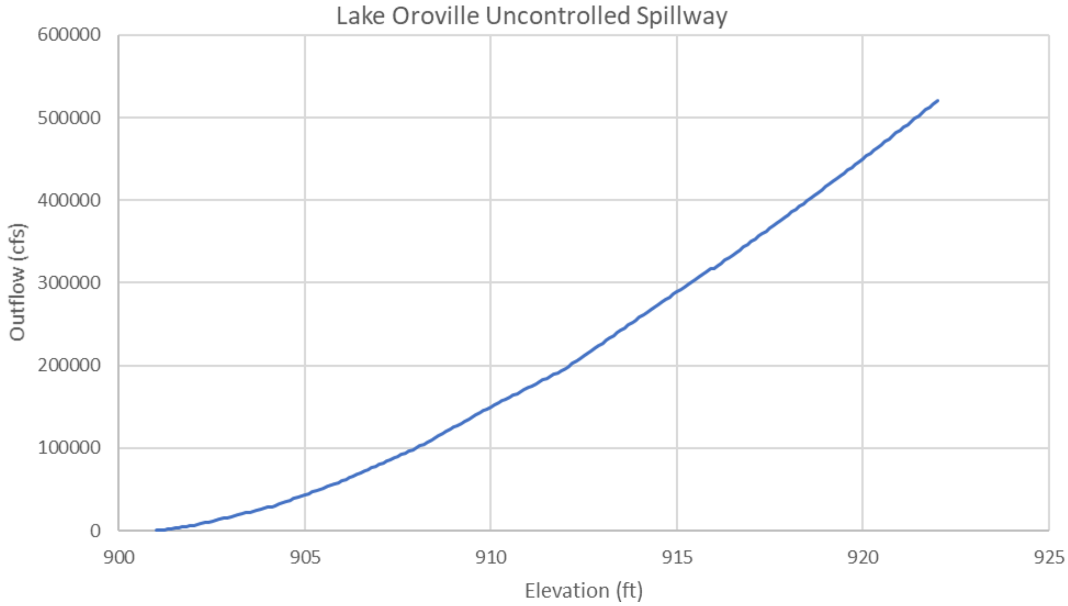


Figure G-7. *Lake Oroville uncontrolled spillway rating curve.*

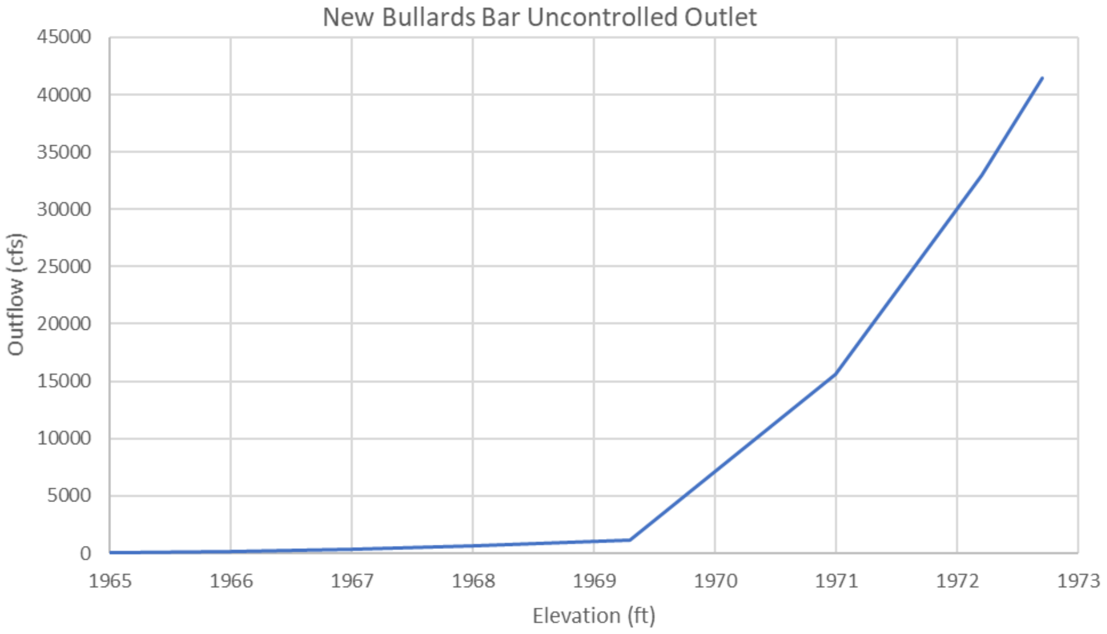


Figure G-8. *New Bullards Bar uncontrolled outlet rating curve.*

The Y-F EFO model utilized Muskingum routing to simulate the attenuation of flow in river reaches between defined model junctions. The Muskingum routing parameters used in the Y-F EFO model were provided in the Y-F ResSim model.

This study was completed to develop and evaluate flood control operations that can utilize forecast information to inform releases and the alternatives evaluated in this study are further described in Section 4. Certain operational rules defined in the WCMs for both Oroville and NBB, however, were incorporated for all alternatives because they apply to multiple types of operations (conservation, flood control and emergency). On the other hand, certain rules were omitted because their original purpose is replaced by the use of forecast based rules that use forecasted hydrology. Descriptions of the primary existing rules considered for this study are provided below:

- Emergency spillway release diagram (ESRD) specifies minimum release from the dam for dam safety, considering current pool elevation and rate of rise of the pool. The objective of the ESRD rule at Oroville and NBB is to prescribe operation that will ensure the integrity of the dam (Yuba- Feather Forecast-Coordinated Operations Program, 2017). These rules apply for both flood control and surcharge pool operations, therefore these rules were used for all alternatives evaluated in this study.

- Release rate of change rules define the rate that releases can increase of decrease per hour. An increasing rate of change of 5 KCFS per hour was applied for Oroville and NBB. A decreasing rate of change of 2.5 KCFS per hour was applied to Oroville and 5 KCFS per hour for NBB.

- Maximum release rates are defined in the WCMs for both reservoirs. Maximum release rates of 150 KCFS for Oroville and 50 KCFS for NBB were applied for all alternatives evaluated in this study.

- Maximum downstream objective flows define flow limits at locations downstream of Oroville and NBB, and flood control releases from Oroville and NBB should not contribute to flows that exceed these limits.
    - The Oroville WCD defines a maximum downstream objective flow for the Feather River at Yuba City (hereafter Yuba City) of 180 KCFS, Feather River below Yuba River (hereafter Confluence) of 300 KCFS and Feather River below Bear River (hereafter Nicolaus) of 320 KCFS.
    - The NBB WCD defines a maximum downstream flow for the Yuba River at Marysville (hereafter Marysville) of 120 KCFS, however it also states "releases may be increased when concurrent flows in the Feather River are low; provided that flows in the Yuba River at Marysville do not exceed" 180 KCFS.
    - To meet the maximum downstream objective flow constraints at the Confluence and Nicolaus, flood control releases must be coordinated between Oroville and NBB for extreme events. This coordination of releases is currently managed under the F-CO program described in Section 1. For this study, initial simulations of alternatives did not consider maximum flow constraints for the Confluence or Nicolaus to evaluate at-site operations without coordinated releases, and assess the potential flooding impacts at the Confluence and Nicolaus with FIRO. More detailed simulations were completed, described in Section 9, that incorporated the simulation of coordinated releases for select alternatives.
    - Inflow based maximum release rules define a maximum release as a function of inflow. The rules defined for Oroville and NBB evaluate the previous 5-day peak inflows to set a release. The max release as a function of inflow for Oroville is provided in Table G-1. For NBB the max release in constrained to equal the maximum inflow. As further discussed in Section 4, these inflow-based maximum release rules were not included in the simulation of the FIRO alternatives for the formulation of storm-event prereleases, because these alternatives formulate releases using forecasted flows.

Table G-1. *Lake Oroville maximum release as a function of inflow.*

Previous 5-day	Maximum
Max Inflow (cfs)	**Release (cfs)**
1	15000
30000	15000
30005	60000
120000	60000
120005	100000
175000	100000
175005	150000
900000	150000

G.5 Flood Control Operations Alternatives

Four alternatives were developed and simulated for Oroville and NBB which are summarized below:

- Baseline – this alternative simulates conditions consistent with the operations defined in the WCMs for Oroville and NBB.
- EFO – this alternative uses the methodology previously described Section 3, which uses a volume tolerance curve to formulate flood control release decisions for the entire reservoir pool.
- Hybrid EFO – this alternative is similar to the EFO alternative however it constrains EFO to a maximum FIRO flood pool encroachment level. When storage levels exceed this encroachment level, operations are consistent with typical guide curve operations.
- PFO – this alternative, called perfect forecast operations, uses the same methodology as EFO, but in place of using the hindcasts, this alternative uses future observed flows, which provides perfect forecast skill. This alternative is not feasible for implementation, but provides a useful bookend to quantify the maximum benefit that could be achieved with the EFO alternatives. Additionally, since this alternative uses a perfect forecast and therefore no forecast uncertainty, the volume tolerance above the flood pool is set to be zero for all forecast lead times.

The FIRO encroachment curves used to simulate the Hybrid EFO alternatives at Oroville and NBB are provided in Figure G-9 and Figure G-10. The Oroville curve sets a winter top elevation of 869 feet, which encroaches into the reservoir flood pool by 8.5% (283 KAF) of total storage capacity (3,538 KAF) and shifts the spring refill from April 1 to March 1 of each year. The NBB FIRO encroachment curve sets a winter top elevation of 1935 feet, which encroaches into the reservoir flood pool by 7% (70 KAF) of total storage capacity of (965 KAF), and also shifts the spring refill date to March 1. Note that the Hybrid EFO alternatives are permitted to pre-release storage from the conservation pool in advance of a storm event as needed based on forecasted conditions. The portion of the conservation pool accessible for a pre-release is formally not limited, but in practice the volume of conservation storage that can be pre- released is limited by lead time and a host of other constraints (physical and regulatory).

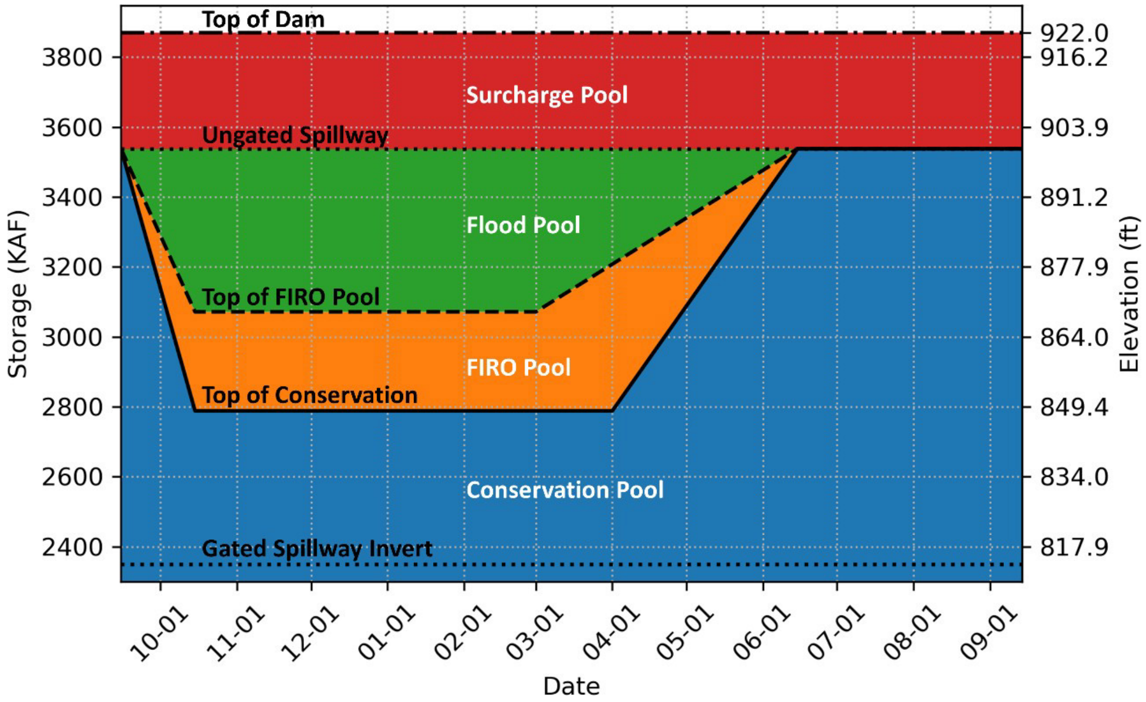


Figure G-9. *Lake Oroville FIRO encroachment curve.*

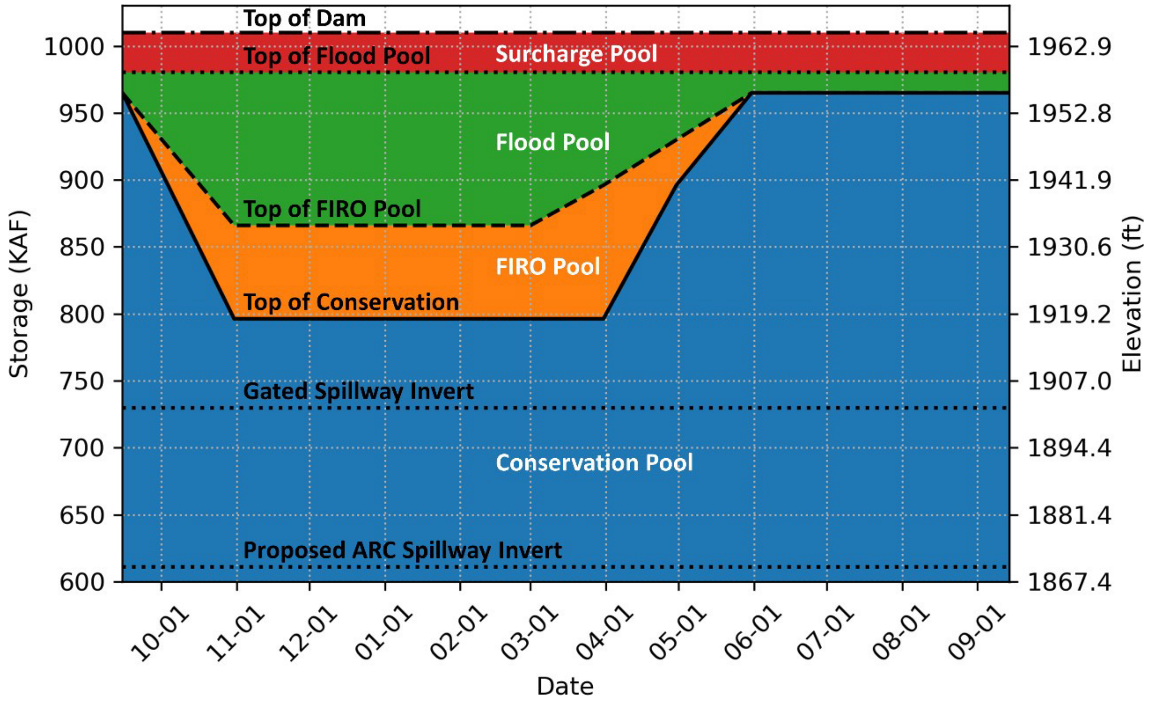


Figure G-10. *New Bullards Bar FIRO encroachment curve.*

Baseline operations for NBB assume existing capacity of the controlled spillway, however simulation of the EFO, Hybrid and PFO alternatives assume that the proposed ARC spillway is in place. The existing and ARC spillway release capacity curves are shown in Figure G-6.

As previously discussed, the WCMs for Oroville and NBB define maximum downstream objective flows for points downstream of Oroville and NBB. The NBB WCD defines a maximum downstream objective flow of 120 KCFS for Marysville, which was used for Baseline. For the EFO, Hybrid and PFO alternatives, however, maximum flow of 180 KCFS was used for Marysville because of the flexibility provided in the NBB WCD as discussed in Section 3.

The Oroville WCD diagram defines maximum downstream objective flows of 300 and 320 KCFS for the Confluence and Nicolaus respectively, but these were not included in the initial simulations of the alternatives of this study to evaluate the at-site operations without the coordination of releases to manage for flooding at Confluence and Nicolaus. Further study was completed (as described in Section 9) which included coordinated operations for the Hybrid alternative.

The alternatives evaluated in this study did not include any rules or constraints associated with releases made for water supply operations. The water supply operations for both reservoirs are complex and therefore not included due to the level of effort required. However for the preliminary assessment of flood control alternatives completed for this study, the incorporation of water supply operations was determined as unnecessary.

The assumptions and constraints defined in the Y-F EFO model for each alternative is summarized in Table G-2.

Table G-2. *Operations alternative assumptions and constraints.*

Constraint/ Assumption	**Oroville**				**New Bullards Bar**			
	Baseline	**Hybrid**	**EFO**	**PFO**	**Baseline**	**Hybrid**	**EFO**	**PFO**
Top of Flood Pool	900 ft.	900 ft.	900 ft.	900 ft.	1956 ft.	1956 ft.	1956 ft.	1956 ft.
Top of Conservation	Existing	FIRO	900 ft.	900 ft.	Existing	FIRO	1956 ft.	1956 ft.
Outlet Capacity	Existing	Existing	Existing	Existing	Existing	ARC Spillway	ARC Spillway	ARC Spillway
Maximum Release	150 KCFS	150 KCFS	150 KCFS	150 KCFS	50 KCFS	50 KCFS	50 KCFS	50 KCFS
Maximum Downstream Flow	180 KCFS Yuba City	180 KCFS Yuba City	180 KCFS Yuba City	180 KCFS Yuba City	120 KCFS Marysville	180 KCFS Marysville	180 KCFS Marysville	180 KCFS Marysville
Ramping	Existing	Existing	Existing	Existing	Existing	Existing	Existing	Existing
ESRD Rule	Existing	Existing	Existing	Existing	Existing	Existing	Existing	Existing
Start of Simulation Storage	2,788 KAF	3,071 KAF	3,360 KAF	3,360 KAF	796 KAF	866 KAF	965 KAF	965 KAF

G.6 Simulation of FIRO Alternatives

Simulation of alternatives was completed at an hourly time step using scaled hydrology for the 1986 and 1997 flood events developed by the CNRFC. These scaled events were developed by scaling precipitation by different factors as summarized in Table G-3. Also included with this table are associated return periods (developed by MBK Engineers), however these return periods were based on hydrology from the Central Valley Hydrology Study (CVHS) (US Army Corps of Engineers Sacramento District, 2015), which scaled observed hydrology by the same factors. It should be noted that the resultant hydrology developed by the CNRFC is not necessarily equivalent to the CVHS hydrology, and the CNRFC hydrology typically exceeds the CVHS hydrology for the same scale factor.

Table G-3. CNRFC Scaled Events.

Year	Scale Factor (%)	Return Period (year)
1986	100	75
1986	110	112
1986	120	164
1986	130	238
1986	140	346
1986	150	499
1997	90	106
1997	100	166
1997	110	268
1997	120	420
1997	130	653

For the simulation of the FIRO alternatives (EFO, Hybrid EFO, and PFO), the CNRFC also developed scaled Hydrologic Ensemble Forecast System (HEFS) hindcasts for the 1986 and 1997 flood events. These were developed by scaling the ensemble mean hindcast precipitation of the Global Ensemble Forecast System (GEFS) by the same scale factors in Table G-3. The scaled precipitation hindcasts were processed through the Meteorological Ensemble Forecast Processor (MEFP) to develop ensemble hindcasts of precipitation and temperature (not scaled), and simulated with the CNRFC hydrologic model to develop ensemble streamflow predictions (hindcasts). The hindcasts provided by the CNRFC use the same modeling process and are analogous to the operational forecasts provided daily and up to four times per day during flood events.

To assess potential risk of the over release of water with the FIRO alternatives in advance of a flood event that could impact storage recovery and water supply, alternatives were simulated for each year of the hindcast period at a daily time step using observed hydrology and hindcasts from 1985 through 2008 provided by the CNRFC. These simulations were completed for the flood control season (November 1 to June 15) for each year of the hindcast using beginning storage levels provided in Table G-2. These simulations did not include any rules for water supply operations (no water supply releases) to maximize storage levels during levels during the flood control season, and thereby maximize the frequency that FIRO pre-releases would be made. Given that this analysis does not include any water supply operations to continually draw down storage through the flood control season, any over release of water made during an event will likely be recovered by subsequent storms in a given year. Therefore, this approach of simulating the alternatives for each flood control season of the hindcast period most accurately assesses the risk of over releasing water for the last storm of the season. Given that water supply operations were not included in these simulations, water supply benefits cannot be determined from these results. However, since all alternatives are simulated with consistent assumptions, results from this analysis are useful for comparative evaluation between the FIRO alternatives and Baseline to assess whether the over release of water due to the over forecast of a storm event could result in end-of-flood- season storage below Baseline operations.

G.7 Calibration of the EFO Volume Tolerance Curves

A central component of the EFO and Hybrid EFO alternatives evaluated in the study are the volume tolerance curves used by the Y-F EFO model to formulate release schedules. The volume tolerance values for each of the 14-days of forecast lead time are not independent from each other. Therefore, given an infinite number of possible tolerance curves, a brute force method for optimization would be impractical. For this study, a methodology was developed that evaluates plausible candidate volume tolerance curve shapes and selects a curve that could be used to support a proof-of-concept simulation of the EFO methodology. The volume tolerance curves used for this study at Oroville and NBB were developed by modeling numerous candidate curves and formulating a curve that meets the project objectives of minimizing flood and dam safety risk while also balancing storage recovery after a flood event to retain water for water supply needs. To explain this process, examples are provided for the development of NBB Hybrid alternative, although a very similar process was incorporated for EFO and Hybrid alternatives for each reservoir.

To formulate candidate risk tolerance curves for evaluation, perfect forecast operations (PFO) were simulated for each of the scaled flood events provided by the CNRFC. PFO incorporates the same methodology of formulating flood releases as EFO, but instead of using HEFS hindcasts of inflows into the reservoirs, PFO uses observed inflows. For each day of the PFO simulation for each scaled event, forward looking modeled ensemble storage levels assuming no reservoir releases were generated using the hindcasts with the beginning storage determined by the PFO storage level at that time step. These daily, forward-looking simulations were used to provide the hindcast ensemble storage levels with a starting storage set by the PFO simulation. The maximum hindcasted volume above the top of flood pool is calculated for each of the 14 days of the hindcast horizon, producing one candidate tolerance curve.

This process is demonstrated in Figure G-11, which shows a candidate tolerance curve formulated for NBB from the February 9, 1986 hindcast.

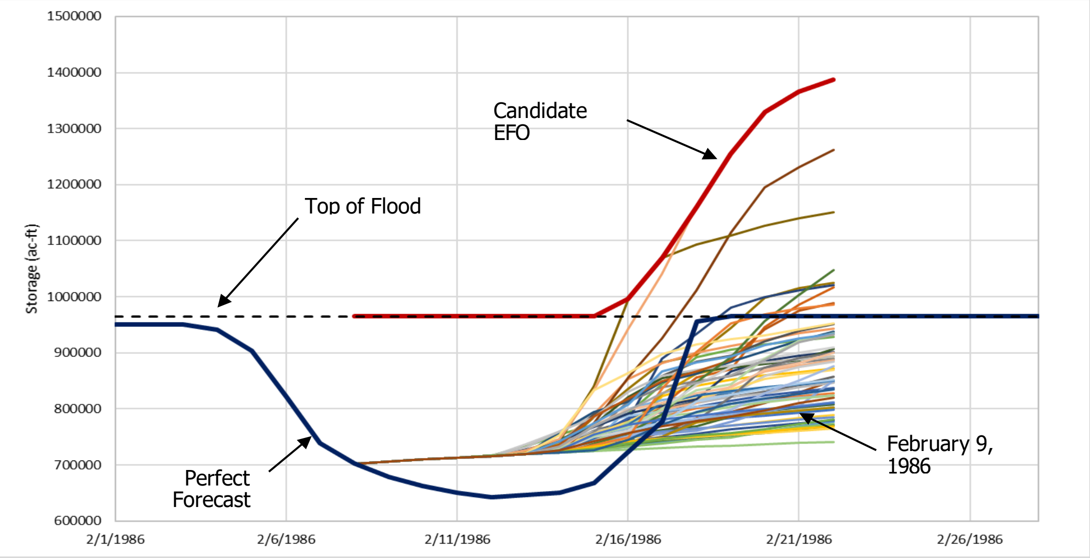


Figure G-11. *Development of a single candidate EFO volume tolerance curve for NBB from the scaled 120% February 9, 1986 hindcast.*

Using this process, a different candidate curve is formulated for each day of the PFO simulation. For NBB this process generated 746 unique, candidate EFO volume tolerance curves as shown in Figure G-12. A similar process for developing candidate risk tolerance curves was used for the development of EFO for Lake Mendocino (Delaney, et al., 2020).

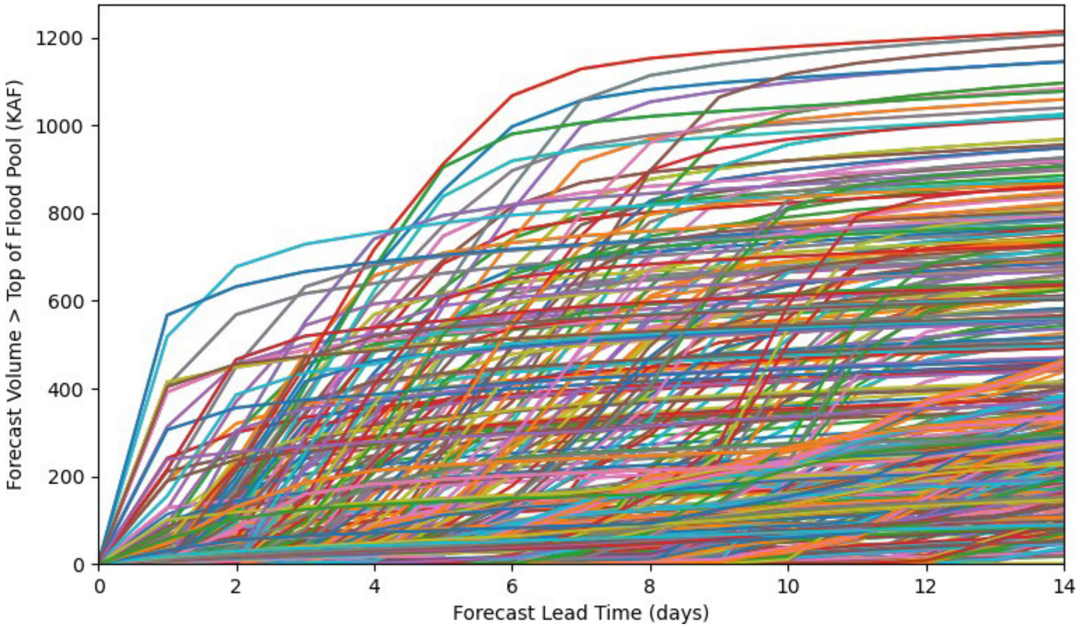


Figure G-12. *Candidate volume tolerance curves for NBB evaluated in the development process.*

Each of the candidate risk tolerance curves was simulated with the Y-F EFO model for the 1986 and 1997 scaled events at a daily time step, using the methodology previously described in Section 2 where the hindcasts are used to forecast storage levels, and a candidate curve (the red dashed line in the top panels of Figure G-2) is used to formulate release volumes.

An objective function consisting of 4 decision variables (provided in the Equation 1) was developed to evaluate the simulation results for each of the candidate curves. This objective function was formulated based on the project objectives to reduce flood risk and improve dam safety while not impairing storage capture for water supply needs.

$$Max\,J = (F + R + SR) \times B \tag{1}$$

The *F* decision variable captures the objective to maximize reduction of flood risk at Marysville. For each of the (*n*) simulated scaled events (11 events) each (*j*) candidate curve is evaluated by calculating the volume of flow that exceeds the flood stage of 180 KCFS, which is multiplied by the unregulated frequency (*freq*) of each (*k*) scaled event. The unregulated frequencies used in this analysis were developed by MBK Engineers using the hydrology of CVHS study (Table G-3). The mean of the frequency weighted flood volumes (f_j in ac-ft) is evaluated for each of the (*j*) candid curves. To calculate the *F* decision variable for each candidate curve, the mean frequency weighted flood volumes (*f*) are normalized by taking the difference of the maximum *f* result of all the candidate curves from the *f* result of each candidate curve, divided by the range of *f* results for all curves. These calculations are summarized in Equations 2 and 3, given *t* is the number of days of simulation for a given scaled event, q^{flood} is flow at Marysville that exceeds flood stage, *n* is the number of scaled events simulated, and 1 cfs for 24 hours is 1.9835 ac-ft. The *F* decision variable captures the objective to minimize flow that exceeds flood stage at Marysville, therefore, higher values of *F* favor curves with a lower tolerance of volume exceeding the top of the flood control pool.

$$F_j = \frac{f_j - \min(f)}{\max(f) - \min(f)} \tag{2}$$

$$f_j = (\textstyle\sum_{i=1}^{n} (\sum_{k=1}^{t} (q_k^{flood} \times 1.9835)) \times freq_i)/n \tag{3}$$

The *R* decision variable captures the objective to maximize dam safety by evaluating releases when storage exceeds to top of dam elevation of 1965 feet (1,010 KAF storage). The calculation of this decision variable (summarized in equations 4 and 5) is very similar to the calculation of the *F* decision variable, but instead of evaluating the volume of flow that exceeds flood stage, this decision variable evaluates the volume of release when storage exceeds the top of dam (q^{spill}). The *R* decision variable captures the objective to minimize risk to dam safety, therefore, higher values of *R* favor curves with a lower tolerance of volume exceeding the top of the flood control pool.

$$R_j = \frac{r_j - \min(r)}{\max(r) - \min(r)} \tag{4}$$

$$r_j = (\textstyle\sum_{i=1}^{n} (\sum_{k=1}^{t} (q_k^{spill} \times 1.9835)) \times freq_i)/n \tag{5}$$

The *SR* decision variable captures the objective to maximize storage recovery at the end of a flood event. FIRO pre-releases are made in advance of a flood event to reduce flood risk and improve dam safety, however we would also like a tolerance curve that allows for the reservoir to refill and recover as much of the pre-released water as possible for water supply needs. For each of the simulated scaled events each (*k*) a candidate curve is evaluated by taking the difference of end of simulation storage from the beginning of simulation storage, which multiplied by the unregulated frequency (*freq*) of each (*k*) scaled event. The mean of the frequency weighted storage differences (*sr* in ac-ft) is evaluated for each of the (*j*) candid curves. To calculate the *SR* decision variable, the *sr* result for each candidate curve is normalized in a similar fashion as described for the *F* decision variable. These calculations are summarized in Equations 6 and 7, given *t* is the last day of simulation for a given scaled event, s_1 is the beginning of scaled event simulation storage, s_t is the end of simulation storage, and *n* is the number of scaled events simulated. Given that the *SR* decision variable captures the objective to minimize storage not recovered at the end of a flood event, higher values of *SR* favor curves with a higher tolerance of volume exceeding the top of the flood control pool.

$$SR_j = \frac{sr_j - \min(sr)}{\max(sr) - \min(sr)} \tag{6}$$

$$sr_j = \left(\sum_{k=1}^{n}\left(s_1^k - s_t^k\right) \times freq_k\right)/n \tag{7}$$

During the process of information gathering for this study, water managers expressed a strong aversion to emergency releases due to high storage levels or uncontrolled releases through the emergency spillway at Oroville or over the top of dam at NBB. Simulations of existing operations show no or small emergency or uncontrolled releases for certain scaled years, which were the 100% and 110% scaled 1986 events and for the 90% and 100% scaled 1997 events. Therefore, to capture the importance of this criteria to the stakeholder and potentially reduce flood risk and improve dam safety, the decision variable *B* is defined as an indicator variable such that if there are any simulated emergency releases or releases over the top of dam for the scaled events previously indicated then *B* is set to a value of 0, and if there are no emergency releases or releases made over the top of dam then *B* is set to a value of 1.

Results of the objective function computations for each of the 746 candidate volume tolerance curves are provided in Figure G-13, with results sorted by objective function value (J). Simulation of some of the candidate risk tolerance curves result in a release above the top of dam and the B indicator variable is 0, and therefore have objective function values of 0 as can be seen for some of the J results at the left side of the figure.

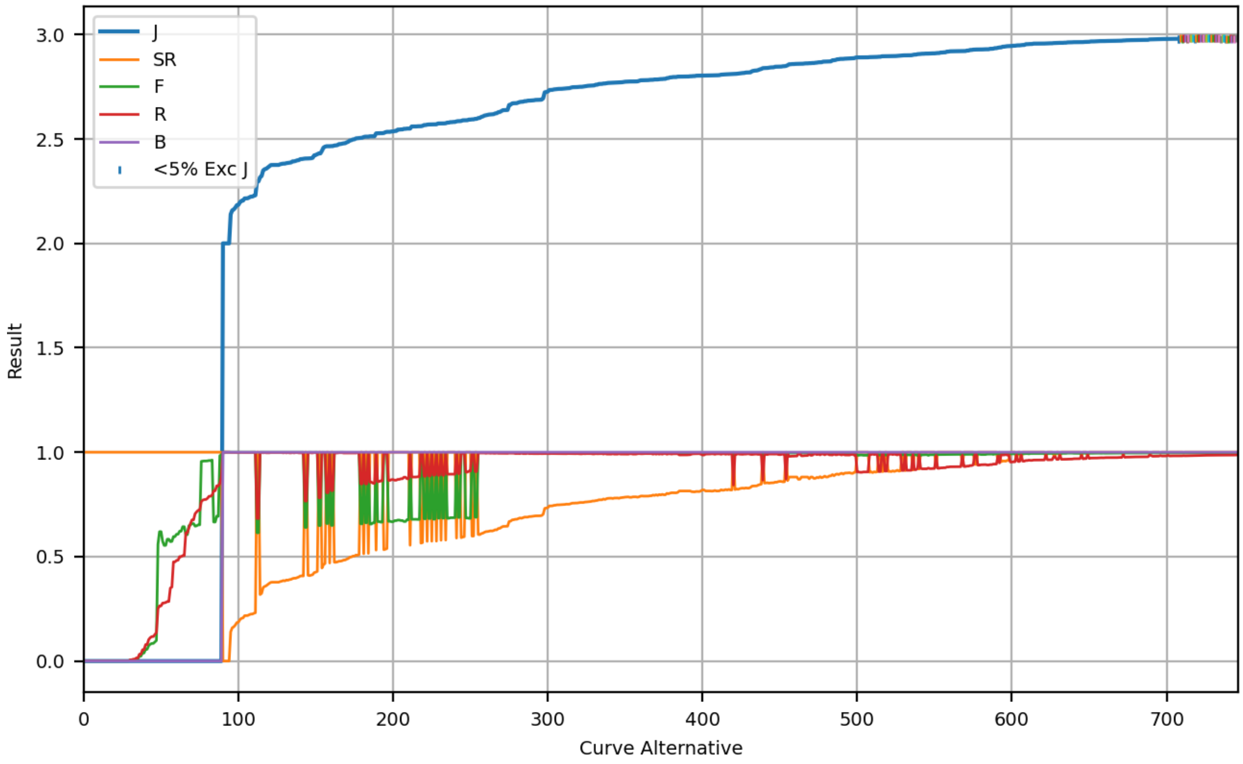


Figure G-13. *Objective functions and decision variable results of candidate risk tolerance curves for the NBB Hybrid alternative; results indicated with the vertical-colored markers show the objective function (J) results less than 5% exceedance where marker colors correspond to the curves provided in Figure G-14.*

The simulations to evaluate the candidate tolerance curves included the 2 historical flood events (1986 and 1997) with different scaling factors to evaluate performance under extreme flood events. The events evaluated in this study are adequate in magnitude for proper testing of the of the candidate curves, but given that only 2 historical events were scaled, the simulation hydrology lacks diversity of hydrologic timing and hindcast skill and reliability for the development of robust tolerance curves. Given this lack of diversity of flood events, and to avoid over fitting the volume tolerance curves to specific scaled events, the final tolerance curves for this study were interpolated to multiple curves between the 0% and 5% exceedance range of objective function (J) results. The objective function results less than the 5% exceedance (38 results) are indicated with the colored vertical markers and on the right side of Figure G-13. It should be noted that the curves below the 5% exceedance range as shown in Figure G-13, demonstrate similar performance for all decision variables, and do not show a needed tradeoff in system objectives.

The 38 candidate risk tolerance curves below the 5% exceedance range (indicated by the vertical- colored markers in Figure G-13) are provided as the colored lines in Figure G-14. The dashed black curve shown in Figure G-14 is interpolated from the 38 displayed candidate curves using least squares regression. This interpolated tolerance curve was used to formulate release volumes for the NBB Hybrid EFO alternative when storage levels are below the FIRO encroachment level as previously discussed in Section 4.

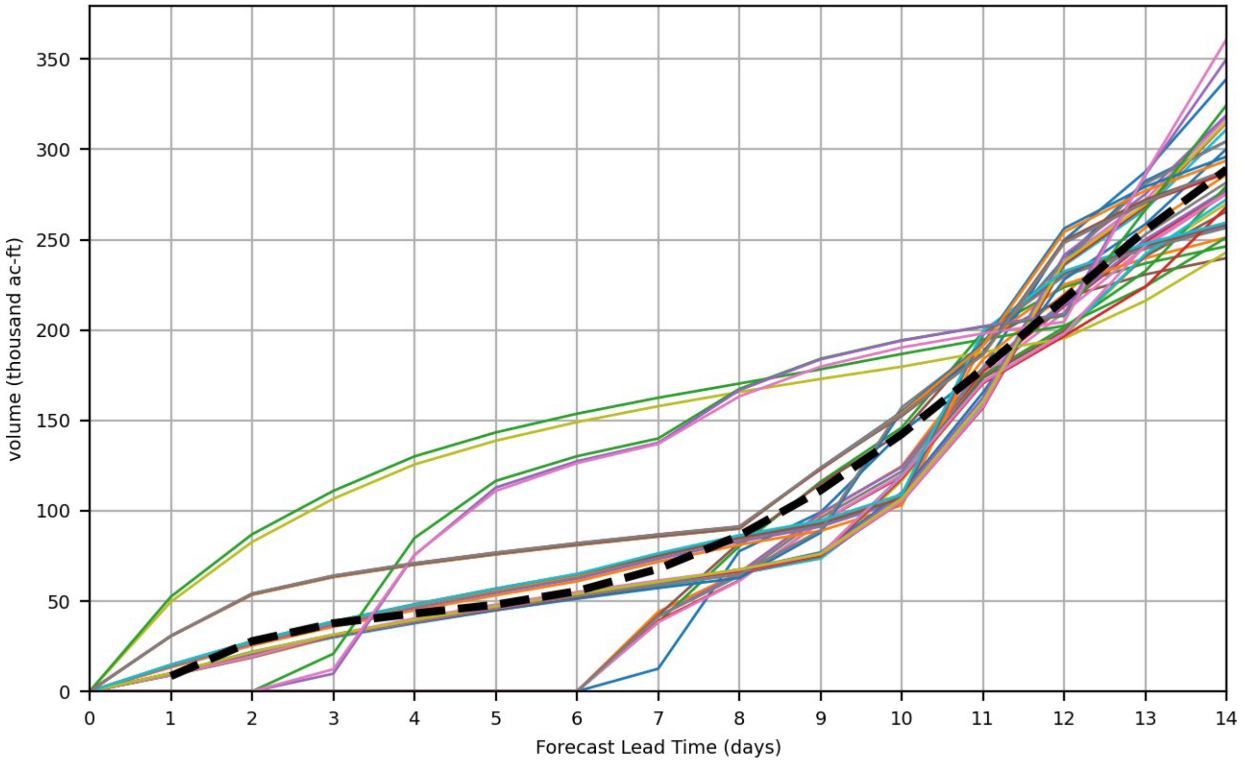


Figure G-14. *EFO Volume tolerance curve for the NBB Hybrid alternative where the candidate risk tolerance curves below the 5% exceedance objective function results are shown by the colored lines and the line colors correspond to the marker colors provided in Figure G-8; the volume tolerance curve is shown as the dashed black line, which is interpolated to the 38 colored lines.*

A similar methodology was employed for developing a volume tolerance curves for all of the EFO and Hybrid EFO alternatives. The interpolated curve developed for the Oroville Hybrid EFO alternative is presented in Figure G-15 was used for simulation of Oroville Hybrid EFO operations.

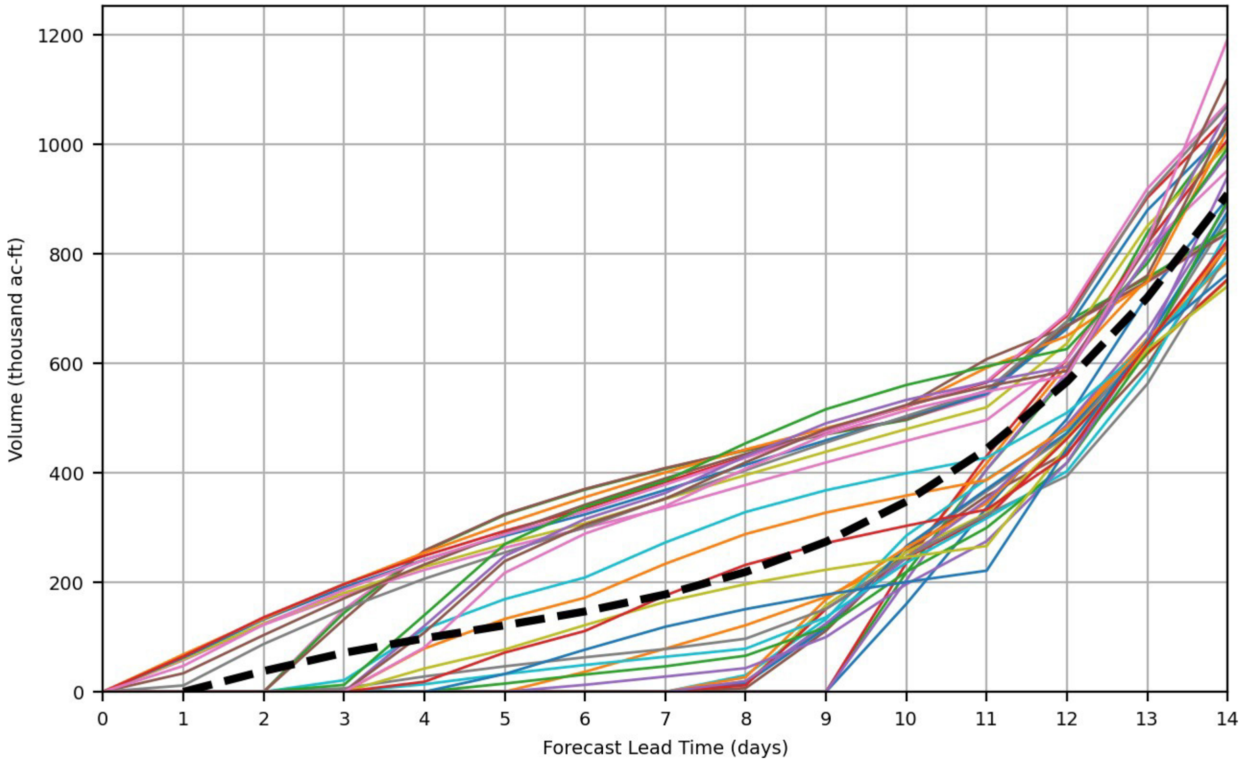


Figure G-15. *EFO volume tolerance curve for Oroville.*

The methodology presented here was designed to provide a volume tolerance curve that is adequate for proof-of-concept testing and evaluation of EFO and Hybrid EFO alternatives for Oroville and NBB. The limited number of hindcasted scaled events is likely not adequate to develop robust volume tolerance curves that are adequate for full implementation. The candidate curves within the 0% to 5% objective function range (the colored curves included in Figure G-14 and Figure G-15) show variability of tolerance, with the greatest amount of variability in lead times less than 9-days. Selecting the single optimal curve from the candidate curves would likely provide a curve that is well suited for a few scaled events included in the training process but may not be robust to future events. To avoid over fitting of the volume tolerance curve, an interpolated curve was developed from multiple candidate curves that showed good objective functions scores (less than 5% exceedance), which is shown as the black dashed line in Figure G-14 and Figure G-15. The volume tolerance curves developed for the Oroville and New Bullards Bar EFO alternatives are also included in Attachment G-1.

To address the issue of over fitting, future research could be completed that incorporates more extreme hydrology both for flooding and drought. Future research could look at scaling additional historical events to evaluate different flood hydrology and hindcast skill and reliability. Future efforts to refine the risk tolerance curve may also integrate a cross validation approach that incorporates multiple trials.

These trials would include a training period to identify optimal curves in a similar fashion as used in this study and a blind testing period to evaluate performance of the volume tolerance curve identified from the training period. Such an approach can be useful to understand the sensitivity of the tolerance curve to training hydrology and other parameters, and the potential robustness of the tolerance curve to future flood events. A similar cross validation approach was used for the evaluation of EFO for Lake Mendocino (Delaney, et al., 2020). Further research could also be completed to verify the approach presented here against more established optimization methods such as stochastic dynamic programming (Stedinger, Sule, & Loucks, 1984).

G.8 Results: Scaled Flood Events

Model results for the Baseline, EFO, Hybrid EFO, and PFO alternatives for the 110% scaled 1986 and 1997 events are presented in Figure G-16 and Figure G-17 respectively. Additional results of all the scale factors for both the 1986 and 1997 flood events are also included in Attachment G-2.

These model results show that operations of the Hybrid EFO alternatives at Oroville and NBB begin making FIRO prereleases for each reservoir up to 10-days in advance of peak inflows for the 110% scaled 1986 event and up to 11 days in advance of peak inflows for the 110% scaled 1997 event. Prereleases of Hybrid EFO initiate quickly at Oroville for the 1986 event reaching a peak release in advance of the flood event of 100 KCFS within 2-days and then taper off as storage draws down and reduces controlled release capacity. Prereleases of Hybrid EFO at NBB increase at a slower rate for the 1986 event reaching a peak release of 42 KCFS after 4-days and then also taper off due to release capacity. Pre-releases of Hybrid EFO for the 110% scaled 1997 event show similar trend reaching a peak release in advance of the event of 122 KCFS for Oroville and 44 KCFS at NBB.

The Hybrid EFO alternatives at Oroville and NBB set no storage floor for FIRO prereleases and are therefore able to drain the reservoir pools in advance of the 110% scaled 1986 event to elevation 827 ft. (274 KAF below the top of conservation) for Oroville and elevation 1891 ft. (110 KAF below the top of conservation) for NBB. The 110% scaled 1997 event demonstrated similar results with a pre-storm elevation of 828 ft. at Oroville (267 KAF below the top of conservation) and elevation 1889 ft. for NBB (110 KAF below the top of conservation).

The EFO alternatives at Oroville and NBB start the flood event simulations at a much higher storage level and also attempt to maximize storage in the reservoirs. Even with these constraints the model simulations show that pre-storm event storage levels are well below the top of conservation for Oroville for both the 1986 and 1997 events. For NBB the EFO alternative shows to draw down storage to comparable levels as the NBB Hybrid EFO alternative.

The PFO alternative is using perfect information to inform release decisions, and therefore, as to be expected, this alternative demonstrates the most significant levels of pre-release and storage reduction in advance of the scaled flood events. This alternative is not feasible for implementation due to the impossibility of having perfect knowledge of future hydrology, however these results provide a useful bookend of the maximum extent of future benefits with improved forecasting capabilities.

Both the EFO and Hybrid EFO alternatives also show improved conditions downstream with reduced flows relative to Baseline. Flows at the Confluence and Nicolaus also show a reduction relative to Baseline even though these at-site alternatives do not include any rules for the coordination releases at Oroville and NBB to limit flooding downstream of the confluence. The simulated reduction in downstream flooding may indicate a reduced need for coordinated operations of Oroville and NBB. The PFO alternative shows the most significant benefit for all points downstream and once again provides a useful bookend of potential future benefits with improved forecasting skill.

For both reservoirs and both events (110% 1986 and 1997), we see the initiation ESRD releases made by all alternatives as storage rapidly rises during the flood event. Most notable are the ESRD releases made by the EFO and Hybrid EFO alternatives at NBB. In the days prior to these ESRD releases the reservoir releases are reduced in the simulation to minimize flooding at Marysville, which causes the rapid rise in storage that triggers the ESRD releases. In this case, the cutback in releases to minimize flooding at Marysville is not an optimal operation given that the ESRD releases that occur after the cutback of releases contribute to greater flooding at Marysville for 1997 and at the Confluence and Nicolaus for 1986 and 1997.

Figure G-18 shows the peak Oroville water surface elevations for all of the 1986 and 1997 scaled events. These results indicate a reduction of maximum elevation for the FIRO alternatives (EFO, Hybrid EFO and PFO) relative to Baseline for most scaled events with the exception of some events that do not exceed the spillway crest. The PFO and EFO alternative are designed to maximize storage after a flood event, therefore it is expected that the storage levels will exceed baseline due to their starting and ending simulation results as shown for the 100% and 110% scaled 1986 events and the 90%, 100%, and 110% scaled 1997 events.

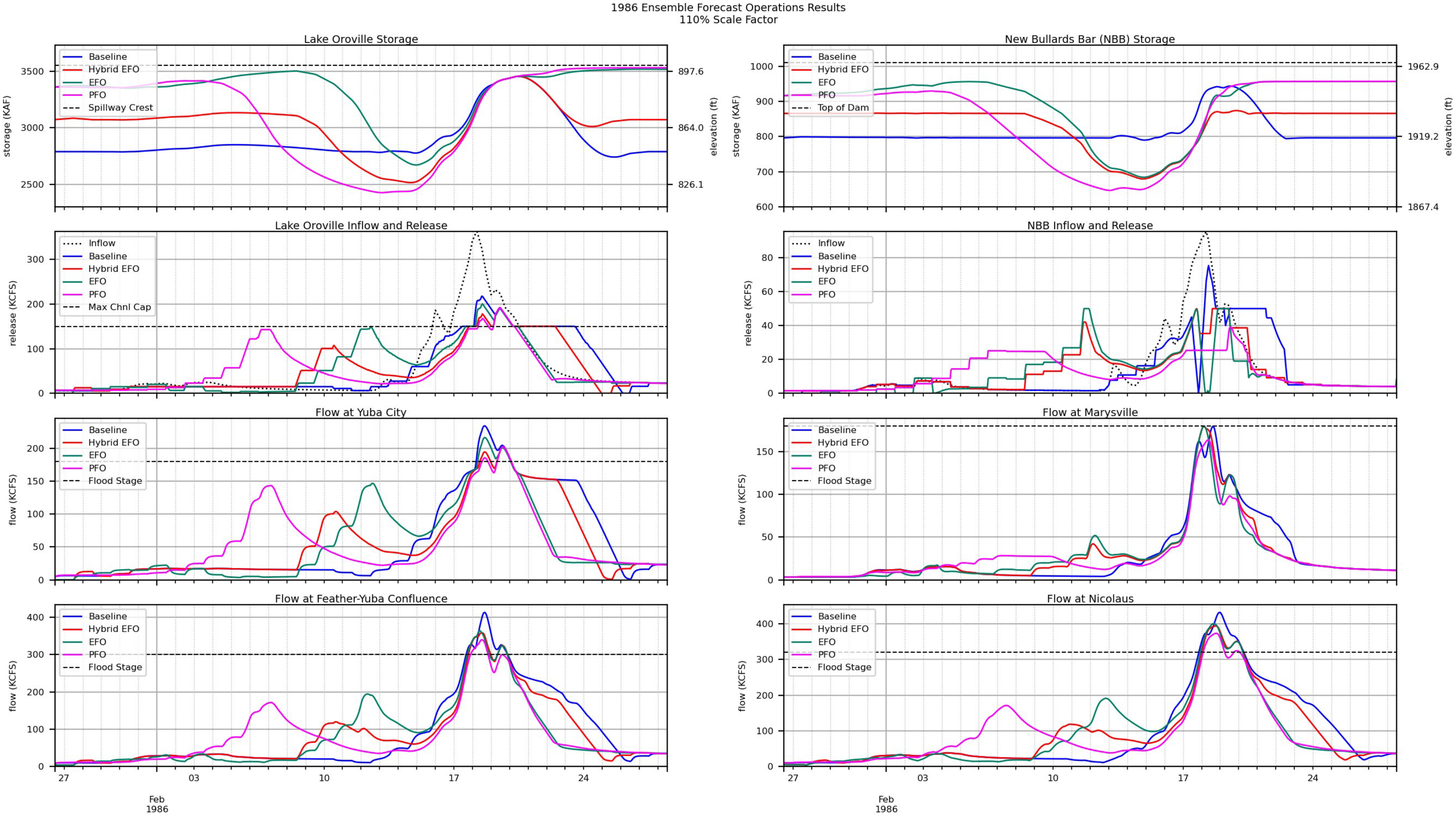


Figure G-16. *EFO Model results for 110% scaled 1986 flood event.*

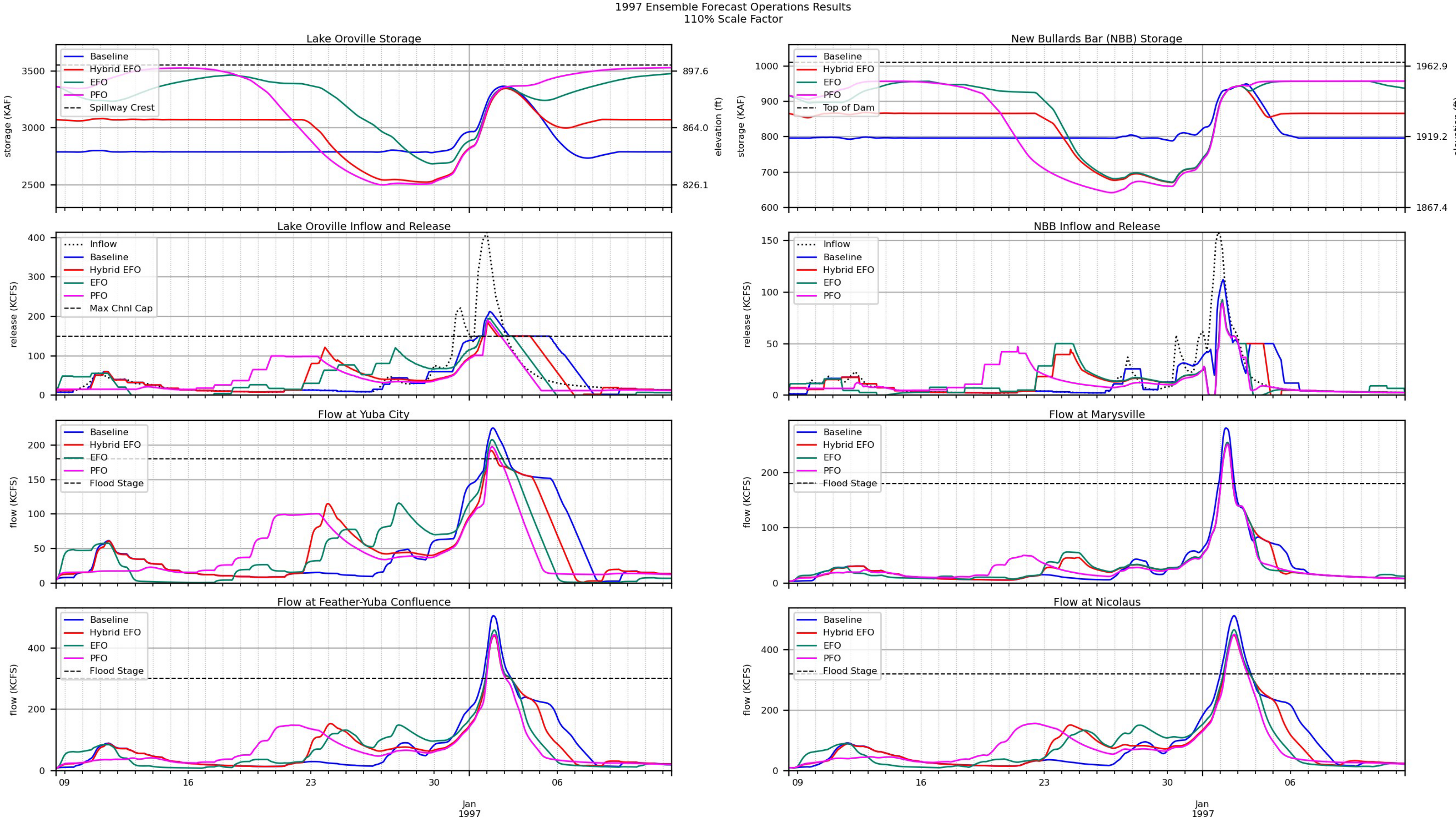


Figure G-17. EFO Model results for 110% scaled 1997 flood event.

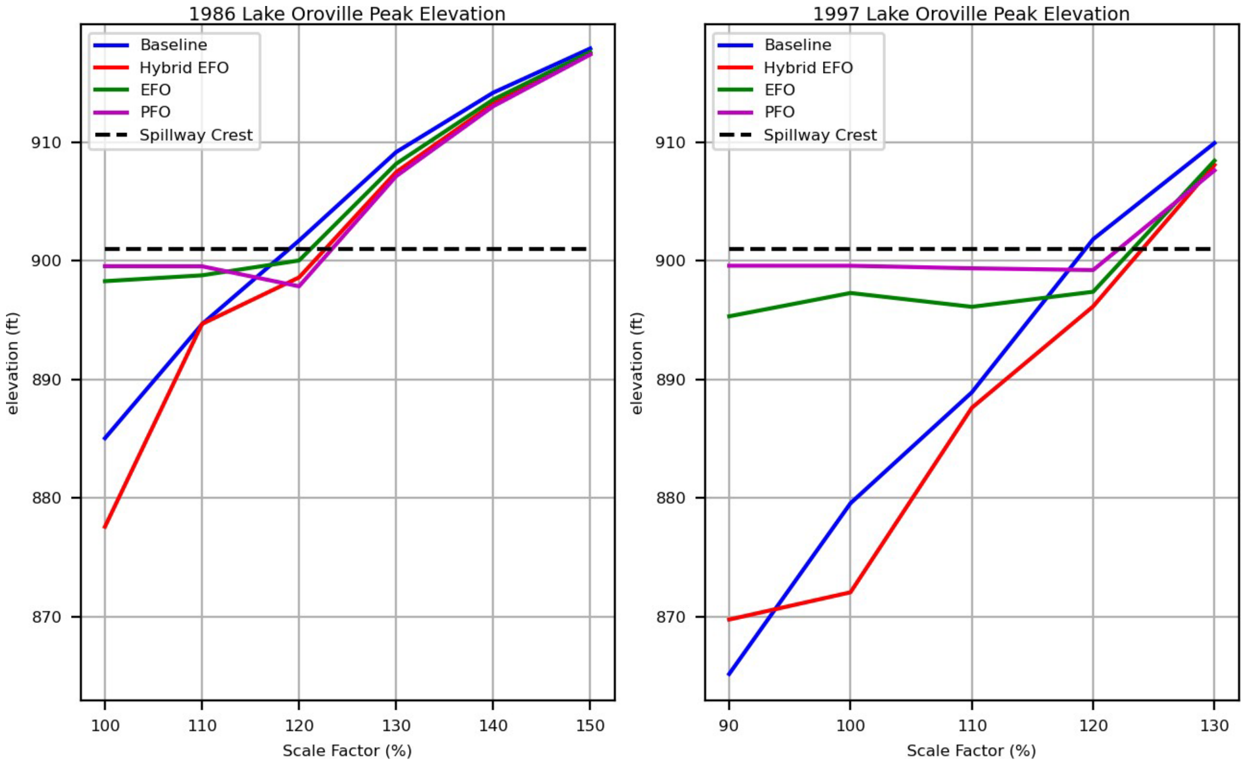


Figure G-18. *Max Oroville elevation for the 1986 and 1997 scaled event simulations.*

Figure G-19 shows the peak NBB water surface elevations for 1986 and 1997 scaled events. These results show a reduction of maximum elevation for the Hybrid EFO alternative relative to Baseline for all scaled events. Similar to the results at Oroville, the PFO and EFO alternatives also show storage levels above Baseline for the smaller scaled events due to higher storages at the end of the simulations. For the largest scaled events, the Baseline simulation results indicate storage levels above the top of dam while the FIRO alternatives show elevations significantly lower than Baseline.

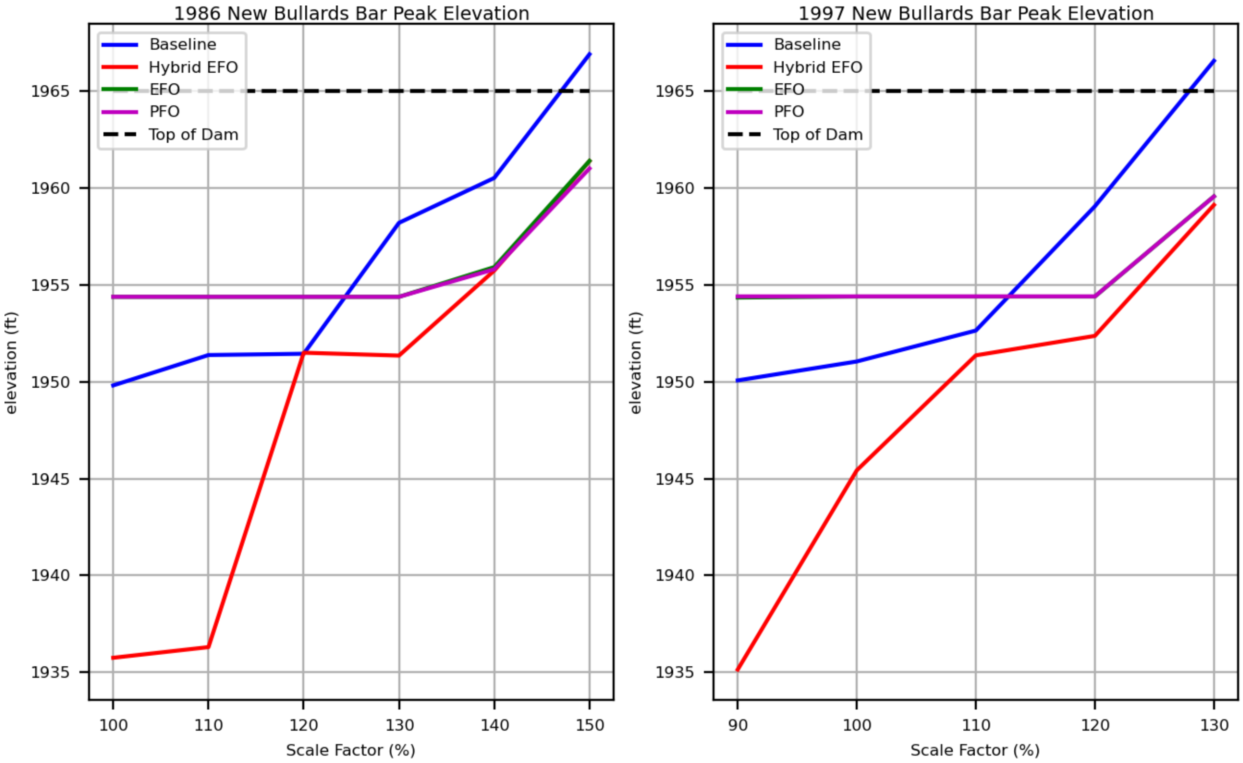


Figure G-19. *Max NBB elevation for the 1986 and 1997 scaled event simulations.*

Figure G-20 shows the peak flows at Yuba City for 1986 and 1997 scaled events. The results for the FIRO alternatives (EFO, Hybrid EFO and PFO) show a reduction in flows above flood stage (180 KCFS) relative to Baseline for all scaled events.

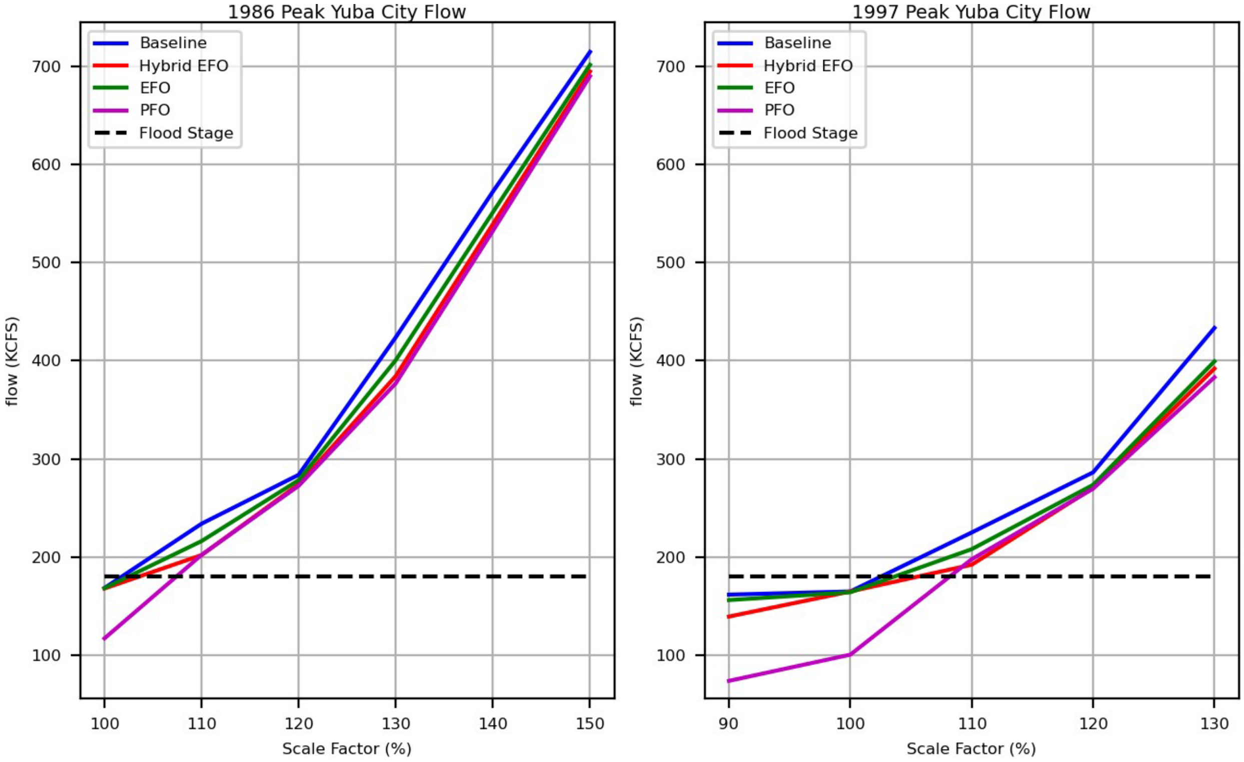


__Figure G-20.__ Peak flow at Yuba City for the 1986 and 1997 scaled event simulations.

Figure G-21 shows the peak flows at Marysville for 1986 and 1997 scaled events. Results of the 140% scaled 1986 event show that Marysville flows for the FIRO alternatives exceed Baseline. This is due to the timing and travel times of ESRD releases of the FIRO alternatives relative to the timing of downstream natural flows, even though peak releases of the FIRO alternatives are below Baseline for that event. The 120%, 130% and 150% scaled 1986 event show a reduction of flows above flood stage (180 KCFS) relative to Baseline. For the 1997 scaled events the FIRO alternatives show a reduction in flows above flood stage relative to Baseline for all scaled events. Additionally, the 100% 1997 results show that the FIRO alternatives prevent flooding whereas Baseline exceeds flood stage.

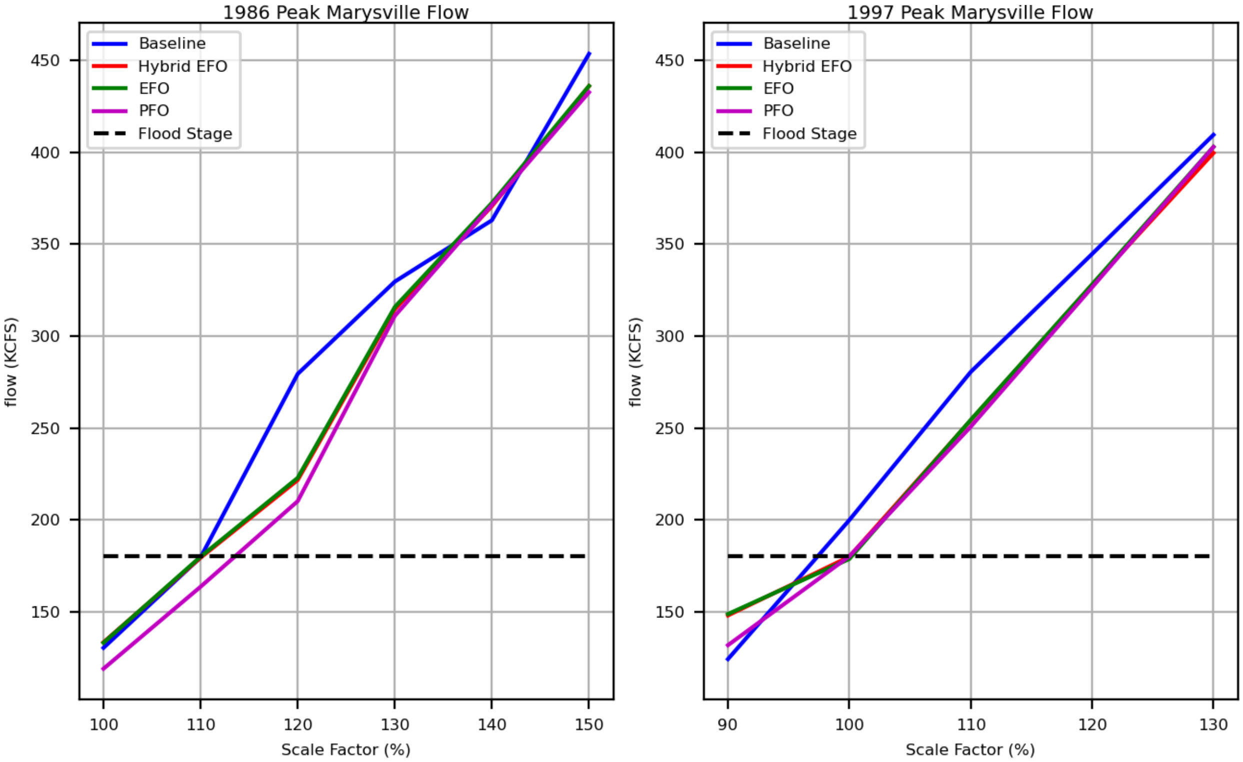


Figure G-21. *Peak flow at Marysville for the 1986 scaled event simulations.*

Figure G-22 and Figure G-23 show the peak flows at the Confluence and Nicolaus for 1986 and 1997 scaled events. These results show a reduction in flows above flood stage (300 KCFS at Confluence and 320 KCFS at Nicolaus) relative to Baseline for most scaled events, with the greatest reductions shown for the 1997 scaled events. None the alternatives modeled in these initial simulations incorporated any rules for coordinated releases between the reservoirs to limit flooding downstream of the confluence of the Feather and Yuba Rivers (Confluence or Nicolaus). However, even without any rules for coordinated operations and a higher max flow at Marysville (180 KCFS for the FIRO alternatives versus 120 KCFS for Baseline), the FIRO alternative show reductions in peak flows above flood stage for locations downstream of the confluence. Additionally, the results for the 100% 1997 event show that PFO prevents flooding, while EFO and Hybrid EFO result in flooding (however still below Baseline), which indicates that results could improve by including simulation of coordinated operations.

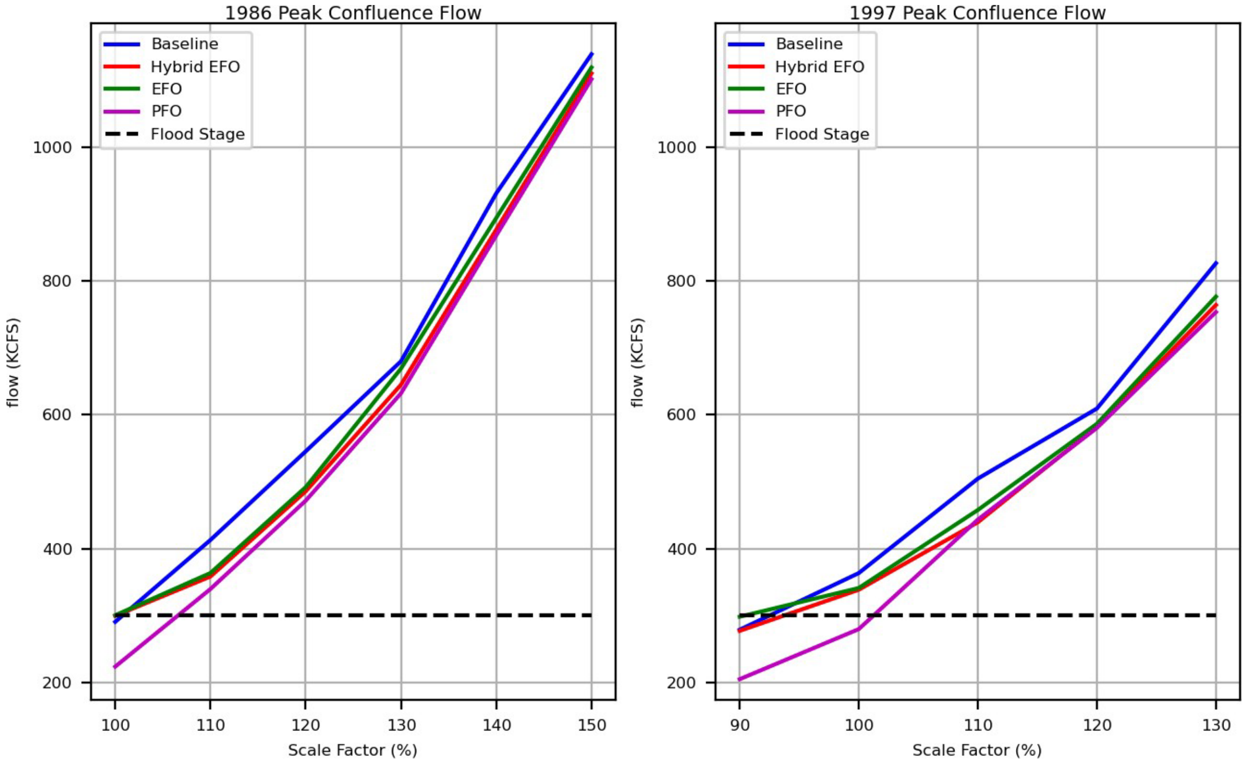


Figure G-22. *Peak flow at the Feather Yuba Confluence for the 1986 and 1997 scaled event simulations.*

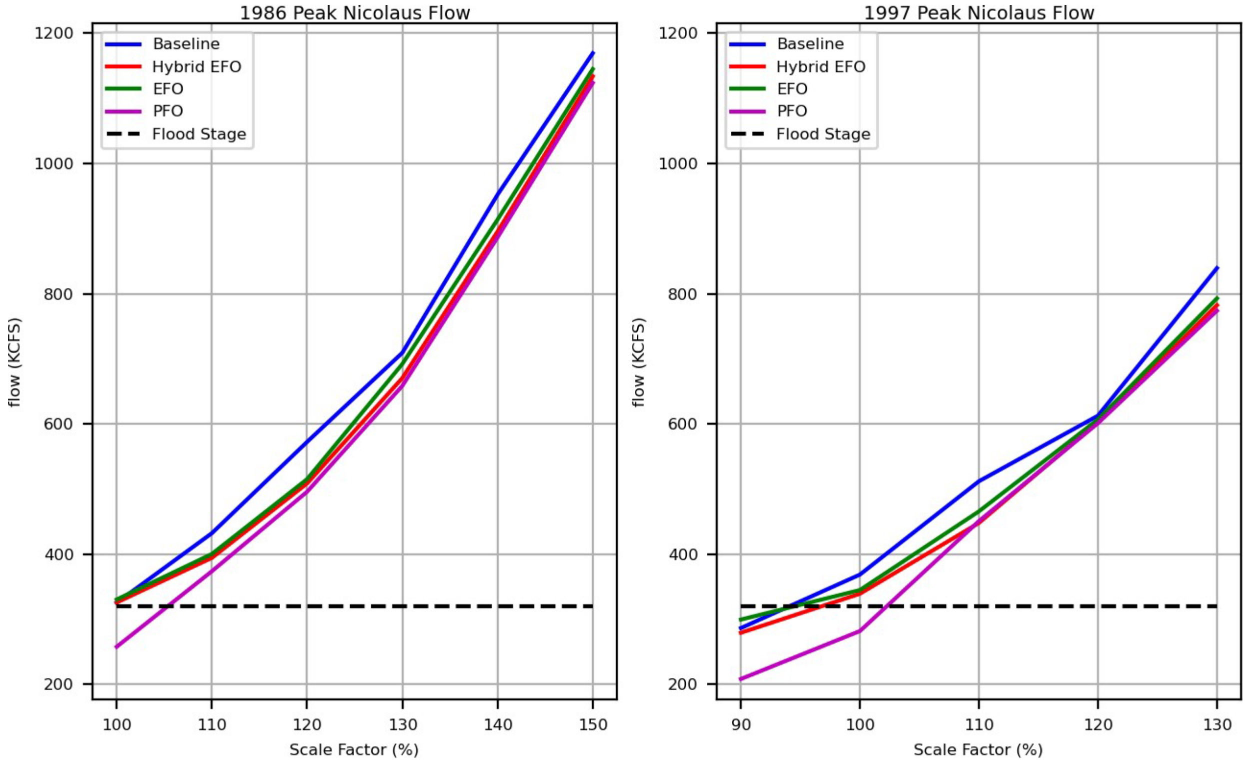


Figure G-23. *Peak flow at the Feather River at Nicolaus for the 1986 and 1997 scaled event simulations.*

G.9 Results: Period of Record Simulations

Oroville end of flood season (June 1) storage levels simulated for the hindcast period of record (1985 – 2008) described in Section 5 are shown as probability exceedance and box and whisker plots in Figure G-24. These results show that all of the FIRO alternatives result in generally higher storage levels for most of the exceedance probability distribution relative to Baseline. This indicates that FIRO prereleases are likely not to affect post event storage recovery that would result in a storage level lower than Baseline at the end of the flood management season. At the right side of the distribution, it can be seen that there are 2 years where end of flood season storage for EFO and Hybrid EFO are significantly lower than PFO indicating an over release of water for those years, however these results are still significantly above Baseline. Median end of flood season storage for Hybrid EFO (the lowest of all the FIRO alternatives) is approximately 210 KAF greater than baseline. The Hybrid EFO alternative for the lowest year (the right side of the distribution or the lower whisker of the box and whisker plots) shows storage levels 270 KAF greater than the lowest Baseline year.

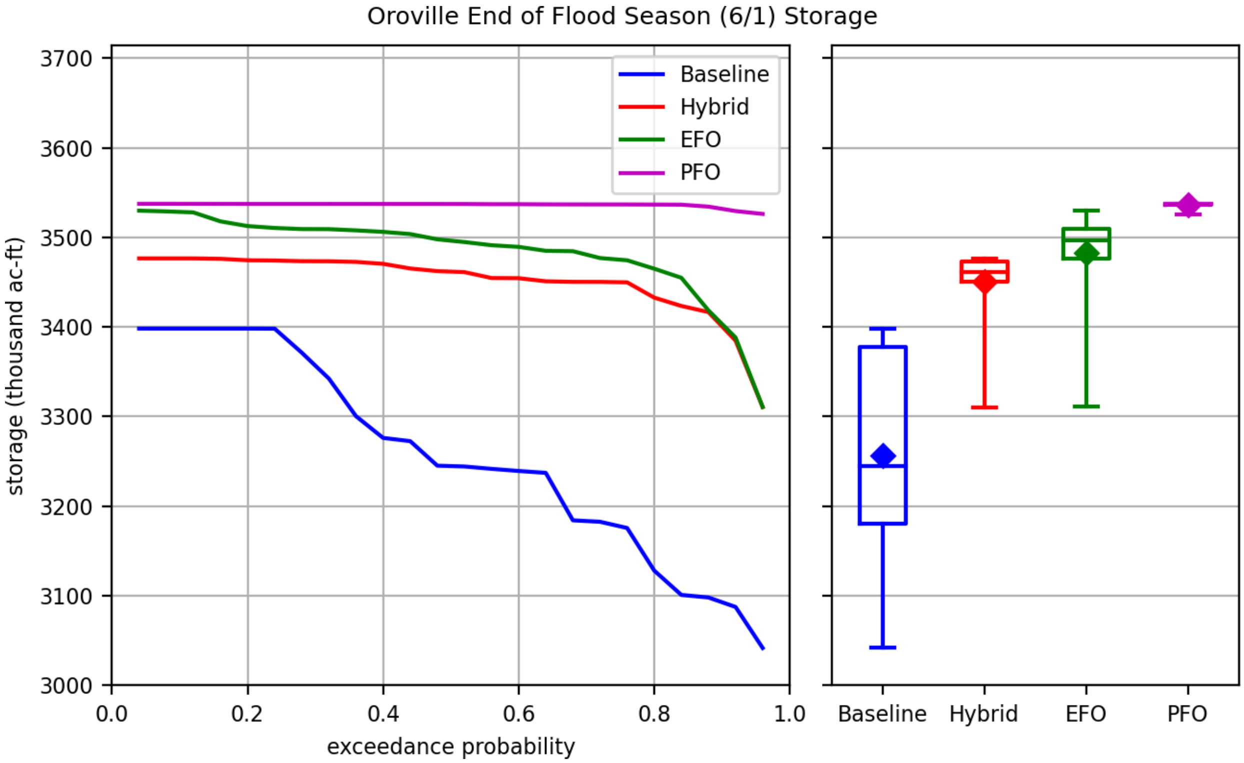


Figure G-24. *Oroville end of flood season (6/1) storage shown as probability exceedance (left panel) and box and whisker plots (right panel) for each alternative.*

NBB end of flood season (June 1) storage levels simulated for the hindcast period of record are provided as probability exceedance and box and whisker plots in Figure G-25. These results show that all of the FIRO alternatives result in generally higher storage levels for the drier years (60% to 100% distribution). As with Oroville, these results indicate that FIRO prereleases are likely not to affect post event storage recovery that would result in a storage level lower than Baseline. These results also indicate that FIRO is less likely to provide a water supply benefit for NBB, considering the lowest year for Hybrid and EFO are only 43 KAF greater than Baseline.

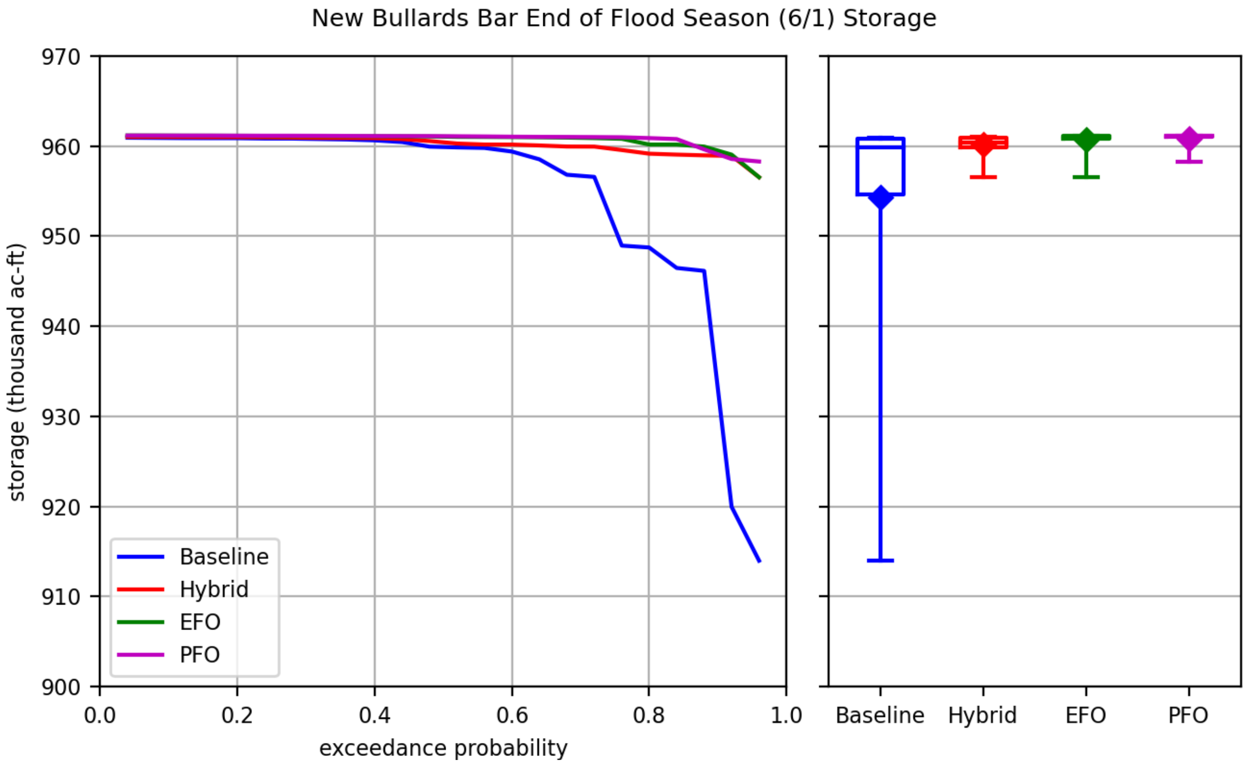


Figure G-25. *NBB end of flood season (6/1) storage shown as probability exceedance (left panel) and box and whisker plots (right panel) for each alternative.*

G.10 Expanded Analysis if Hybrid EFO Alternative

Based on the encouraging results of the initial simulations presented in Sections 7 and 8, further study was completed for the Hybrid EFO alternative. For this expanded analysis, simulation of Hybrid EFO involved a 2-step modeling process that included simulation with the Y-F EFO model and the Y-F ResSim model. Under this process each alternative was first simulated with the EFO model to formulate forecast based release schedules. These release schedules were then simulated with Y-F ResSim by defining the series of forecast-based releases from the EFO model as a rule in the alternative rule stack. This allows ResSim to evaluate a forecast-based release and potentially override this release should it violate an operational rule or system constraint. Additionally, the Y-F ResSim model includes rules that simulate coordinated operations practiced under the FCO program as described in Section 1. The routing of releases from Hybrid EFO alternative through the Y-F ResSim model provides a more accurate simulation of this alternative given current operational practices and constraints compared to the initial simulations described in Section 4 and 5.

The Y-F ResSim model was modified in order to properly simulate and apply the proposed releases made by the Y-F EFO model for the Hybrid EFO alternative. These modifications to the Y-F ResSim model were completed in close consultation with the USACE Hydrologic Engineering Center (HEC). Building from the operation sets of Oroville and NBB provided in the Y-F ResSim model that are designed to simulate current operations, new operation sets were developed in the Y-F ResSim that included a new rule for the proposed Y-F EFO releases. At the recommendation of HEC, certain rules from the existing operation sets were modified to properly accommodate the suggested releases from the Y-F EFO model. A modification log has been included as Attachment G-3 which describes these changes in detail.

In addition to the scaled flood events, described in Section 5, used for the initial simulations, the expanded analysis included additional hydrologic data for the development of new simulations. This included hydrology developed for the CVHS study, 2006 and 2017 flood events, and standard project floods from the Oroville WCM (U.S. Army Corps of Engineers, 1970) and NBB WCM (U.S. Army Corps of Engineers, 1972). A summary of these simulations is provided in Table G-4.

Table G-4. *Hybrid EFO expanded analysis hydrology.*

Source	Event(s)	Scale Factors
CVHS	1986, 1997	0.2,0.4,0.6,0.75,0.8,0.85,0.9,0.95,1,1.05,1.1,1.15,1.2,1.25,1.3,1.35,1.4,1.45,1.5, 1.55,1.6,1.65,1.7,1.75,1.8,1.85,1.9,1.95,2,2.05,2.1,2.15,2.2,2.4,2.6,2.8,3,3.2,3.4
CVHS	2006, 2017	1
HEFS	1986	1,1.1,1.2,1.3,1.4,1.5
HEFS	1997	1,1.1,1.2,1.3,1.4,1.5
HEFS	2006, 2017	1
WCM	SPF1	1
WCM	SPF2	1

Simulation results of the expanded analysis were post-processed and analyzed, which are included in the PVA (Yuba-Feather FIRO Steering Committee, 2022).

G.11 Summary and Conclusions

This study evaluates the Ensemble Forecast Operations (EFO) methodology for Lake Oroville and New Bullards Bar Reservoir. Different alternatives were explored for each reservoir that incorporated the EFO methodology in different ways. The EFO alternatives utilized the forecast uncertainty of ensemble forecasts to manage storage levels for flood control for the entire pool at both reservoirs; the Hybrid alternatives defined a maximum level within the reservoir pool the EFO methodology would be applied at each reservoir; and the Perfect Forecast Operations (PFO) alternatives are similar to the EFO alternatives, but utilize perfect information (observed flows as forecasts). The Baseline alternative was also included that approximates operations as defined in the reservoir water control manuals.

Simulation of these alternatives was enabled by the development of scaled hydrology and hindcasts of the 1986 and 1997 flood events prepared by the California Nevada River Forecast Center (CNRFC). The alternatives of this study were simulated with this scaled hydrology using the EFO model that has been formulated to simulate the EFO methodology. The EFO methodology developed for Oroville and NBB heavily relies on the maximum ensemble member to formulate release schedules, therefore simulations of the hindcast period of record (1985-2008) were also completed to assess potential impacts of FIRO due to the over release of water in response to a forecasted storm event.

Simulation results demonstrated that FIRO alternatives (EFO, Hybrid EFO and PFO) could adequately manage the reservoirs at generally higher storage levels during the winter season and still provide flood control management to a level equal to or greater than Baseline. Results for the 110% 1997 scaled event simulation showed that PFO resulted in flows lower than flood stage while all other alternatives (including Baseline) exceeded flood stage, indicating that coordinated operations with FIRO could decrease the frequency of flooding at the confluence and further downstream.

Model results show that high ESRD releases can increase flooding for points downstream of both reservoirs. This is most notable for cases when releases at NBB are reduced to manage for flooding at Marysville (flows above 180 KCFS), which results in rapid increases in storage and subsequent ESRD releases. If forecasted storage for both reservoirs indicated a risk of high storage levels that would trigger ESRD releases, it may be beneficial to relax some release constraints, such as maximum releases or maximum downstream objective flows, to maintain higher prereleases in advance of the flood event and possibly reduce ESRD releases during the flood event. Such a strategy could results in peak downstream flows even lower than what was presented in this study.

Results of the hindcast period of record simulations showed that FIRO pre-releases are unlikely to impact end of flood season (June 1) storage that could result in levels below Baseline, however results for Oroville showed a few years where end of flood control season storage levels were below perfect forecast operations. This indicates a potential risk of over release of water due to over forecasted spring storms. The volume tolerance curves developed for this study were solely calibrated using scaled hydrology of the 1986 and 1997 flood events, and therefore these curves are likely overfit and may not be well suited for less extreme spring storms.

The purpose of this study is to evaluate the preliminary viability and proof-of-concept of the volume- based ensemble forecast operations methodology described in Section 2. This methodology accounts for forecast uncertainty through evaluating the maximum storage forecast ensemble member above a defined storage threshold. Other statistics besides the maximum ensemble were also evaluated (not described in this report) such as the mean plus a quotient of standard deviation of ensemble storage above a defined storage threshold. These other statistics also demonstrated robust results however given that this methodology was developed with the scaled 1986 and 1997 flood events, the maximum statistic (most conservative) demonstrated the best results for the defined objectives and therefore was used in this proof-of-concept study. It should be noted that the maximum ensemble displays the greatest amount of variability between forecasts cycles, therefor the use of this statistic could create high variability in releases proposed by this methodology. This potential variability of releases should be evaluated to assess potential impacts on downstream flows and the frequency of operation changes.

Additionally, further evaluation should also include assessment of other statistics of the ensemble distribution.

EFO alternatives were evaluated in this study to demonstrate a range of benefits to water supply and flood control given current forecast skill, and to show proof of concept of this methodology for the Y-F system. However, results of this study have also shown areas of further investigation that could be pursued to refine the EFO methodology for Oroville and NBB, which are summarized below:

- The hydrology provided by the CNRFC did not include any regulation of flows upstream of Oroville, however this portion of the watershed is affected by flow regulation from a number of reservoirs. A more complex model should be assembled that simulates regulation to further refine the model results.
- Results from this study indicate a generally lower overall flood risk under FIRO, however forecast informed coordinated operations could be developed and evaluated for further reduction of flood risk at the Confluence and further downstream.
- The volume tolerance curves of the EFO and Hybrid EFO alternatives were calibrated using multiple scale factors of 2 historical flood event (1986 and 1997). The events used in the process were sufficient in magnitude for development of the tolerance curves, however since only 2 events were used in this process, the calibration hydrology lacked diversity of hydrologic timing and hindcast skill and reliability for the development of robust tolerance curves. Further analysis should be completed that incorporates the entire period of record as well as additional scaled events to develop curves that are more robust to future flood events.
- Further evaluation of this methodology should include evaluation of other statistics of storage exceedance above the defined storage threshold. Other statistics could include mean plus a quotient of standard deviation, or a percentile of the ensemble members above the storage threshold. This evaluation should include simulation of period of record hydrology to assess release variability for more common storm events. Additionally, metrics of release variability could also be incorporated in the objective functions used for the calibration of the volume tolerance curve.
- The top-of-FIRO-pool curves used for the Hybrid EFO alternatives in this study were developed in coordination with DWR SWP and Yuba Water staff. Further evaluation and refinement of these curves could be explored to evaluate varying levels of water supply and flood protection.
- Forecast based ESRD rules could be formulated to maximize prereleases made in advance of a flood event and minimize emergency releases made during the event to further reduce downstream flooding.
- Results of the hindcast period of record simulations indicate that FIRO could improve carry over storage from the flood control season to the dry season, especially for Oroville. These simulations did not incorporate any rules of water supply releases or downstream diversions. Simplified water supply rules could be formulated for the EFO model, or the EFO model could be loosely coupled with a water supply model as used by DWR SWP or Yuba Water.
- The period of record hindcast simulation also indicated that there could be risk of over releases from over forecasted spring storms that may not be fully recovered in the reservoir from inflows after a spring storm event. A potential solution (as identified by John Lehigh of DWR) for this could be explored that uses seasonally varying volume tolerance curves for the winter months (December – March) that are calibrated for the

larger storms that typically occur that time of year and different curves for the spring, summer and fall that are calibrated for those seasons.

- This study used hydrologic routing to estimate flow rates for points downstream of Oroville and NBB, however an area of future work could be to route the reservoir releases through a hydraulic model such as HEC-RAS for improved estimates flow and flood stage.
- With the development of a hydraulic model another area of future research could be completion of a flood frequency study to estimate the change in regulated flood frequency under FIRO.
- With the quantification of flood frequency, and benefits to water supply, an economic study could be completed that evaluates and quantifies the potential benefits of FIRO for critical beneficial uses such as water supply, flood control, fisheries and recreation.
- Efforts were made to validate the Y-F EFO model against the Y-F ResSim model, which is not covered in this report. However final review of model results has shown that further refinement of Y-F EFO could be pursued to improve agreement between the models.

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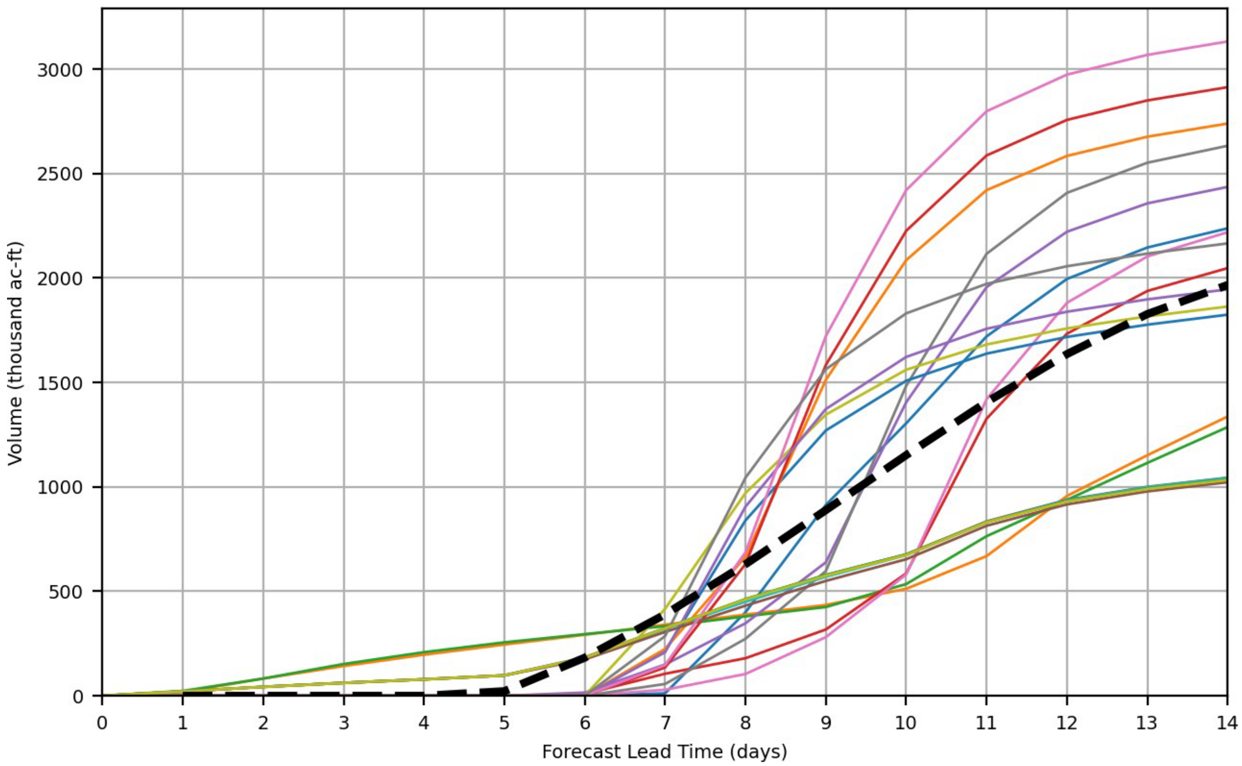
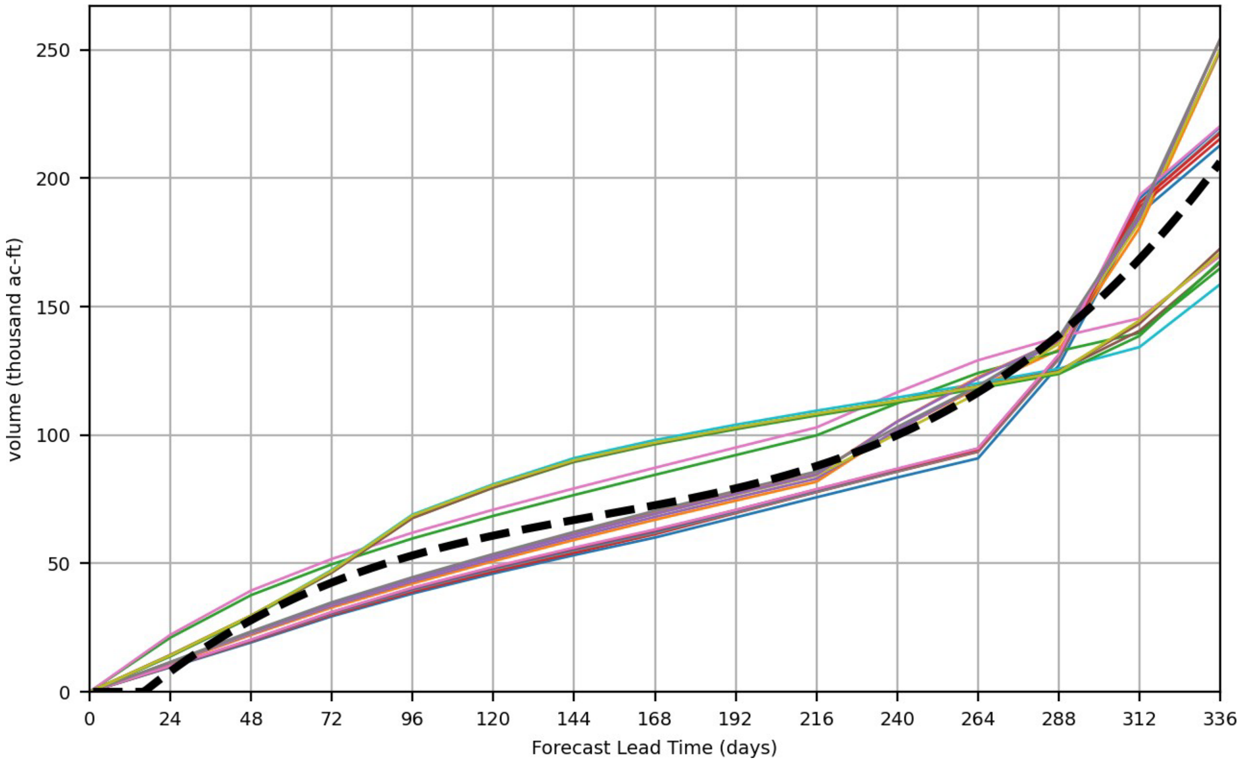
Attachment G-1: EFO Volume Tolerance Curves

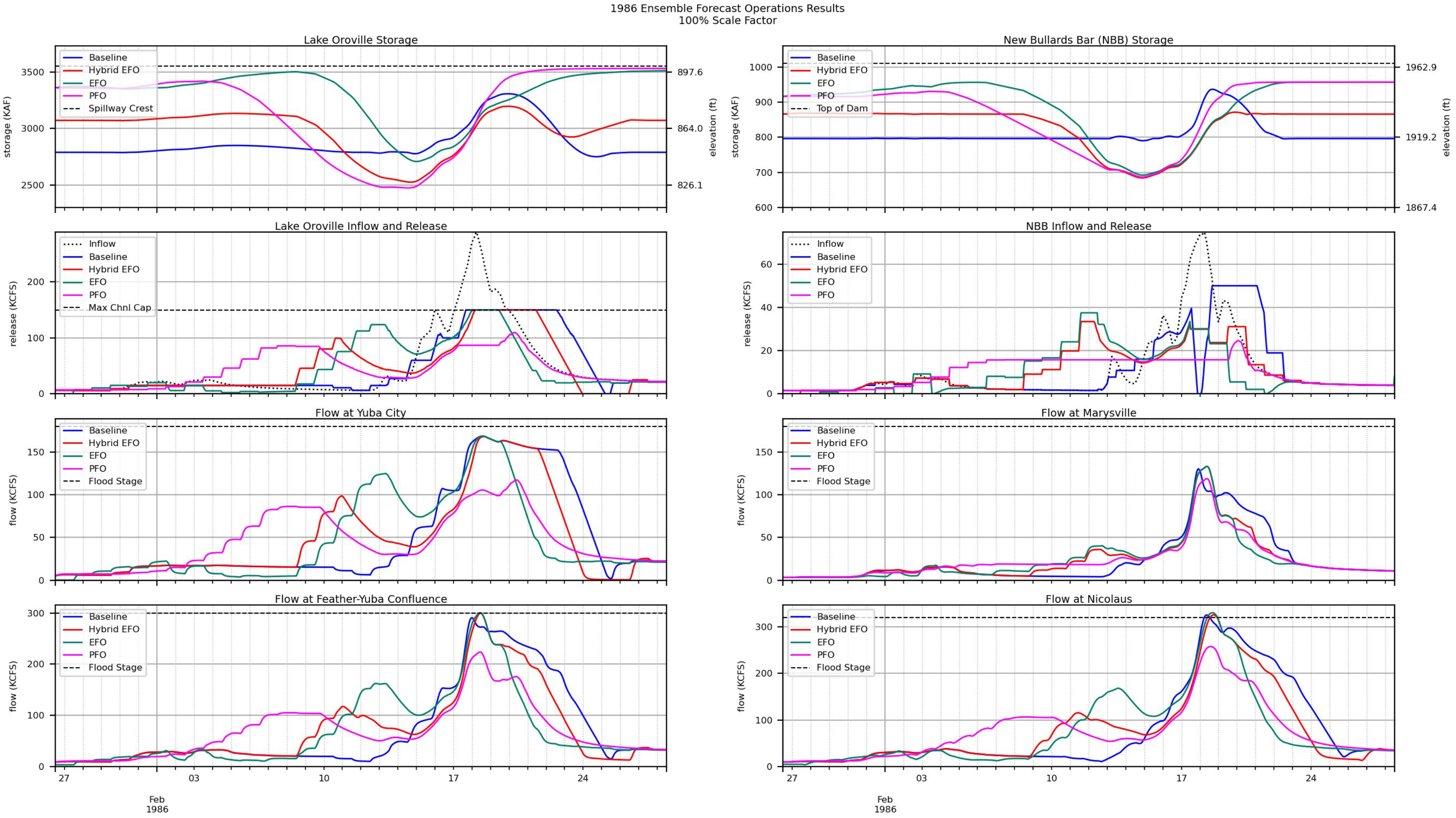


Lake Oroville EFO Alternative Volume Tolerance Curve



New Bullards Bar EFO Alternative Volume Tolerance Curve

Attachment G-2: Scaled Event Hydrographs



1986 Ensemble Forecast Operations Results
100% Scale Factor

Lake Oroville Storage

New Bullards Bar (NBB) Storage

Lake Oroville Inflow and Release

NBB Inflow and Release

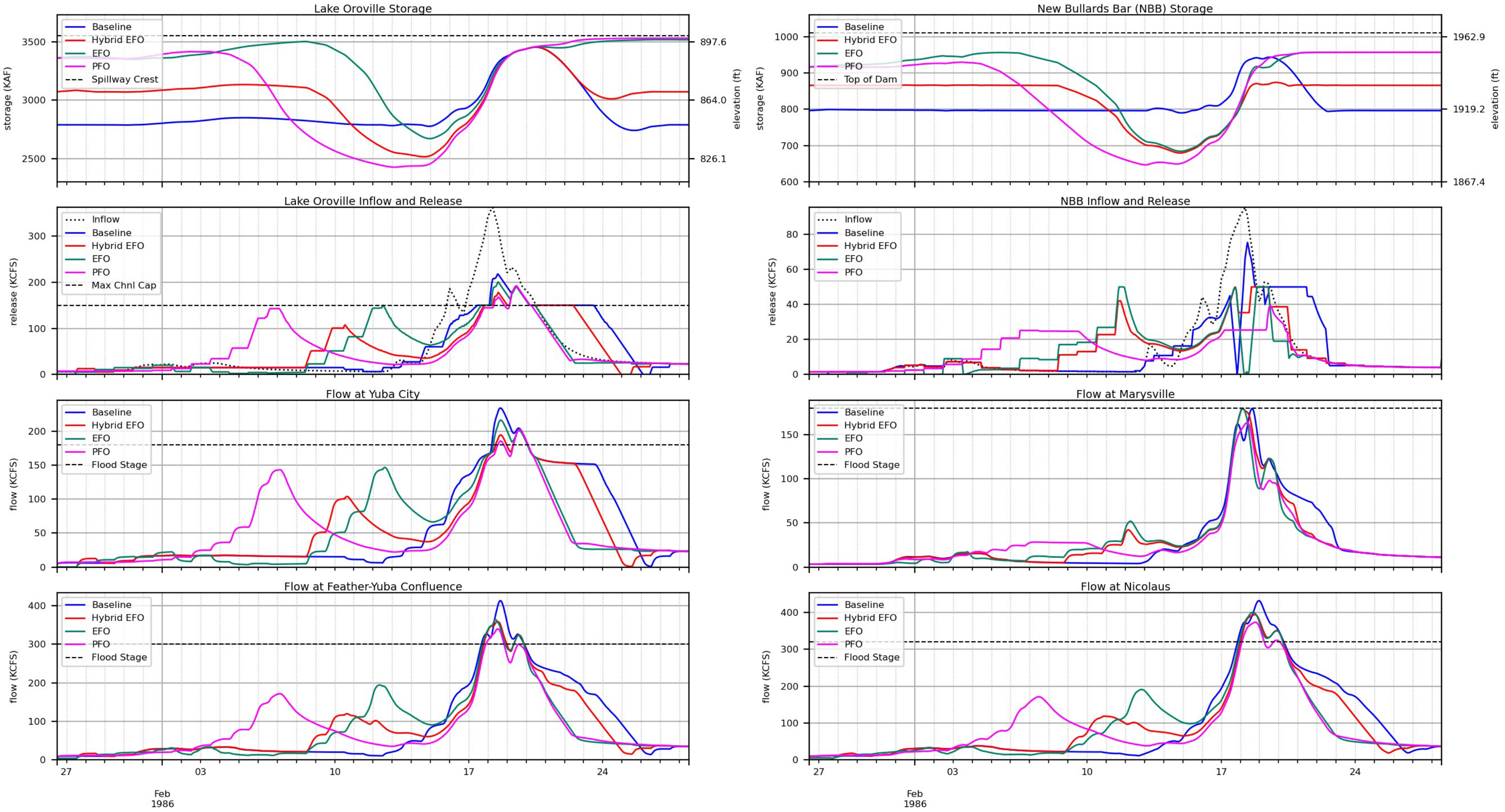
Flow at Yuba City

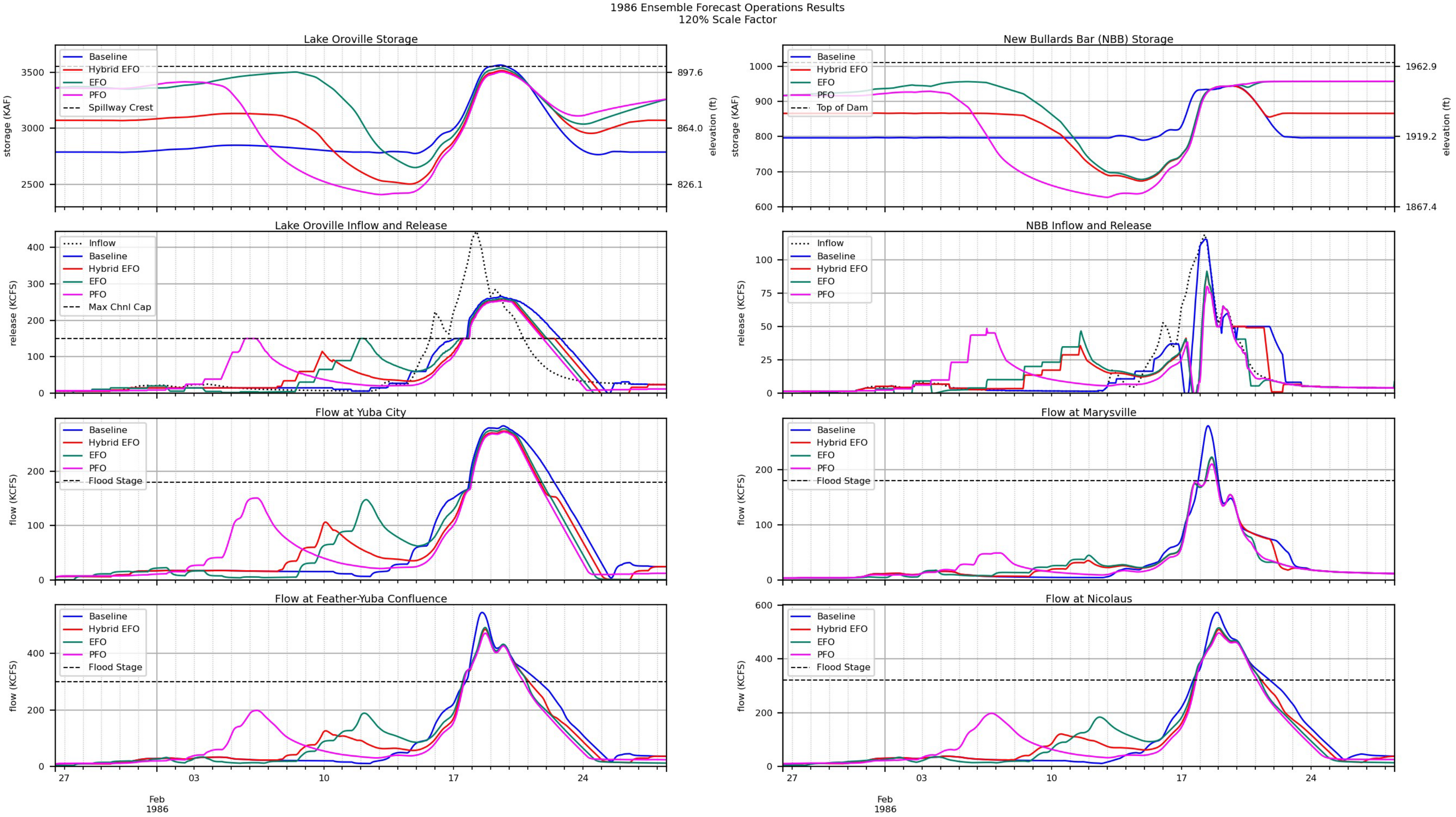
Flow at Marysville

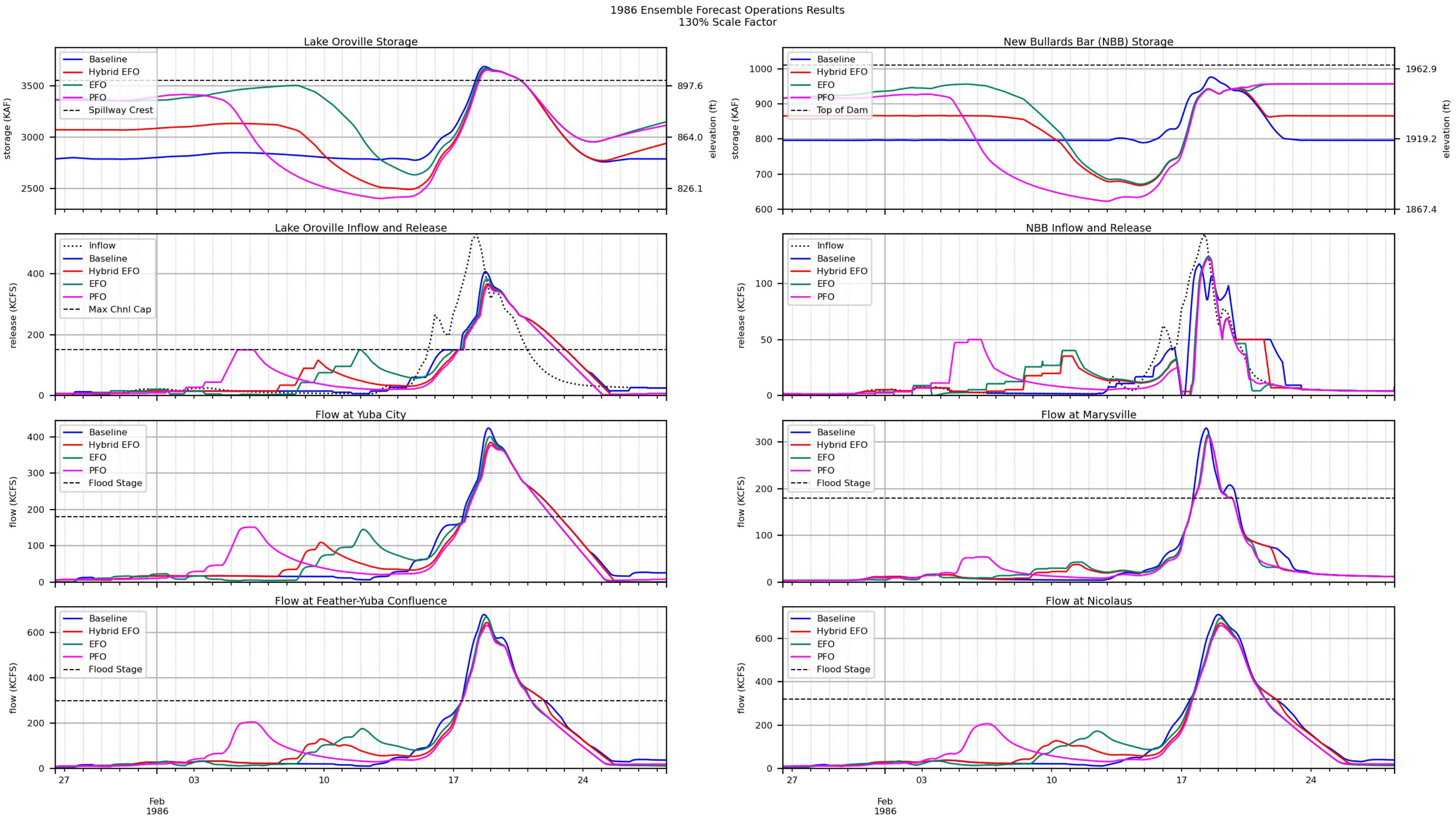
Flow at Feather-Yuba Confluence

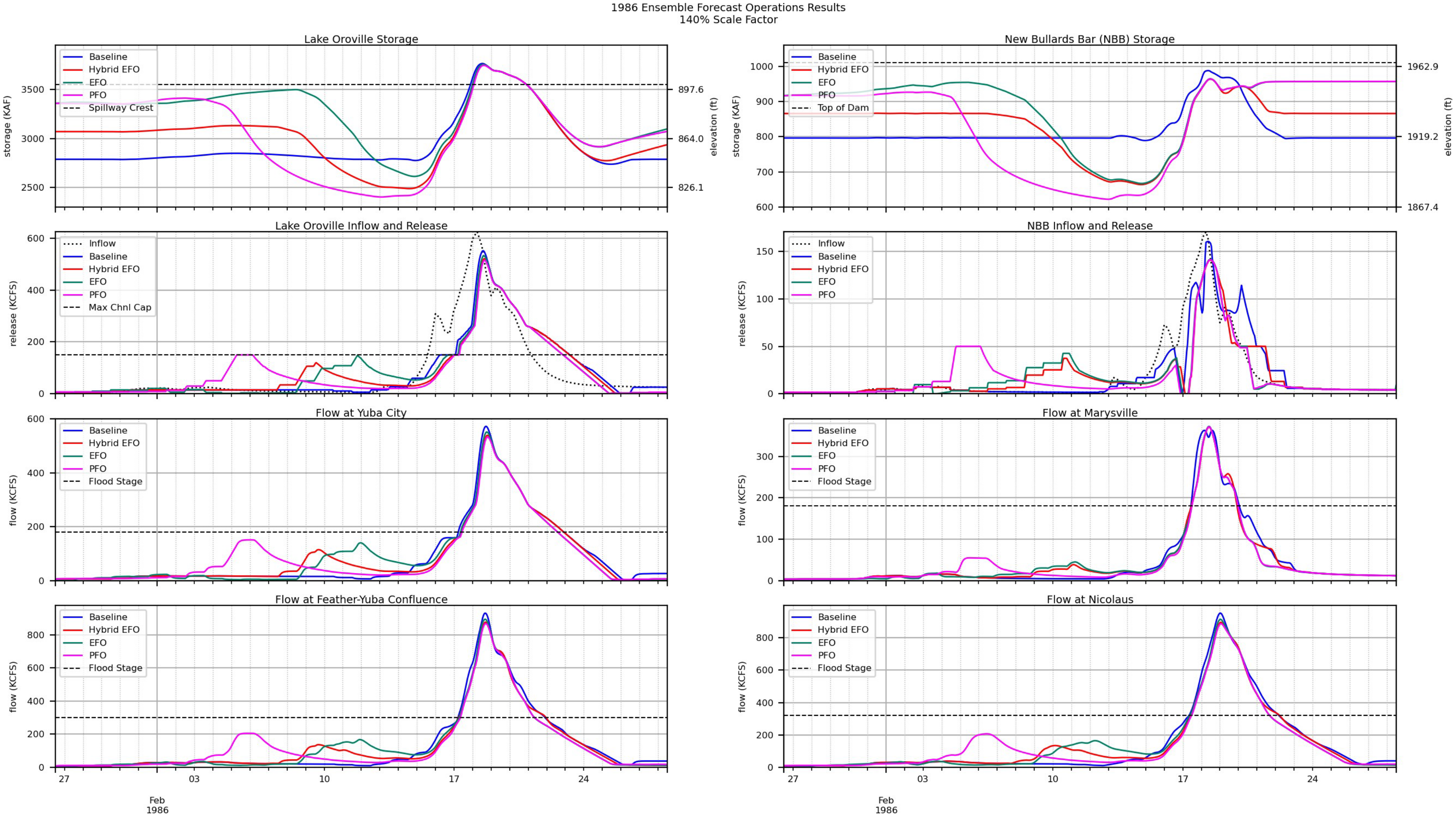
Flow at Nicolaus

1986 Ensemble Forecast Operations Results
110% Scale Factor

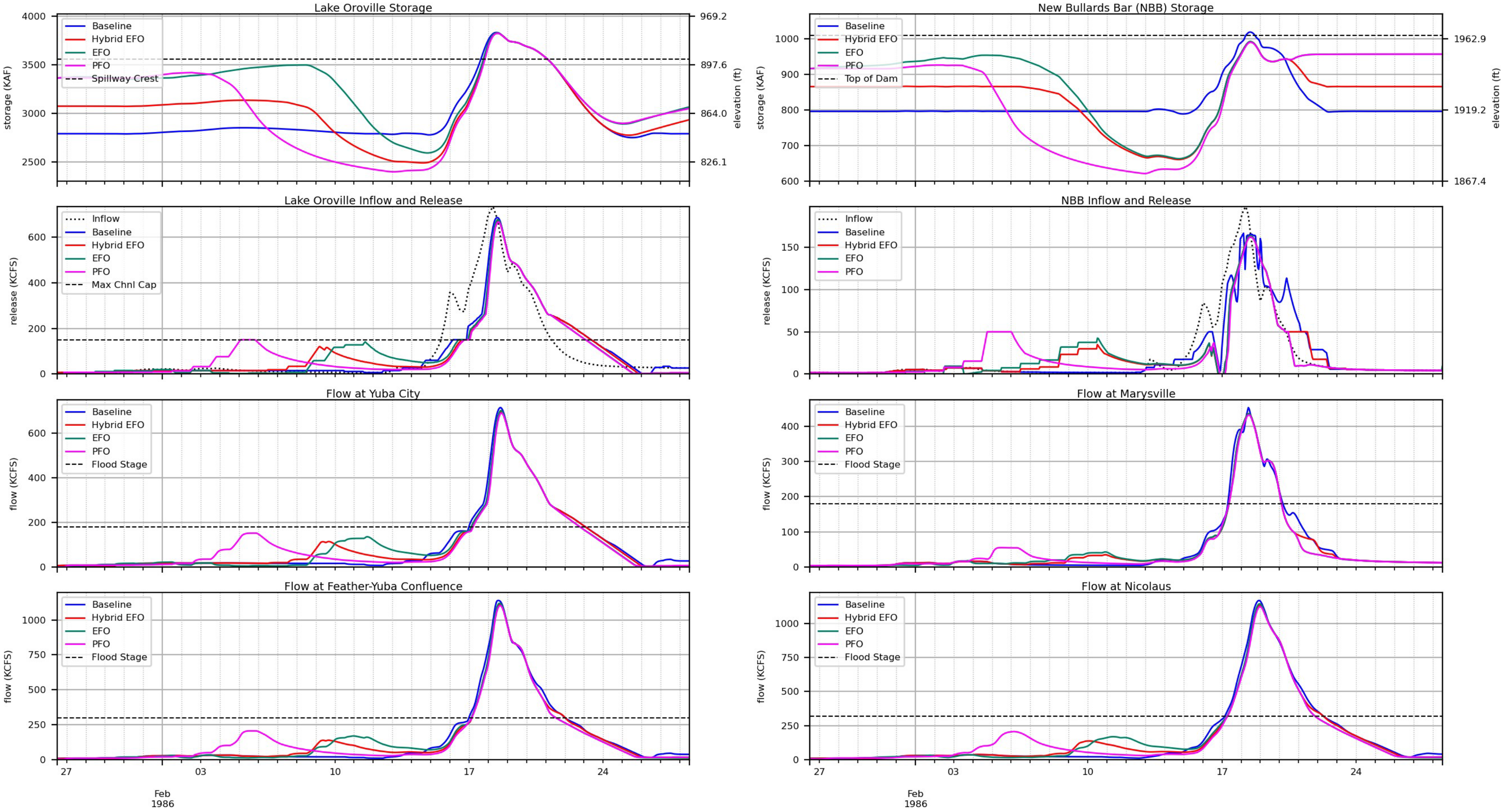



1986 Ensemble Forecast Operations Results
120% Scale Factor
Lake Oroville Storage
storage (KAF)
elevation (ft)
3500
3000
2500
897.6
864.0
826.1
Baseline
Hybrid EFO
EFO
PFO
Spillway Crest
New Bullards Bar (NBB) Storage
1000
900
800
700
600
1962.9
1919.2
1867.4
Top of Dam
Lake Oroville Inflow and Release
release (KCFS)
400
300
200
100
0
Inflow
Max Chnl Cap
NBB Inflow and Release
100
75
50
25
0
Flow at Yuba City
flow (KCFS)
200
100
0
Flood Stage
Flow at Marysville
Flow at Feather-Yuba Confluence
400
200
0
Flow at Nicolaus
600
400
200
0
27
03
10
17
24
Feb
1986

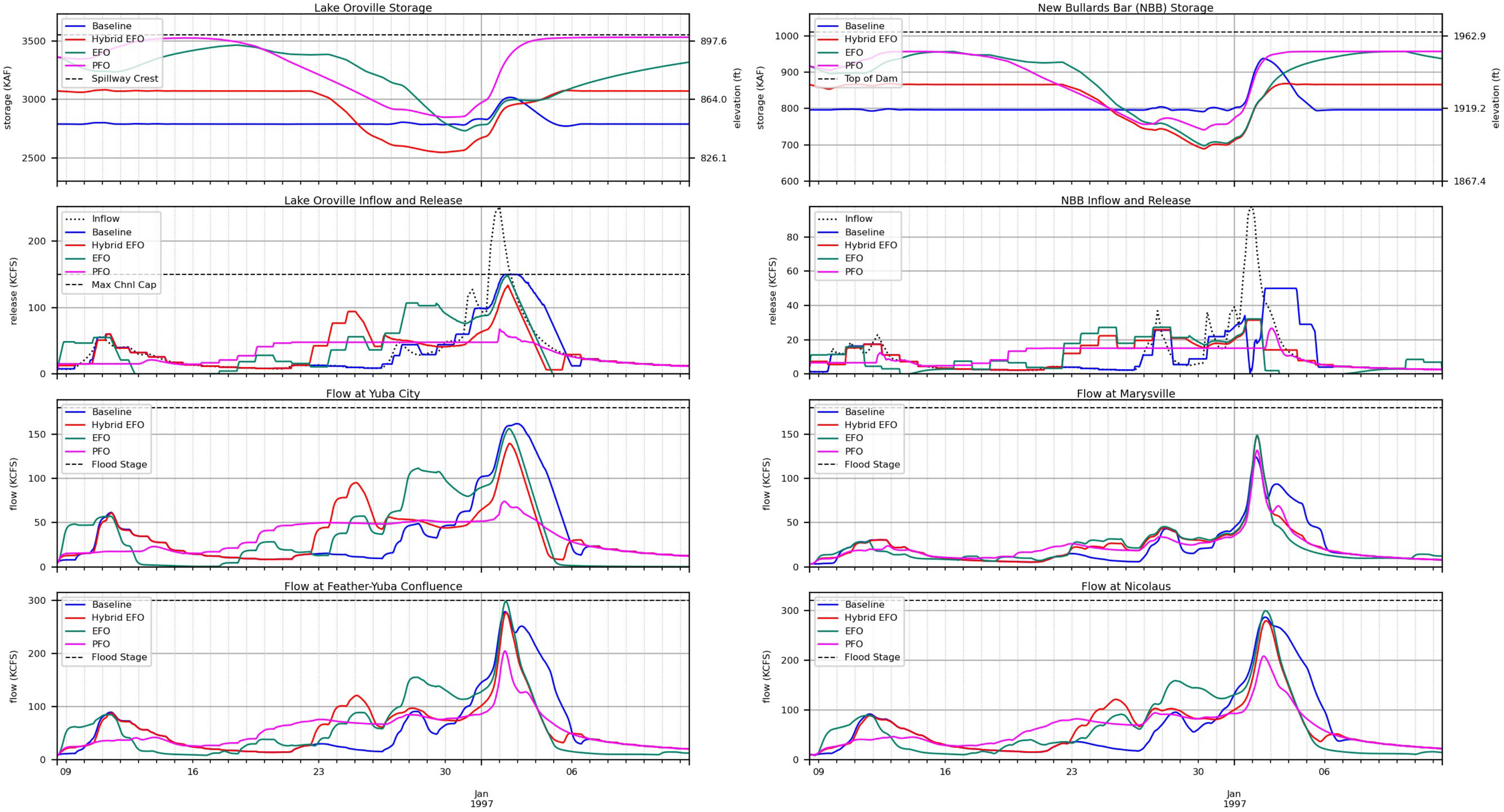

1986 Ensemble Forecast Operations Results
130% Scale Factor


1986 Ensemble Forecast Operations Results
140% Scale Factor
Lake Oroville Storage
storage (KAF)
elevation (ft)
3500
3000
2500
897.6
864.0
826.1
Baseline
Hybrid EFO
EFO
PFO
Spillway Crest
New Bullards Bar (NBB) Storage
1000
900
800
700
600
1962.9
1919.2
1867.4
Top of Dam
Lake Oroville Inflow and Release
release (KCFS)
600
400
200
0
Inflow
Max Chnl Cap
NBB Inflow and Release
150
100
50
Flow at Yuba City
flow (KCFS)
Flood Stage
Flow at Marysville
300
200
100
Flow at Feather-Yuba Confluence
800
Flow at Nicolaus
27
03
10
17
24
Feb
1986

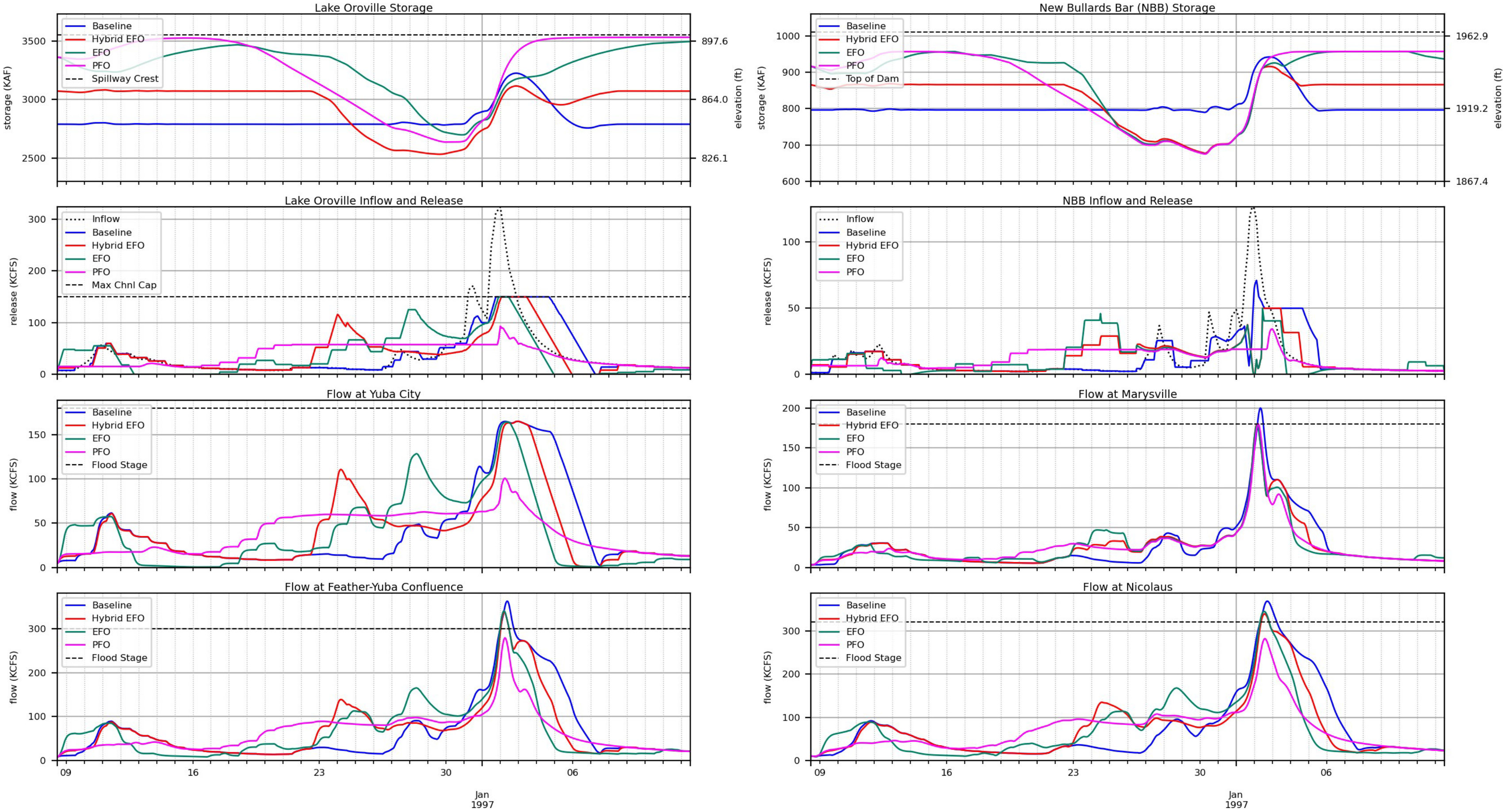
1986 Ensemble Forecast Operations Results
150% Scale Factor

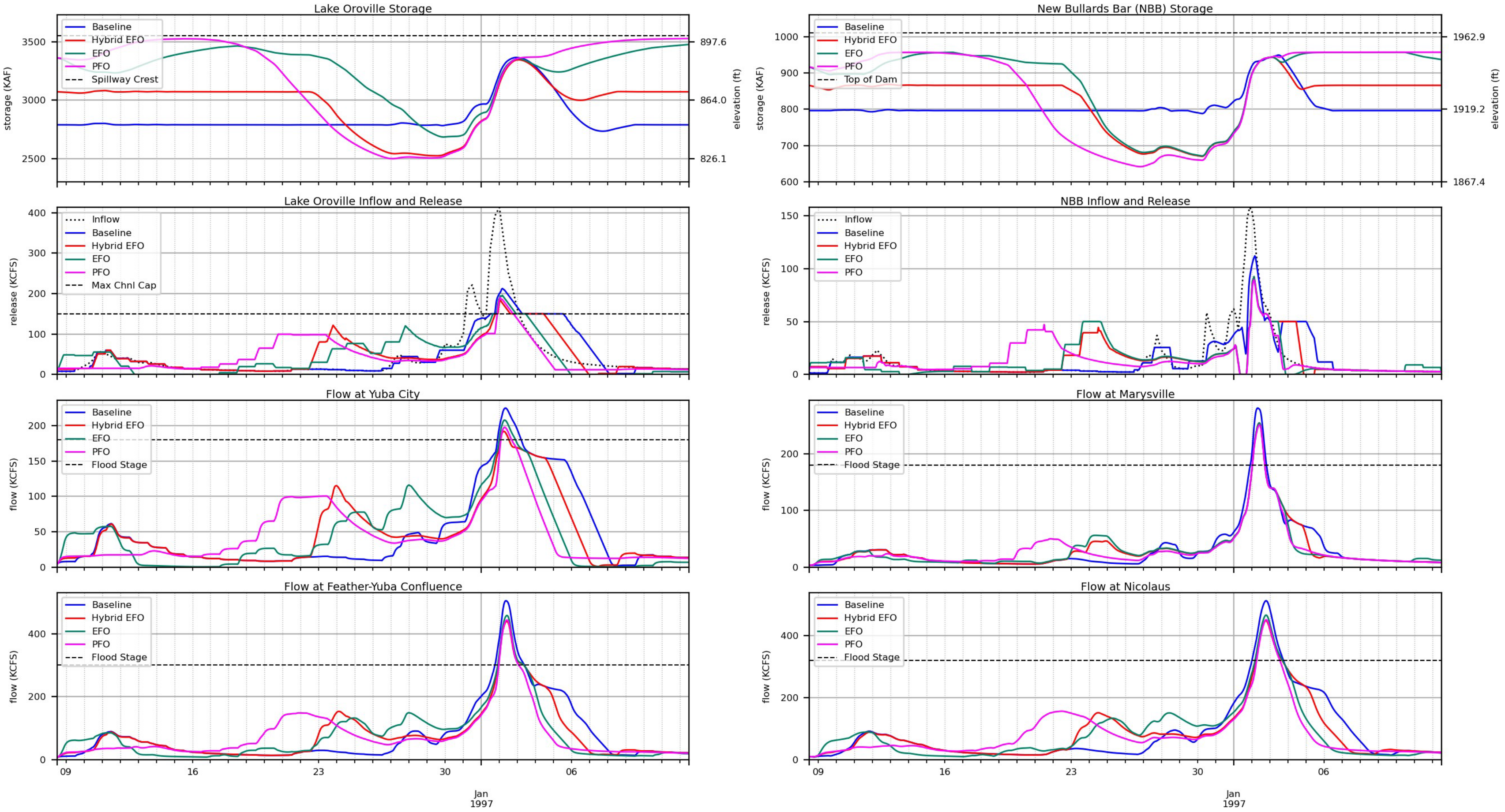


1997 Ensemble Forecast Operations Results
90% Scale Factor



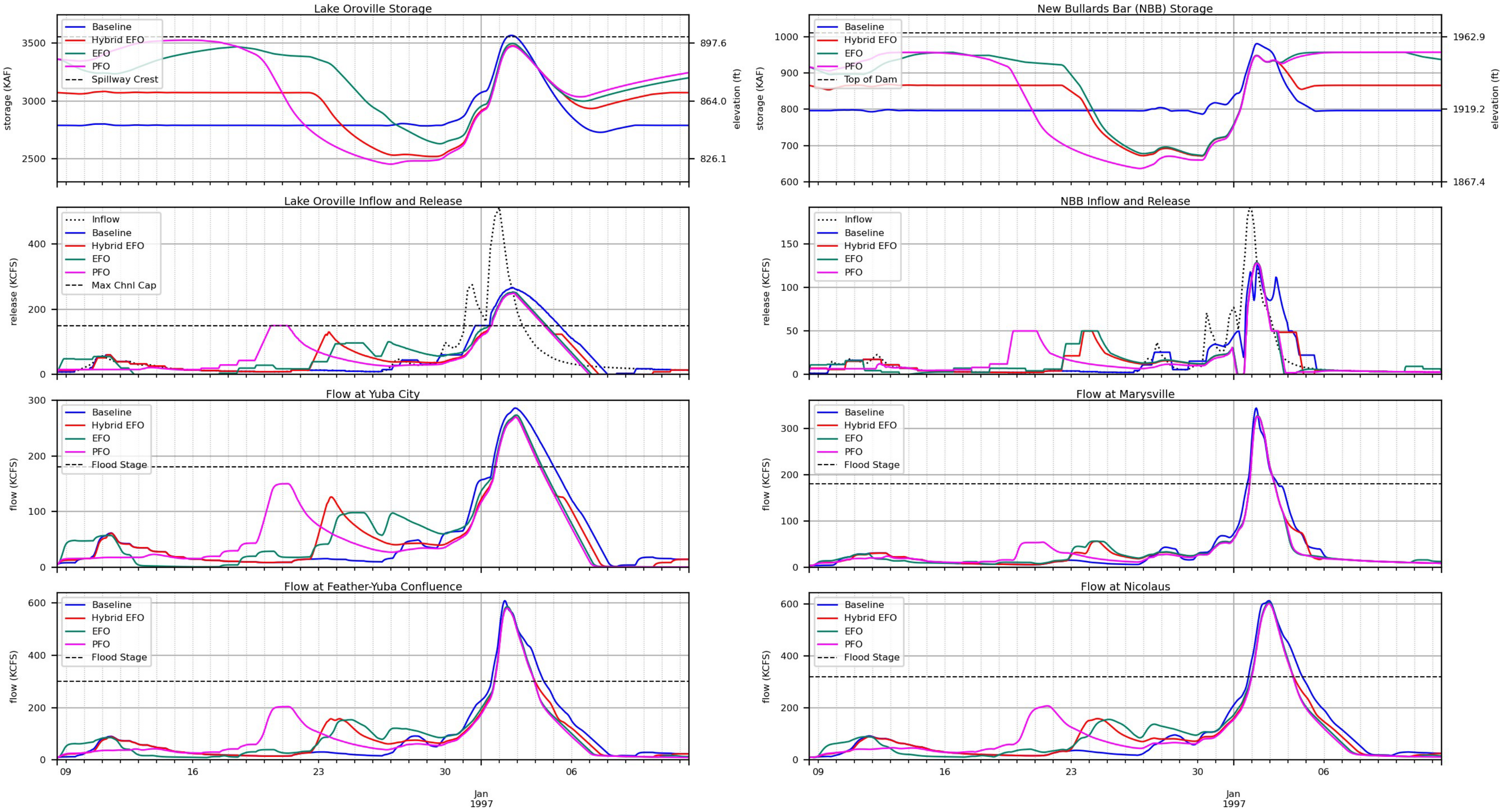
1997 Ensemble Forecast Operations Results
100% Scale Factor

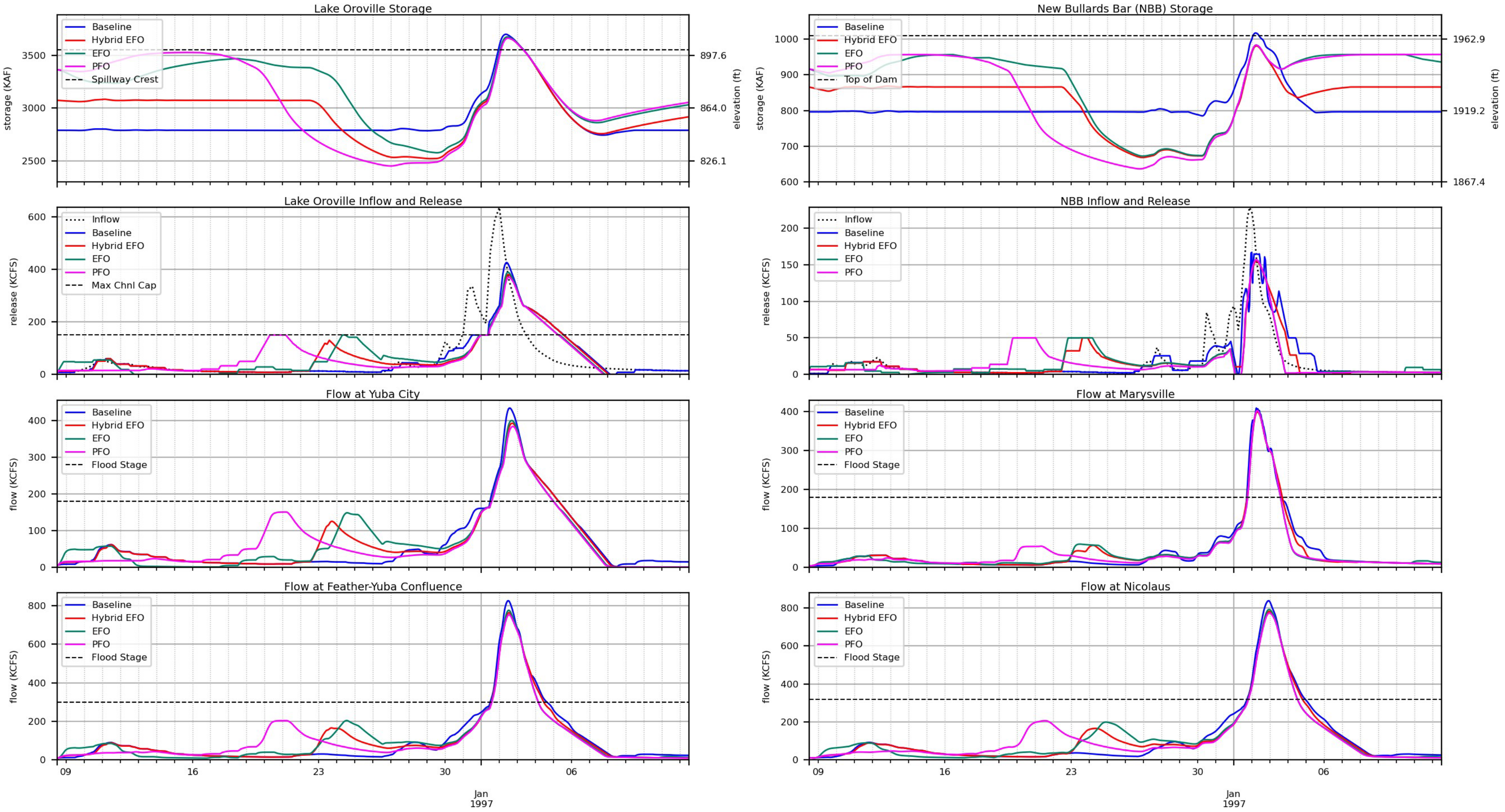




1997 Ensemble Forecast Operations Results
110% Scale Factor

1997 Ensemble Forecast Operations Results
120% Scale Factor





1997 Ensemble Forecast Operations Results
130% Scale Factor

Attachment G-3: Description of Modifications Made to Y-F ResSim Model

ResSim Model – Yuba Feather PVA Alt 3

Model Overview

ResSim Model Names:

1) Yuba-Feather_2021_FIRO_PVA_StartingPoint_REV_20220114\Yuba - Feather_2021_FIRO_PVA.wksp
2) Yuba-Feather_2021_FIRO_PVA_20220404_V04\Yuba-Feather_2021_FIRO_PVA.wksp

ResSim Model Overview Table

Model Number	Network	ResSim Alternative	Observed Hydrology	Events	Forecast Hydrology
#1	Sacramento-FIRO	"CVHS" + Scaling + Year	CVHS	1986, 1997	CVHS
		"HYBHEFS" + Year	CVHS	2006, 2017	HEFS
		"HYBCV" + Year	CVHS	2006, 2017	CVHS
		"HYBSPF" + #	SPF	SPF	SPF
#2	Sacramento-FIRO	"HYB" + Scaling + Year	HEFS	1986,1997	HEFS

Changes to Model

New Forecast Hydrology DSS File:

- YfEfoResults_CVHS_v6.dss
  - Includes EFO release from Python EFO Model to be used in ResSim model

New Operation Rules:

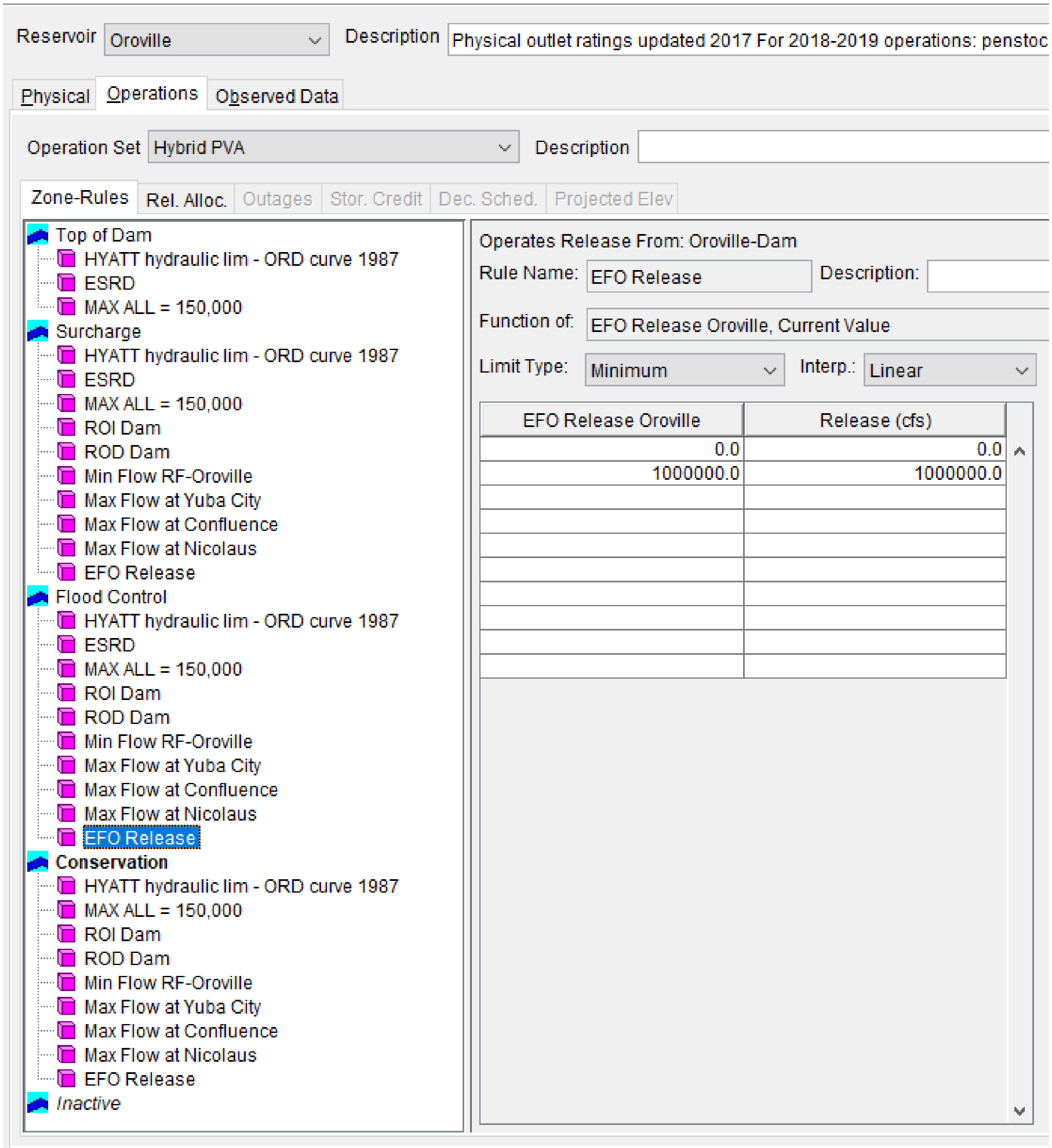
- EFO Release
  - Release Function Rule that applies at both Oroville-Dam and New Bullards Bar-Dam. The rule applies the EFO Release timeseries as a minimum flow from the dams. The rule is set at a low priority so as not to override the original current operation rules.
- Max ROI-NBB Dam/Min ROD-NBB Dam
  - Flow Rate of Change Limit Rule applied at New Bullards Bar-Dam. This rule replaces the previous Max ROI-NBB/Min ROD-NBB rules, which only applied to

    the Controlled Outlet and didn't take into account releases from the proposed Arc Spillway.

- Max Flow – NBB (Model #1) and 50k cfs Max Flow (Model #2)
  - Release Function Rule that apples at New Bullards Bar-Dam. Sets a maximum release constraint of 50,000 cfs in the Conservation and Flood Pools of New Bullards Bar.

New Operation Set:

- Oroville: Hybrid PVA (Model #1, Figure G3-1) and PVA – Alt 3 (Model #2)
  - Add EFO Release Rule
  - Remove Inflow Based Rising Pool Rule
    - This rule was removed because it was constraining releases by overriding higher priority rules.
  - Turn of Consider ROC Constraints for downstream control rules
    - This was turned off to remove fluctuations in releases caused by applying the EFO Release Rule and the downstream control rules in the same rule stack. Although fluctuation were removed, the downstream control rule is not performing as well.
- New Bullards Bar: Hybrid PVA (Model #1, Figure G3-2) and PVA – Alt 3 (Model #2)
  - Add EFO Release Rule
  - Remove Max Flow RF Inflow-NBB Rule
    - This rule was removed because it was constraining releases by overriding higher priority rules.
  - Turn of Consider ROC Constraints for downstream control rules
    - This was turned off to remove fluctuations in releases caused by applying the EFO Release Rule and the downstream control rules in the same rule stack. Although fluctuation were removed, the downstream control rule is not performing as well.



Reservoir: Oroville

Description: Physical outlet ratings updated 2017 For 2018-2019 operations: penstoc

Operation Set: Hybrid PVA

Description:

- Top of Dam
  - HYATT hydraulic lim - ORD curve 1987
  - ESRD
  - MAX ALL = 150,000
- Surcharge
  - HYATT hydraulic lim - ORD curve 1987
  - ESRD
  - MAX ALL = 150,000
  - ROI Dam
  - ROD Dam
  - Min Flow RF-Oroville
  - Max Flow at Yuba City
  - Max Flow at Confluence
  - Max Flow at Nicolaus
  - EFO Release
- Flood Control
  - HYATT hydraulic lim - ORD curve 1987
  - ESRD
  - MAX ALL = 150,000
  - ROI Dam
  - ROD Dam
  - Min Flow RF-Oroville
  - Max Flow at Yuba City
  - Max Flow at Confluence
  - Max Flow at Nicolaus
  - EFO Release
- **Conservation**
  - HYATT hydraulic lim - ORD curve 1987
  - MAX ALL = 150,000
  - ROI Dam
  - ROD Dam
  - Min Flow RF-Oroville
  - Max Flow at Yuba City
  - Max Flow at Confluence
  - Max Flow at Nicolaus
  - EFO Release
- *Inactive*

Operates Release From: Oroville-Dam

Rule Name: EFO Release

Description:

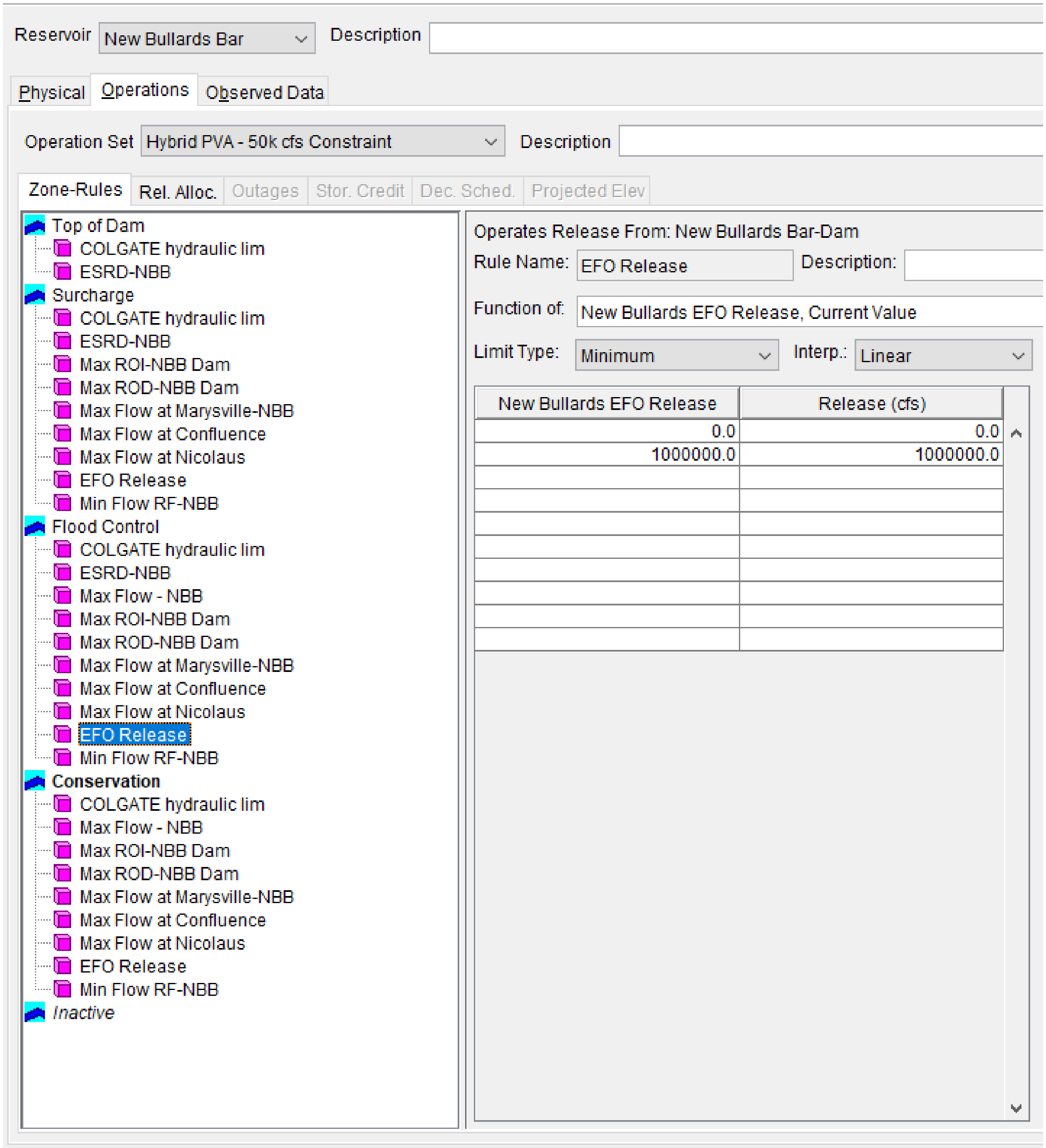
Function of: EFO Release Oroville, Current Value

Limit Type: Minimum

Interp.: Linear

EFO Release Oroville	Release (cfs)
0.0	0.0
1000000.0	1000000.0

Figure G3-1. Oroville: Hybrid PVA Operation Set Screenshot



Reservoir: New Bullards Bar

Description:

Operation Set: Hybrid PVA - 50k cfs Constraint

Description:

- Top of Dam
  - COLGATE hydraulic lim
  - ESRD-NBB
- Surcharge
  - COLGATE hydraulic lim
  - ESRD-NBB
  - Max ROI-NBB Dam
  - Max ROD-NBB Dam
  - Max Flow at Marysville-NBB
  - Max Flow at Confluence
  - Max Flow at Nicolaus
  - EFO Release
  - Min Flow RF-NBB
- Flood Control
  - COLGATE hydraulic lim
  - ESRD-NBB
  - Max Flow - NBB
  - Max ROI-NBB Dam
  - Max ROD-NBB Dam
  - Max Flow at Marysville-NBB
  - Max Flow at Confluence
  - Max Flow at Nicolaus
  - EFO Release
  - Min Flow RF-NBB
- Conservation
  - COLGATE hydraulic lim
  - Max Flow - NBB
  - Max ROI-NBB Dam
  - Max ROD-NBB Dam
  - Max Flow at Marysville-NBB
  - Max Flow at Confluence
  - Max Flow at Nicolaus
  - EFO Release
  - Min Flow RF-NBB
- *Inactive*

Operates Release From: New Bullards Bar-Dam

Rule Name: EFO Release

Description:

Function of: New Bullards EFO Release, Current Value

Limit Type: Minimum

Interp.: Linear

New Bullards EFO Release	Release (cfs)
0.0	0.0
1000000.0	1000000.0

Figure G3-2. New Bullards Bar: Hybrid PVA Operation Set Screenshot

Appendix H—Sensitivity to Downstream Flow Constraints (Section 4)

MEMORANDUM

DATE:	November 18, 2021
TO:	Yuba-Feather FIRO Water Resources Engineering Team
PREPARED BY:	Carissa Abraham, EIT
REVIEWED BY:	Carly Narlesky, PE
SUBJECT:	Yuba-Feather System Operations: Sensitivity to Downstream Flow Constraint Split

H.1 Introduction

The Yuba-Feather (YF) system is somewhat unique in its pairing of major, multi-benefit reservoirs, Oroville (ORO) and New Bullards Bar (NBB) with joint flood operating rules, which explicitly require ORO/NBB coordinated operation to manage flows in the river network below the dams. To further complicate things, the United States Army Corps of Engineers (USACE) joint operating rules assumed the addition of a third system reservoir, Marysville Dam (MRY) when they were developed fifty years ago. The reservoir operating rules for ORO and NBB also assumed that MRY would help NBB control flows on the Yuba River, adding 260 TAF of flood reserve (USACE-SPK, 1970; USACE-SPK, 1972; USACE-SPK, 1971). Without MRY, NBB has shouldered an unanticipated flood operations burden for the last fifty years, and this imbalance may also adversely affect ORO, as NBB's system operations partner.

This burden has been recognized in the interim, and the NBB operating rule limiting releases to a challenging downstream flow threshold has been informally relaxed. NBB has been allowed to manage Yuba River flows to a higher value in flood operations, which creates a disconnect with two other joint ORO/NBB WCM operating rules limiting flows in the Feather River below the Yuba River and the Feather River below Bear River. As a consequence, operators are reliant on reservoir simulation models and their algorithms to determine how the Yuba and Feather flows are balanced to meet these joint Feather River mainstem constraints.

Yuba Water Agency (YWA) and the California Department of Water Resources (DWR) are currently engaged in updating the water control manuals (WCMs) for NBB and ORO. The WCM Update team has composed an initial set of flood risk management objectives that identifies the at-site and system goals of the two related WCM updates. A second document records additional considerations for the evaluation of operations alternatives, including the directive to "incorporate more explicit defined cutback responsibility between NBB/ORO for downstream constraints more clearly. Disambiguate Yuba River shared downstream 180/120 kcfs constraint." The WCM update process for NBB and ORO will finally correct the assumption of MRY's contribution to the FRM in the current operating rules. The WCM update provides an opportunity for an explicit rule for how contributions to the Feather below Yuba River constraint are split between NBB and ORO. This memorandum summarizes the impact of potential combinations of

Yuba and Feather River operational flows to meet the joint system constraint in the Feather River below Yuba River, pro- viding a first step in this important endeavor. These potential combinations of operational flows are intended to provide background and context only, since it is anticipated that a dynamic flow split may be used to meet the join system constraints, possibly using forecasts.

H.2 Flow Constraints

The Yuba River and Feather River Watersheds are managed with a joint downstream flow constraint of 300 kcfs in the Feather below Yuba. Both ORO and NBB are expected to constrain releases so that flows in the Feather River below Bear River do not exceed 320 kcfs. The existing WCMs also define downstream flow constraints specific to the Feather and Yuba Rivers at locations above the Feather below Yuba; these flow constraints are listed in Table H-1.

Table H-1. *Flow Constraints defined in the NBB and ORO WCMs*

Location	Flow Constraint (kcfs)	NBB	ORO
Feather River below Yuba River	300	x	x
Feather River below Bear River	320	x	x
Yuba River near Marysville	120 when Feather is high	x	
Yuba River near Marysville	180 when Feather is low	x	
Feather River at Yuba City	180		x
Feather River downstream of ORO	150		x

The text from the NBB Flood Control Diagram reads: "Water will not be released at such rates as will cause flows to exceed 120,000 cfs in Yuba River at Marysville when concurrent flows in Feather River are high. If necessary, however, releases may be increased when concurrent flows in Feather River are low; provided that flows in Yuba River at Marysville do not exceed 180,000 cfs" (USACE-SPK, 1972). This was written assuming that Middle and South Yuba contributions to flow near Marysville would be managed through the proposed Marysville Dam. Because MRY was never constructed, much of the Yuba River watershed runoff remains unregulated, which places a larger burden on NBB to meet downstream flow constraints than was originally anticipated.

Figure H-1 demonstrates that, for the 1997 x 100% scaled flood event modeled as described in Methods, NBB releases contribute less than half of the peak flow at the Yuba River near Marysville. This means more than half of the peak flow is from unregulated streams that join the Yuba River below NBB (namely the Middle Yuba, South Yuba, Deer Creek, and Dry Creek). For comparison, over 80% of the peak Feather River flow at Yuba City is regulated (ORO releases), as seen in Figure H-2. Only 30 kcfs is from unregulated flow below ORO (Honcut Creek and other local accretions).

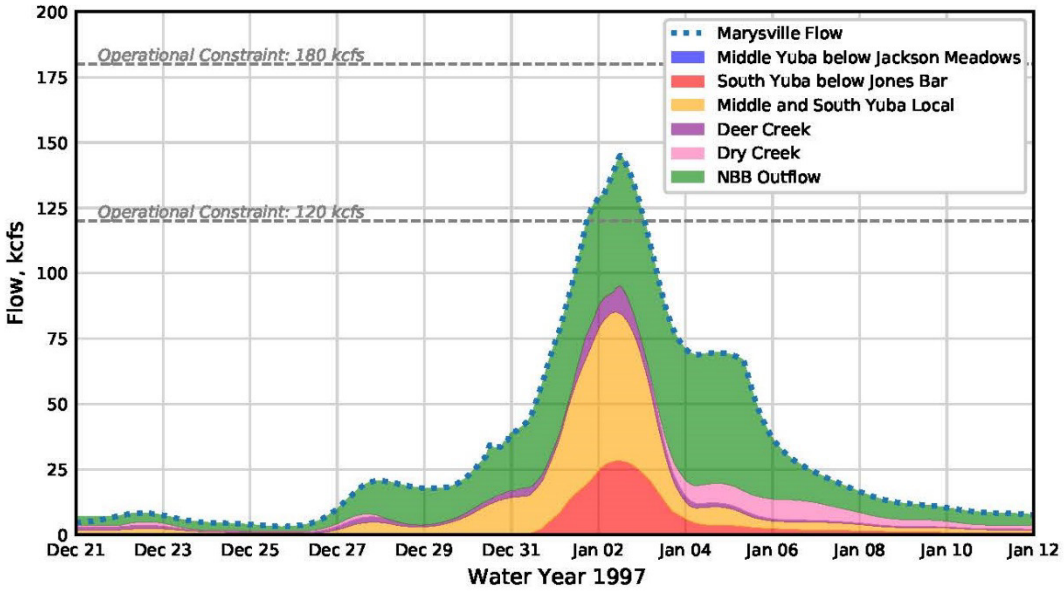


Figure H-1. *Flow Components for Yuba River at Marysville; 1997 x 100% Baseline*

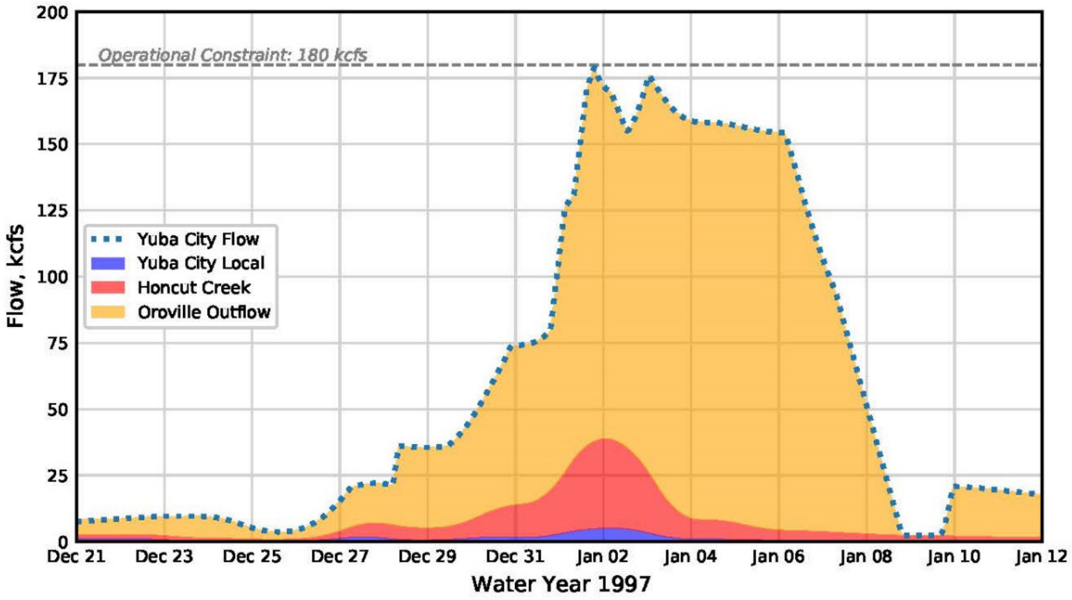


Figure H-2. *Flow Components for Feather River at Yuba City; 1997 x 100% Baseline*

Figure H-3 from the Marysville Reservoir Design Memorandum provides insight into the historical intention for the downstream constraints for the Yuba and Feather rivers (USACE-SPK, 1971). The language in the NBB WCM requires limiting the Yuba River above Mouth to "120,000 cfs under high backwater conditions and 180,000 cfs under low backwater conditions". However, because of the delay in flow released from ORO/NBB reaching the Feather below Yuba, it is difficult to anticipate the backwater conditions at the time of NBB/ORO releases, especially as much of the flow in the Yuba River is unregulated. The current WCMs require non-specified coordination between operators of NBB and ORO to meet the stated 300 kcfs constraint. As a part of the ongoing WCM updates, YWA and DWR aim to determine an appropriate and straightforward relationship for these flow constraints for use in Forecast-Coordinated Operations (F-CO).

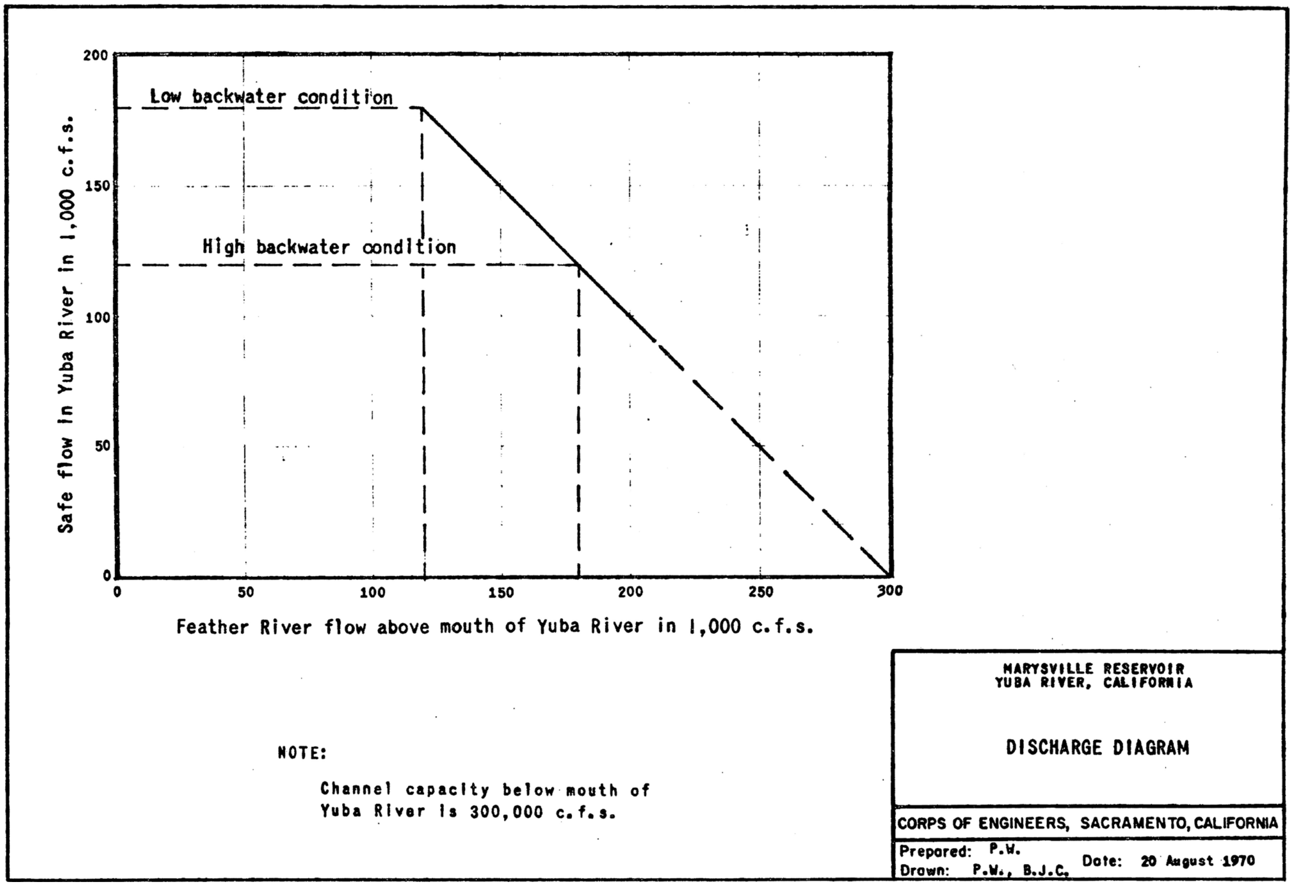


Figure H-3. *Historical Diagram for Flow Constraint Split (USACE-SPK, 1971)*

H.3 Methods

System operations for NBB and ORO were simulated using the MBK reservoir operations model configured in Python. This model represents the Yuba-Feather watershed with boundary conditions and hydrologic inputs adopted from the Central Valley Hydrology Study (CVHS) for flood events in water years 1956, 1965, 1986, and 1997. The model assumes that the release from NBB is limited to 50 kcfs unless the event requires an ESRD release. The Feather below Bear constraint was relaxed to isolate coordination effects of the 300 kcfs constraint for the Feather below Yuba.

The model simplifies the flow split at the Feather below Yuba by allowing NBB and ORO to each contribute 50% of the flow exceeding the 300 kcfs constraint, subject to rate of change and other flow constraints.

To determine the impact of the split of the Feather below Yuba flow constraint, the Yuba-Feather model was run with four different alternatives (labeled 1 to 4) outlined in Table H-2. In alternatives 2 through 4, the individual rivers are limited independently but still sum to 300 kcfs at the Feather below Yuba, which reduces the amount of coordination necessary between NBB and ORO for reservoir operations. The flow split provides an explicit method for coordination to meet the downstream flow constraints.

Table H-2. *Summary of Simulation Alternatives*

Alternative Name	Yuba River (kcfs)	Feather River (kcfs)	Feather below Yuba (kcfs)
(1) Baseline	180	180	300
(2) Yuba 120: Feather 180	120	180	-
(3) Yuba 150: Feather 150	150	150	-
(4) Yuba 180: Feather 120	180	120	-

System performance was evaluated using two primary metrics: NBB and ORO reservoir utilization and Feather below Yuba channel utilization. These metrics are described in detail in *Frame- work to Depict System Risk Balance* (MBK, 2021).

H.4 Results

The model was run for the four alternatives outlined in Table H-2 without the Atmospheric River Control (ARC) spillway at NBB. Figure H-4 shows how the downstream constraints affect the Feather River channel utilization compared to the reservoir utilization for NBB and ORO. Each color represents a different alternative. NBB is represented by the dots and ORO by the x's. The blue squares, green triangles, and pink hexagons highlight the smallest event where the NBB Reservoir Utilization, ORO Reservoir Utilization, and Channel Utilization, respectively, reach 100% for alternatives 2 and 4. The same colors and polygon highlights are used throughout this memorandum.

When the downstream constraint at Yuba River is limited to 120 kcfs (Run 2), the channel capacity constraint is exceeded even while there is flood space remaining in NBB and ORO, which is highlighted with the pink hexagon. Additionally for Run 2, ORO is only 58% utilized when NBB reaches 100% of reservoir utilization, highlighted by the blue square. However, if the downstream constraint at Yuba River is increased to 180 kcfs (Run 4), the ORO flood space is exhausted when the Feather below Yuba is at 84% of channel utilization, which is highlighted with a green triangle. The 120 kcfs and 180 kcfs Yuba River constraints bookend a range of possible flow combinations for the Feather below Yuba, with any other possible flow splits falling between them. Run 2 and 4 also indicate the range of results for channel utilization and reservoir utilization. The Yuba River constrained to 150 kcfs (Run 3) falls closest to the baseline (Run 1), but a 150 kcfs constraint uses less channel capacity and less flood space than the baseline for the same sized event; i.e., it has better overall FRM performance. Overlapping points for NBB and ORO at the same channel utilization indicate the system operation is more balanced between the two reservoirs.

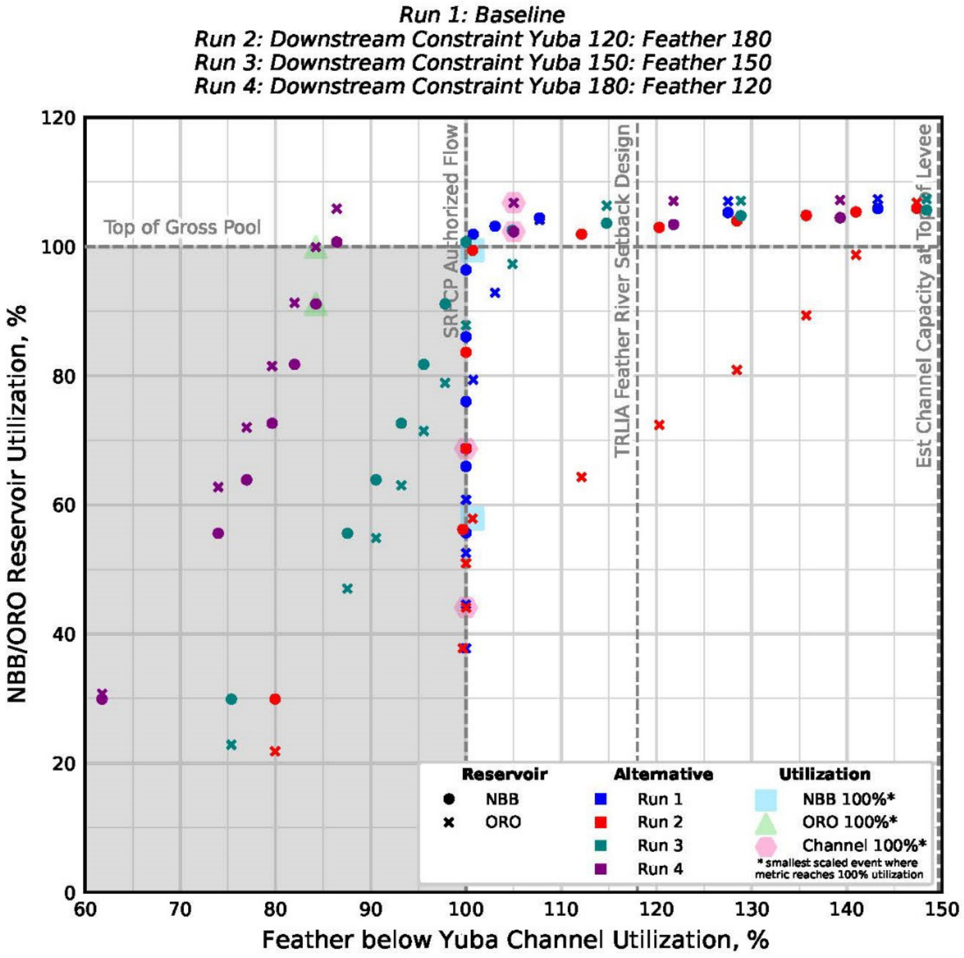


Figure H-4. *Reservoir Utilization versus Channel Utilization; 1997*

Utilization comparisons for the other scaled historical flood events (1956, 1965, and 1986) are shown in Figure H-5, Figure H-6, and Figure H-7 and demonstrate similar trends.

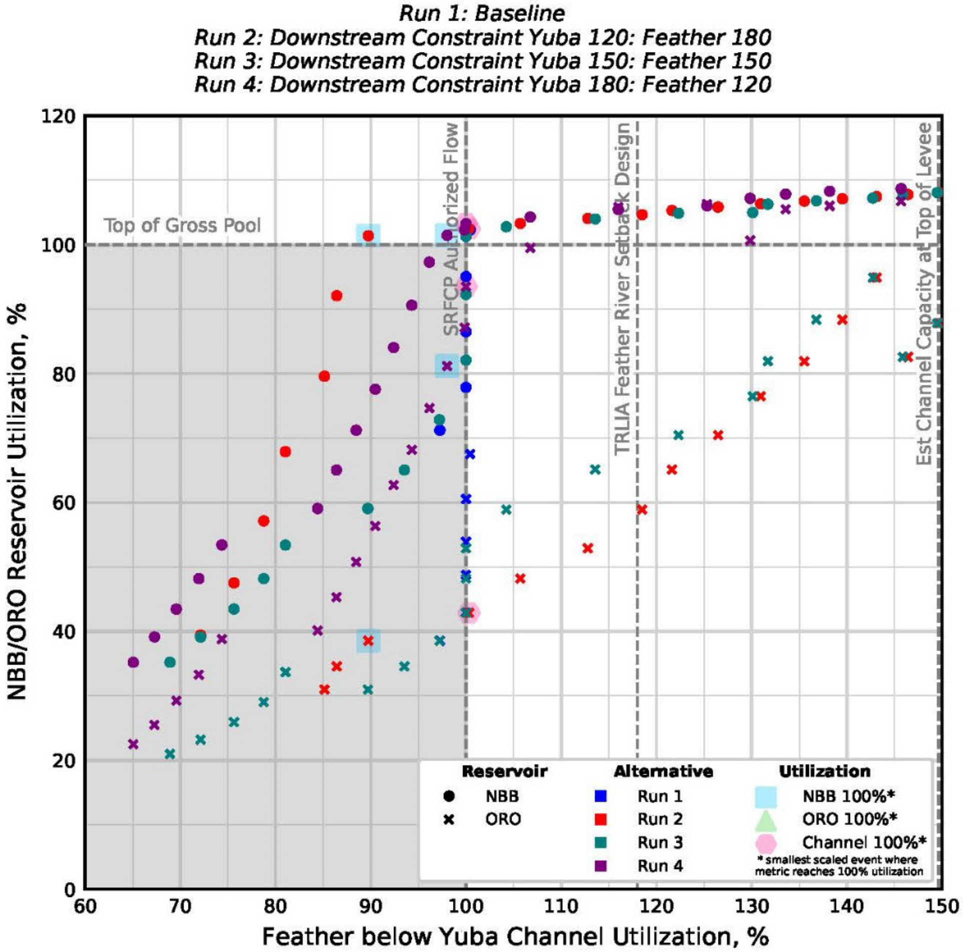


Figure H-5. *Reservoir Utilization versus Channel Utilization; 1956*

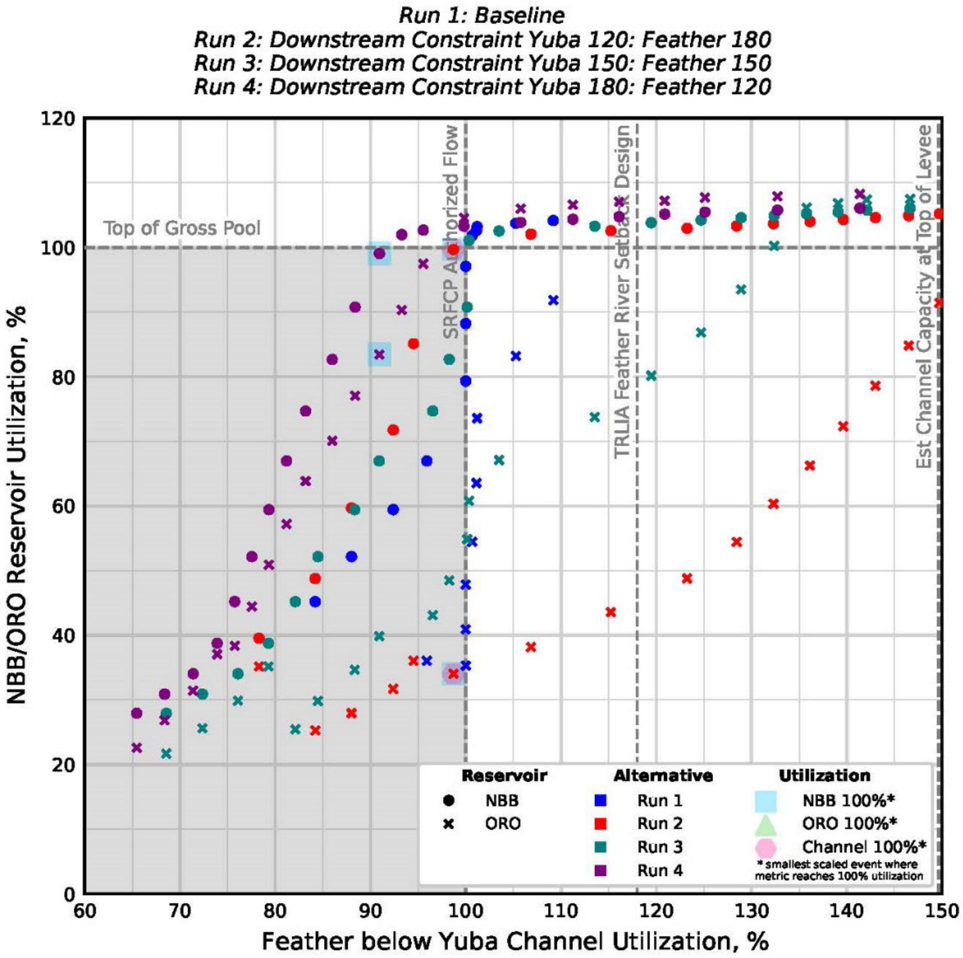


Figure H-6. *Reservoir Utilization versus Channel Utilization; 1965*

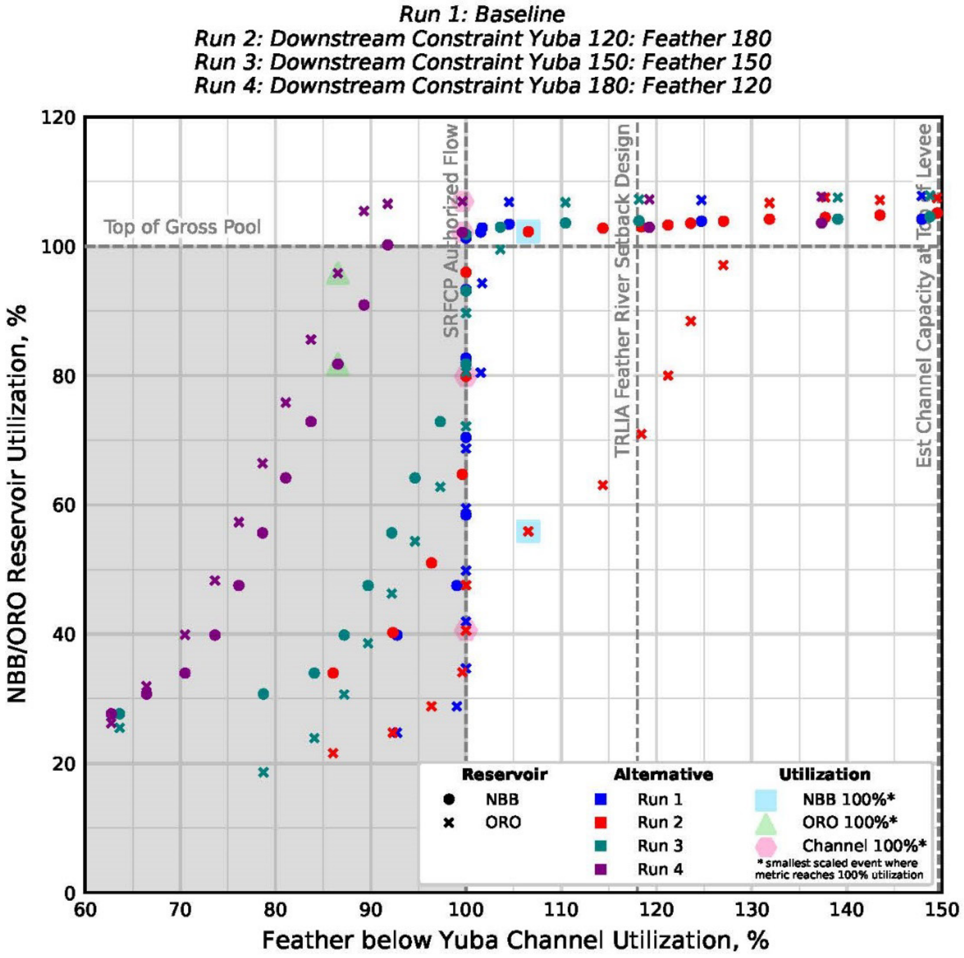


Figure H-7. *Reservoir Utilization versus Channel Utilization; 1986*

Figure H-8 shows the balance between NBB and ORO more explicitly, with the diagonal line representing an even balance. The Yuba River limited to 120 or 150 kcfs and the Baseline fall below the diagonal line, which means that NBB stores a higher proportion of the system flow relative to the size of its flood reserve. The Yuba River limited to 180 kcfs (Run 4) is the only alternative that falls above the diagonal line, which means ORO stores a higher proportion of system flow. When the Yuba River is limited to 120 kcfs (Run 2), NBB reaches its full reservoir utilization when ORO reaches 58% of flood space utilization, which is highlighted by the blue square. Conversely, when the Feather River is limited to 120 kcfs (Run 4), NBB reaches 91% when ORO reaches 100% of reservoir utilization, which is highlighted by the green triangle. The pink hexagon highlights that neither reservoir is even close to full when the channel utilization exceeds 100% if the Yuba River is limited to 120 kcfs (Run 2).

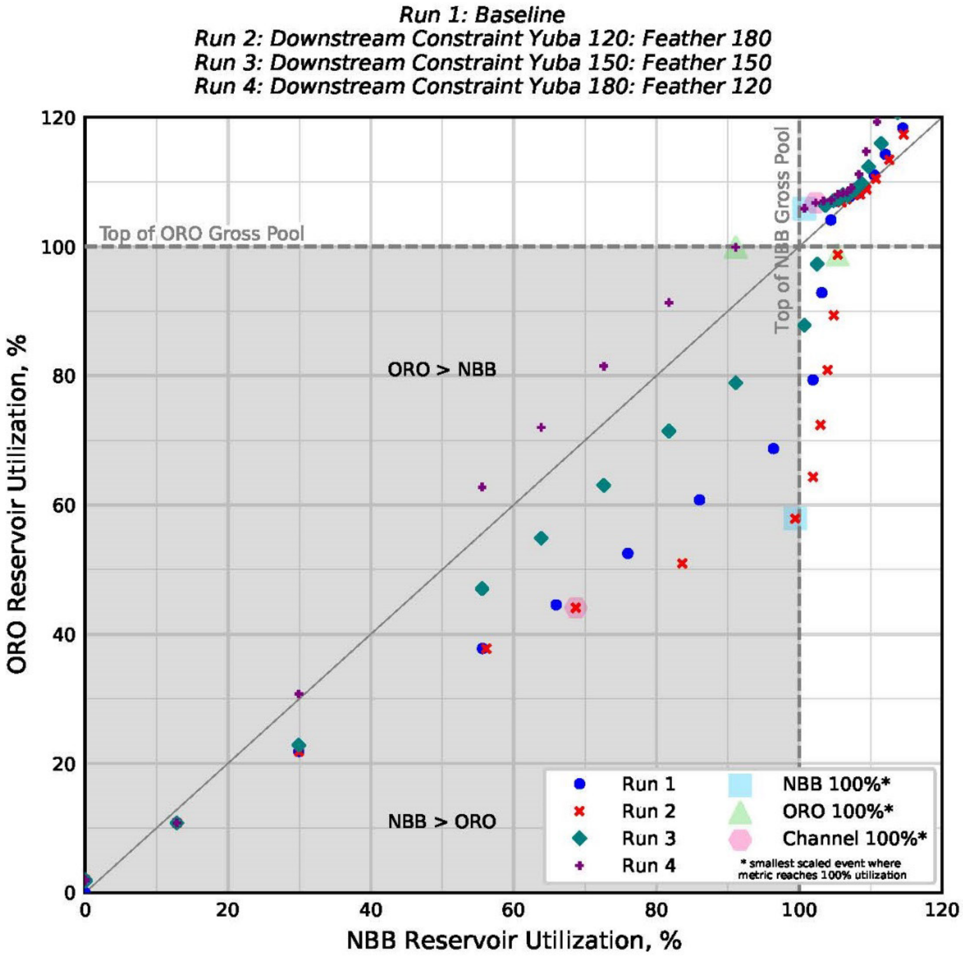


Figure H-8. *Reservoir Utilization Balance; 1997*

Figure H-9 shows how the operation of NBB and ORO is impacted by the downstream constraints for a sample event (1997 scaled 100%). The model assumes that the release from NBB is limited to 50 kcfs unless the event requires an ESRD release. As a result, the NBB outflow and NBB elevation are exactly the same with the Yuba River limited to 150 kcfs and 180 kcfs because NBB does not release more than 50 kcfs (Run 3 and Run 4, respectively) and the unregulated flows in the Yuba River do not exceed 100 kcfs. If the unregulated flows were greater than 100 kcfs, NBB would have had to cut back releases to meet the 150 kcfs constraint for Run 3.

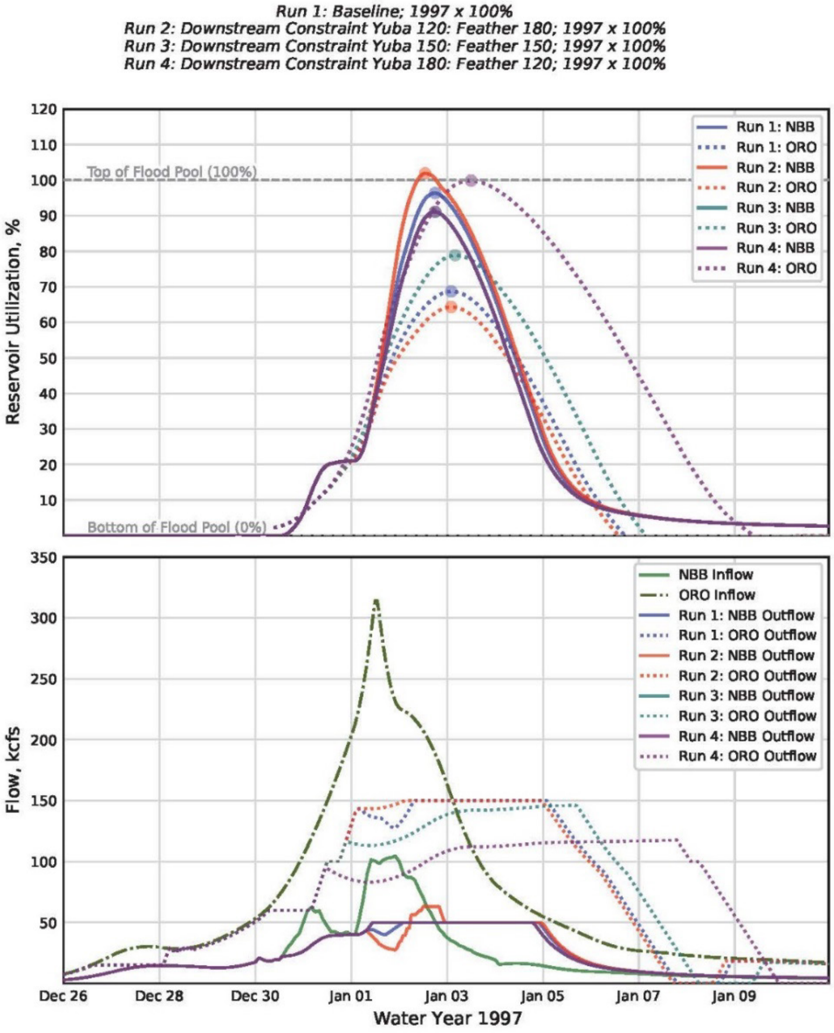


Figure H-9. *Comparison Operations Plot; 1997 x 100%*

Table H-3 summarizes the regulated flood-frequency for the listed metrics. The estimated frequency includes the weighted average of the four historical events: 1956, 1965, 1986, and 1997.

Table H-3. *Regulated Flood-Frequency without NBB ARC Spillway (1/annual exceedance probability)*

Metric	(1) Baseline	(2) Yuba 120: Feather 180	(3) Yuba 150: Feather 150	(4) Yuba 180: Feather 120
100% NBB Reservoir Utilization (170 TAF)	171	125	181	186
100% ORO Reservoir Utilization (750 TAF)	279	411	292	169
100% Channel Utilization (300 kcfs)	153	104	182	229
124% Channel Utilization (354 kcfs)	359	219	327	326

H.5 With Explicit Constraint at Feather below Yuba

The same four alternatives were run again with an explicit constraint of 300 kcfs at the Feather below Yuba. The additional constraint of 300 kcfs assumes that each river is constrained individually to be 120/150/180 kcfs and the combined flow is constrained at the Feather below Yuba to be 300 kcfs. Operationally, this means that ORO will attempt to limit flows to keep the Feather below Yuba flow less than 300 kcfs even after the Yuba River has exceeded 120 kcfs. Adding in the Feather below Yuba limit of 300 kcfs makes no perceptible difference except when the Yuba River is limited to 120 kcfs (Run 2 in red) as shown in Figure H-10. The explicit constraint of 300 kcfs at the Feather below Yuba results in higher reservoir utilization when the flow in the Feather River has exceeded 300 kcfs compared to without the explicit constraint illustrated in Figure H-4, these points are highlighted with yellow circles.

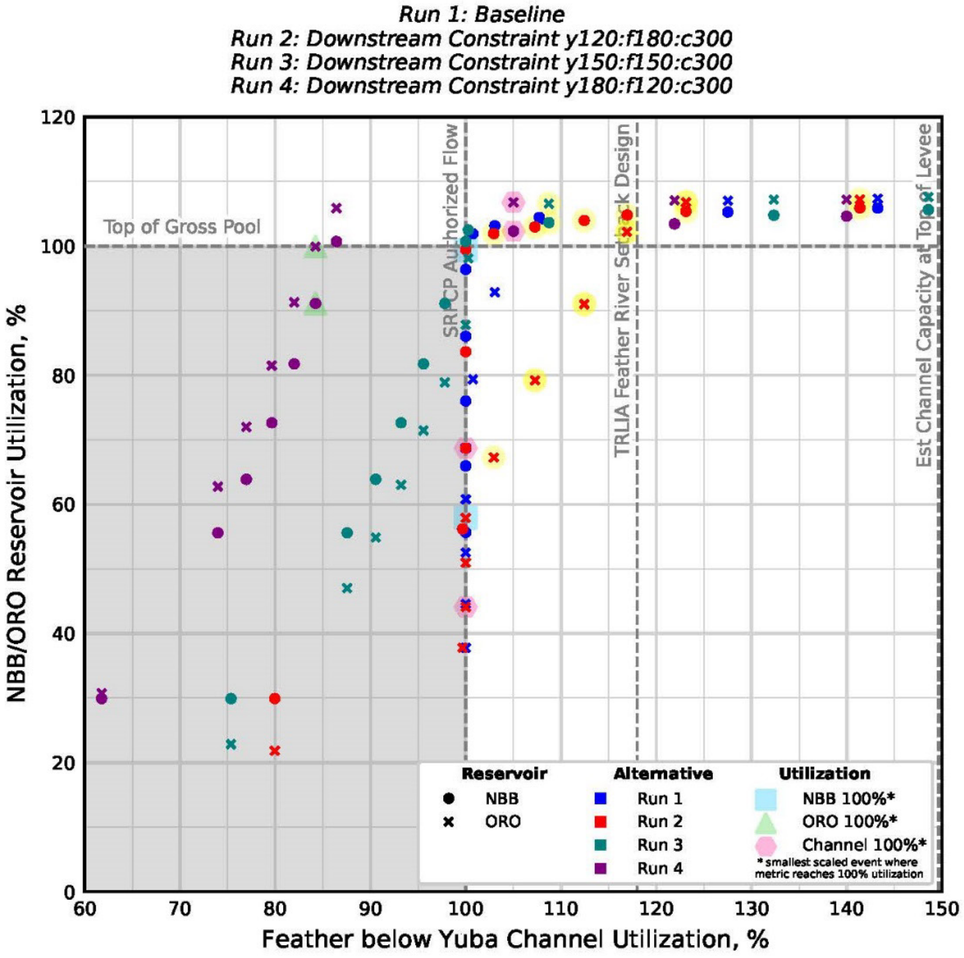


Figure H-10. Reservoir Utilization versus Channel Utilization with Explicit Feather below Yuba River Constraint; 1997

H.6 NBB ARC Spillway

The same four alternatives were run again assuming the use of the future NBB Atmospheric River Control (ARC) Spillway. The results with the spillway in Figure F-11 followed the same overall pattern as without the spillway (Figure H-4). However, the difference in reservoir utilization between ORO and NBB widens for Alternative 4 (purple) because with the ARC spillway NBB can release more water earlier in the event. As a result, the peak NBB reservoir utilization is lower for the same sized event. Events with reservoir or channel utilization at least 5% less than or greater than Figure H-4 are highlighted with yellow circles. For larger events, the channel utilization is also lower with the NBB ARC spillway. Alternatives including the NBB ARC spillway consistently demonstrated improvement of 20 to 40 years (increase in 1/AEP) for managing events below the 300 kcfs and 354 kcfs thresholds compared to the without ARC spillway alternative.

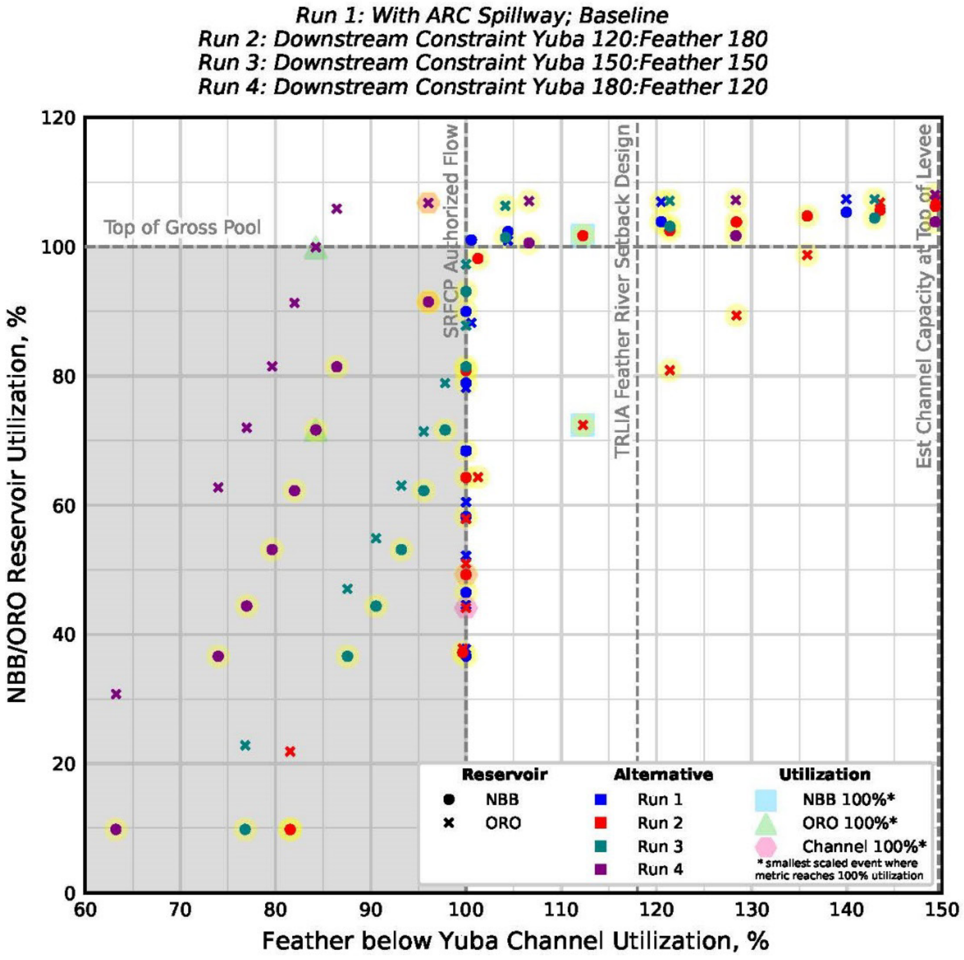


Figure F-11. *Reservoir Utilization versus Channel Utilization with NBB ARC Spillway; 1997*

H.7 Conclusion

The proportion of the Feather below Yuba flow constraint allotted for each contributing river has the potential to majorly impact ORO and NBB reservoir and channel utilization and therefore

FRM performance in the Yuba-Feather system. The downstream flow constraint split changes FRM performance as a trade-off between the system storage and downstream flow. In general, increasing the Yuba River constraint to 180 kcfs improves the flood protection throughout the watershed, but allowing higher flow in the Yuba River requires more reservoir utilization at ORO. An even split of the Feather below Yuba constraint, which means a Yuba River constraint of 150 kcfs, provides better flood protection than the current baseline and uses a balance of channel capacity and system storage. Limiting flow in the Yuba River to 120 kcfs provides a challenge for NBB operators since a large portion of the flow in the Yuba River system is unregulated, and so NBB has to store a proportionally larger share of the watershed runoff compared to ORO. Limiting flow in the Yuba River to 120 kcfs uses more of the channel capacity and less system storage, prior to exceeding the downstream operational flow threshold; ORO still has significant flood space remaining when the downstream flow exceeds that 300 kcfs threshold.

Overall, this analysis indicates that limiting the Yuba River to 120 kcfs is not an optimal split considering the size of NBB and ORO and the proportion of flow that is unregulated contributing to each river. However, it is anticipated that forecasts may be used to determine the flow split required to meet the joint downstream constraints, and so this analysis provides context and back- ground, not a suggested system operations paradigm. Determining an appropriate flow split at the Feather River below Yuba River requires a trade-off between relying more heavily on system storage or on channel capacity downstream. For example, should the SRFCP authorized flow be exceeded before exceeding 50% of the system flood space? Or should the SRFCP authorized flow be exceeded only when all of the system flood space is exhausted? The answers to these questions then affect the implementation of the explicit Feather below Yuba flow constraint. Yuba and Feather River operational flows will have system-wide impacts, changing the operations of each reservoir, the downstream flows, and the resulting FRM performance. Therefore, it is essential that the new WCMs consider all potential impacts outlined in this memorandum when reevaluating the split of the Feather below Yuba downstream constraint.

H.8 References

MBK Engineers (2021). Yuba-Feather System Operations: Framework to Depict System Risk Balance. Final Technical Report dated October 11, 2021.

United States Army Corps of Engineers, Sacramento District (SPK) (1970). Oroville Dam and Reservoir, Feather River, California: Reservoir Regulation for Flood Control.

– (1971). *Marysville Reservoir, Yuba River, California: Hydrology*.

– (1972). *New Bullards Bar Reservoir, North Yuba River, California: Reservoir Regulation for Flood Control*.

Appendix I—System Operation – Risk Balance (Section 4)

MEMORANDUM

DATE:	October 11, 2021
TO:	Yuba-Feather FIRO Water Resources Engineering Team
PREPARED BY:	Carissa Abraham, EIT and Ben Tustison, PE
SUBJECT:	Yuba-Feather System Operations: Framework to Depict System Risk Balance

---

I.1 Introduction

Yuba Water Agency (YWA) and the California Department of Water Resources (DWR), with the U.S. Army Corps of Engineers (USACE) and other project partners, are in the process of updating the water control manuals (WCMs) for New Bullards Bar (NBB) and Oroville (ORO) dams. Simultaneously, both agencies are primary participants in the Yuba-Feather (YF) Forecast Informed Reservoir Operations (FIRO) program. Currently, FIRO is in its initial phase: the Preliminary Viability Assessment (PVA). The PVA has established eight teams, each focused on a particular technical specialty, including a Water Resources Engineering (WRE) team which has the goal of planning for, developing, and evaluating Water Control Plan (WCP) alternatives and attributes considering operational objectives and constraints. A FIRO operational paradigm, which advances both Flood Risk Management (FRM) and other beneficial uses of ORO and NBB, is expected to be the corner- stone of this work.

The WRE team has developed a two-stage WCP development framework. During the first stage, at-site reservoir operations alternatives are being developed. The expectation is that at-site ORO and NBB FIRO operational paradigms be formulated without consideration of each other; i.e., there is no attempt to balance the two reservoir operations. The second stage of the WCP development will feature integrated system operations. In this phase, the operations of ORO and NBB will be tuned together with the goal of balancing the overall FRM.

I.2 Purpose

The purpose of this memo is to define a framework for the depiction of the system risk balance, specifically, the balance of risk both between ORO and NBB, and between the reservoirs collectively and the downstream flood system. If well received, the metrics and visualizations depicted in this memo will become foundational pieces for describing the risk balancing efficacy of WCPs developed by the WRE team.

I.3 Risk Metrics

Metrics are required to quantify the system risks in a flood. There are two types of system risk to be measured: reservoir risk and in-channel risk. At the reservoir, the main risk is for the structural failure of the dam; this risk increases as the loading (water surface elevation) increases against the dam. In the downstream channel system, a similar hydraulic phenomenon is observed: the risk is measured relative to the water surface elevation against the levees. Utilization metrics for each have been designed to measure the risk as a function of the water surface level against each structure (dam or levee). For each dam, storage is used as a proxy for the water surface elevation, as they increase proportionally. For the channel system, flow is used as a similar proxy.

I.4 Reservoir Utilization

Reservoir utilization is computed as the peak percentage of ORO or NBB flood space used during a flood event. This is shown in Equation 1 and **Figure I-1**.

$$\text{Reservoir Utilization} = 100 \times \frac{\text{Peak Storage} - \text{Top of Conservation}}{\text{Winter Flood Reserve}} \qquad \text{(Eq. 1)}$$

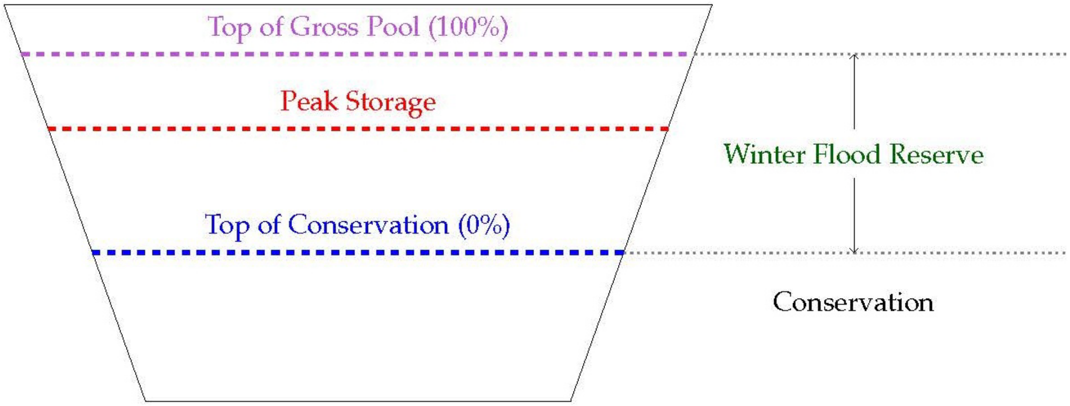


Figure I-1. *Reservoir Utilization Risk Metric Diagram*

I.5 Channel Utilization

The Feather below Yuba channel utilization was computed as the peak percentage of flow between the bank full capacity (the water elevation at the toe of the levee) of approximately 79 thousand cubic feet per second (kcfs) and the Sacramento River Flood Control Project (SRFCP) design capacity in this reach, 300 kcfs. This is shown in Equation 2 and Figure I-2.

$$\text{Channel Utilization} = 100 \times \frac{\text{Peak Flow} - \text{Bank Full Capacity}}{\text{SRFCP Design Capacity} - \text{Bank Full Capacity}} \qquad \text{(Eq. 2)}$$

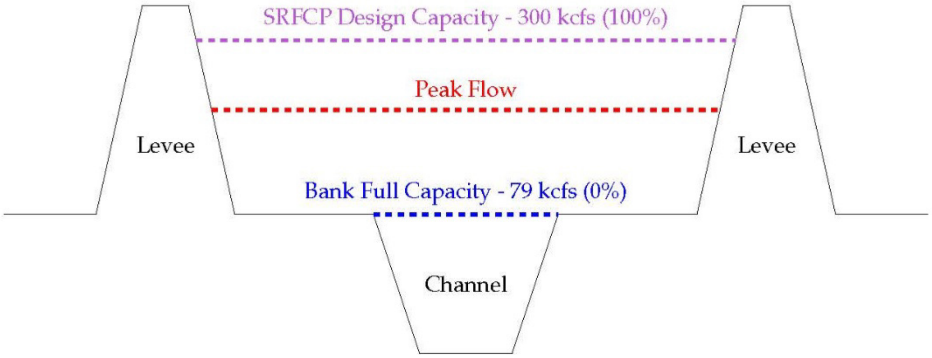


Figure I-2. *Channel Utilization Risk Metric Diagram*

I.6 Risk Balance

A sample application of these risk metrics is included to show how these metrics can be used to illustrate the balance of flood risk in the YF system. For this example, NBB and ORO operations were simulated using the MBK reservoir operations model configured in Python. This model represents the YF watershed with boundary conditions and hydrologic inputs adopted from the Central Valley Hydrology Study (CVHS) for flood events in water years 1956, 1965, 1986, and 1997. The operational rules from the ORO and NBB WCMs, including the joint operating constraints in the Feather River below the Yuba and Bear Rivers, and the 1997 event's scaled variations from CVHS were used in the simulations depicted herein for illustration purposes.

I.7 Inter-Reservoir Risk Balance

The YF system includes two major reservoirs, so it is important to understand how each contributes to the system's FRM objective. To this end, an inter-reservoir risk balancing visualization has been developed by regressing the ORO reservoir utilization metric (see Equation 1) against that of NBB. A 1:1 diagonal line representing an even balance between the two reservoirs has been added for reference.

Figure I-3 shows the balance of storage between ORO and NBB. Each point on this plot represents the reservoir utilization metric for ORO and NBB for 1997 event multiplied by a single scale factor. The plot includes the results from simulations using values from the 1997 event, scaled 10 to 160%. The reservoir utilization for one event (1997 scaled 105%) is depicted in the normalized operations plot in Figure I-4. The peak reservoir utilization values of 79% for Oroville and 102% for NBB correspond to the point highlighted by the sky blue square in Figure I-3.

Colored polygons have been used to highlight points on both Figure I-3 and Figure I-5 representing the same key 1997 scaled events. This coordinated annotation was developed to help build understanding in the relationship between the two risk balance visualizations. The blue squares represent the smallest event that exceeds the flood space in NBB (over 100% of NBB reservoir utilization). The green triangles highlight the smallest event that exceeds the flood space in Oroville. The pink hexagons highlight the smallest event that exceeds the channel capacity (over 100% of channel utilization).

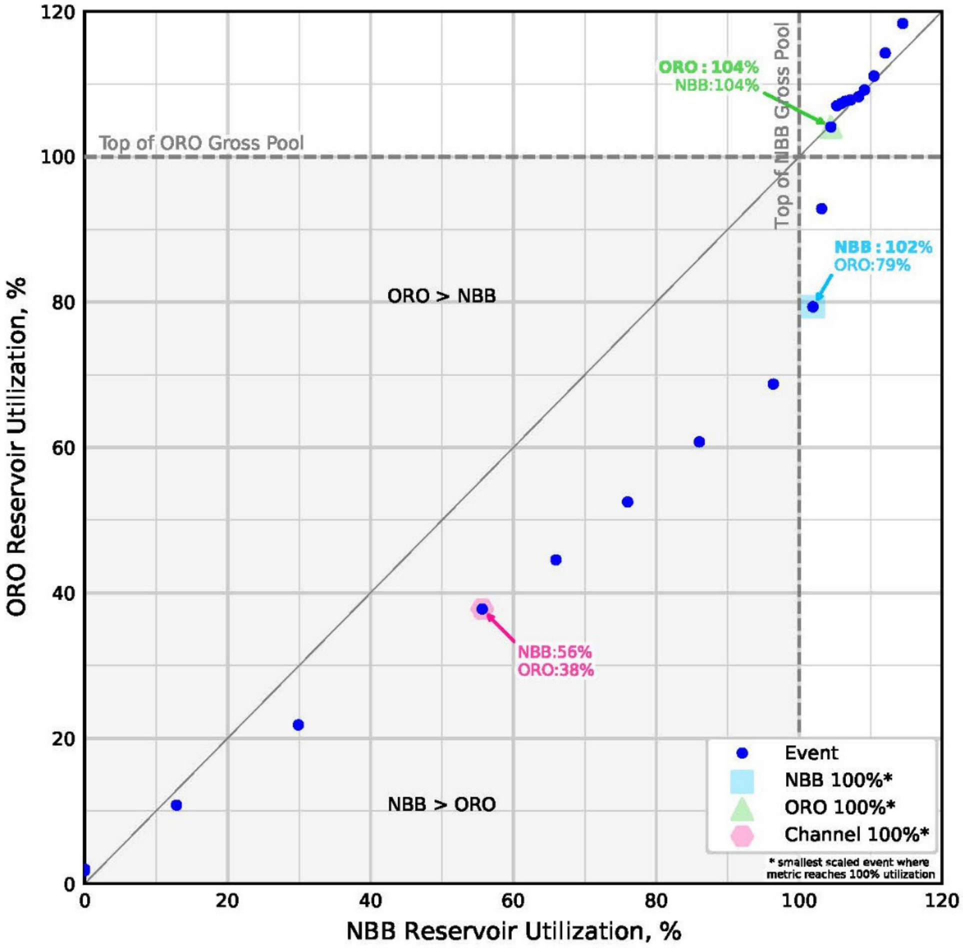


Figure I-3. *Inter-Reservoir Risk Balance; 1997*

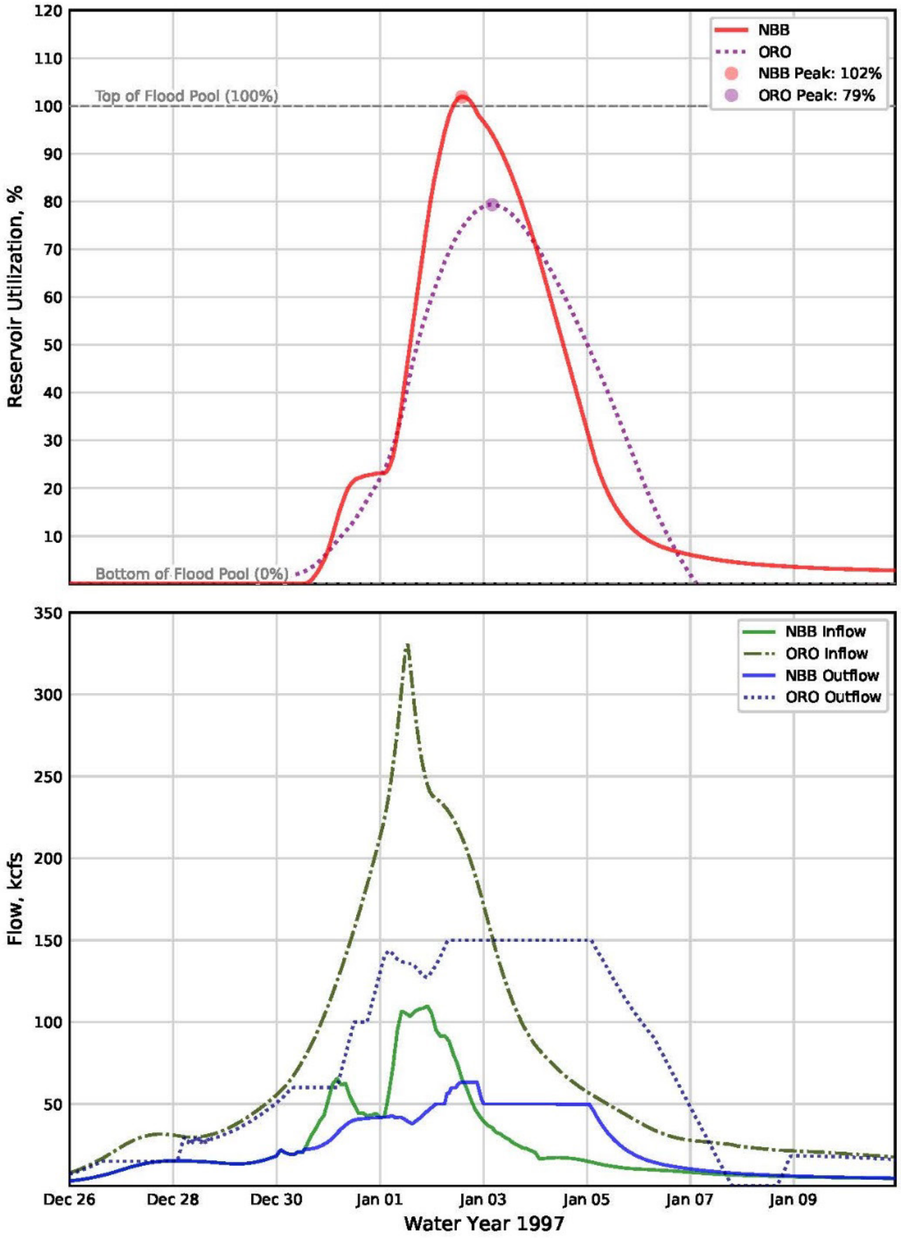


Figure I-4. *Normalized Operations Plot; 1997 Scaled 105%*

I.8 Risk Balance between Reservoirs and Channel

Beyond storing floodwaters in the ORO and NBB reservoirs, the YF system uses channel capacity to convey floodwaters downstream in the advancement of the basin's FRM objective. Therefore, in addition to the inter-reservoir risk balance previously described and illustrated herein, the other important system risk balance to consider is the relationship between the reservoir utilization and the channel utilization.

Figure I-5 shows the balance of risk between ORO or NBB and the downstream channel by regressing the ORO and NBB reservoir utilization metrics against the channel utilization metric.

Each point on this plot represents the reservoir utilization metric for ORO or NBB and the channel utilization metric for a single scaled version of the 1997 event. The points on the plot represent the same 1997 events scalings as in Figure I-3. The channel utilization for one event (1997 scaled 105%) is depicted in the hydrograph for flow at the Feather River below Yuba River in Figure I-6. The peak channel utilization of 101% for 1997 scaled 105% corresponds to the points highlighted by sky blue squares in Figure I-5.

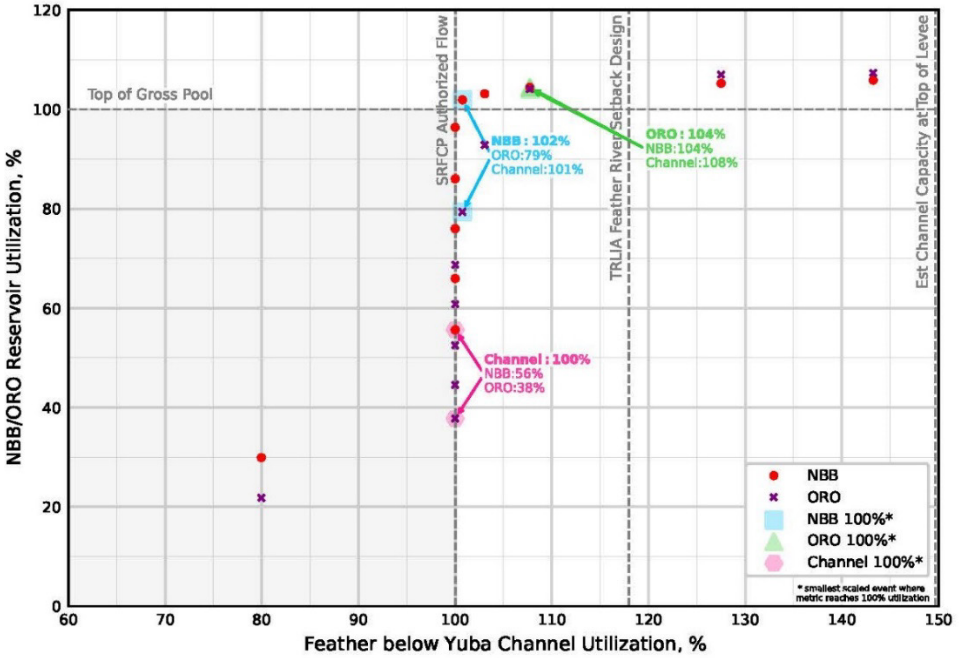


Figure I-5. *Risk Balance between Reservoirs and Channel; 1997*

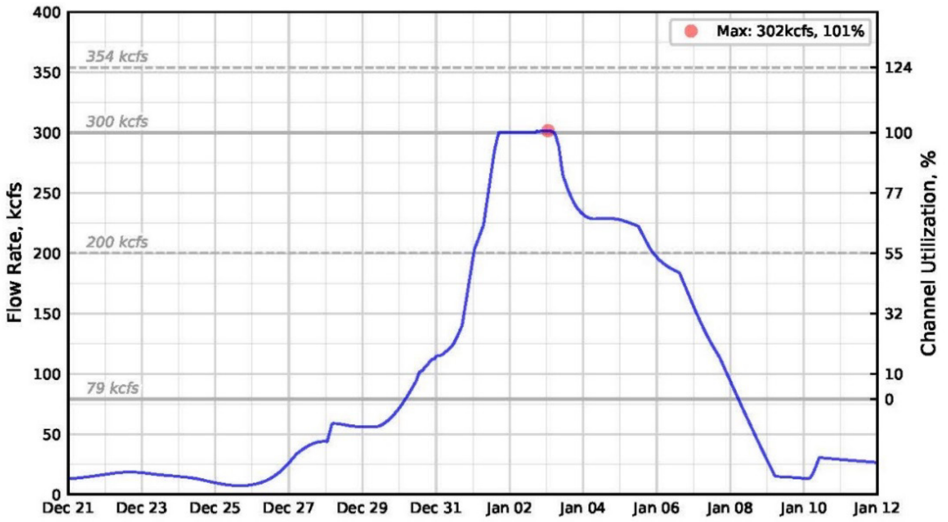


Figure I-6. *Flow at the Feather River below Yuba River; 1997 Scaled 105%*

I.9 Anticipated Application

The goal of these new metrics is to provide a framework for evaluating risk and potential trade-offs between utilizing NBB or ORO storage and also between using the system storage and the downstream channel capacity to manage floods. Normalizing the reservoir utilization metric allows for direct comparison between NBB and ORO for sharing the system storage responsibility. Normalizing the channel utilization metric similarly allows for direct comparison against the reservoir utilization. These metrics and the associated figures will be used in future work to compare alternatives and evaluate the system risk.

Appendix J—System Operation – Storage Balance (Section 4)

MEMORANDUM

DATE:	Wednesday, June 17, 2020
TO:	Yuba-Feather FIRO Team
FROM:	Aimee Kindel, PE; Mike Konieczki, PE; Nathan Pingel, PE; Donna Lee, CFM
SUBJECT:	Yuba-Feather System Storage Balance

J.1 Introduction

The Yuba-Feather Forecast-Coordinated Operations (F-CO) decision support system (DSS) uses an HEC- ResSim model to simulate reservoir releases given observed and forecasted reservoir inflows and local flows for reaches downstream of the reservoirs subject to operational rules defined in the model. In the current HEC-ResSim model used in the DSS, Oroville and New Bullards Bar reservoirs are configured with the rule that *flows in the Feather River below Yuba River do not exceed 300,000 cfs* (USACE 1970, USACE 1972). To meet this operational objective, the available management volume in both reservoirs must be operated jointly as a system. Logic representing this system operation and system storage balance are configured into the current HEC-ResSim model used in the F-CO DSS.

This memo describes the following:

- Options and parameters used to represent reservoir system storage balance within the HEC- ResSim software version 3.2.1.148.
- Configuration of the Oroville-New Bullards Bar reservoir system storage balance within the F-CO DSS HEC-ResSim model.
- Options for integrating system operation modeling into FIRO alternatives.

J.2 Definition of a "System" in Reservoir Modeling

Within reservoir modeling, a "system" is two or more reservoirs that are operated in tandem or in parallel to meet minimum or maximum flow objectives at a common downstream location. The system has a total amount of storage that must be managed. In order to meet a common downstream objective while still operating to individual, reservoir-specific flood management requirements and operation rules (e.g., minimum releases, maximum releases, downstream flow limitations, ramping rates, and so on), storage tradeoffs must sometimes be made between reservoirs within a system.

The priority and amount of storage (or release) is determined by the system's storage balance. When a common downstream rule limits releases, this balance guides the operation of the system reservoirs, analogous to how the boundary between the flood management pool and the conservation pool defines a "guide curve" that determines when to store and when to release.

J.3 Functionalities for System Operation in HEC-ResSim

Reservoir systems can be configured within HEC-ResSim to operate in tandem (reservoirs configured in a chain or series) or in parallel (reservoirs on different tributaries operated for a common downstream point). Within HEC-ResSim, when two reservoirs are configured to operate for a downstream control point using a common rule, a parallel operation "Reservoir System" is automatically created (HEC 2010). When one reservoir is configured to preserve the storage of a downstream reservoir, a tandem operation Reservoir System is created (HEC 2010).

Oroville and New Bullards Bar are operated to manage flows at the Yuba-Feather confluence and are therefore configured as a parallel reservoir system in the F-CO ResSim model.

Two options exist within HEC-ResSim to compute the priority of release in a system operation using storage balance: implicit (the program default) or explicit (user defined).

J.4 Implicit Storage Balance

The program default, implicit storage balance, considers the guide curves of the two reservoirs. At Oroville and New Bullards Bar, the top of the conservation (TOC) pool is the guide curve. The flood pool is not considered; only the volume from the TOC to the top of the dam. The software evaluates a preliminary end-of-period storage using each reservoir's estimated releases, period inflows, and starting storage, then adjusts releases at both reservoirs to maintain each reservoir the same percent encroached above its respective guide curve. Whichever reservoir is more encroached gets the release priority when determining releases to meet the downstream rule (HEC 2010).

After the implicit storage balance release is calculated, rules that are at a higher priority than the common downstream rule are applied. In any given time step that the reservoir is operating for downstream constraints, outlet capacity, rate of increase limitations, rate of decrease limitations, or releases according to either dam's Emergency Spillway Release Diagram (ESRD), this may supersede releases that would balance the two reservoirs. As a result, the reservoirs are not always balanced (just as a reservoir may not always be at its guide curve).

Figure J-1 shows a hypothetical implicit storage balance between Oroville and New Bullards Bar, including three examples of how the model would balance release and storage decisions. The blue and brown lines show the storage that would need to simultaneously occur at both reservoirs to maintain the same percentage use of the volume between the dashed lines. Table J-1 describes how the software would prioritize release or storage based on the three examples.

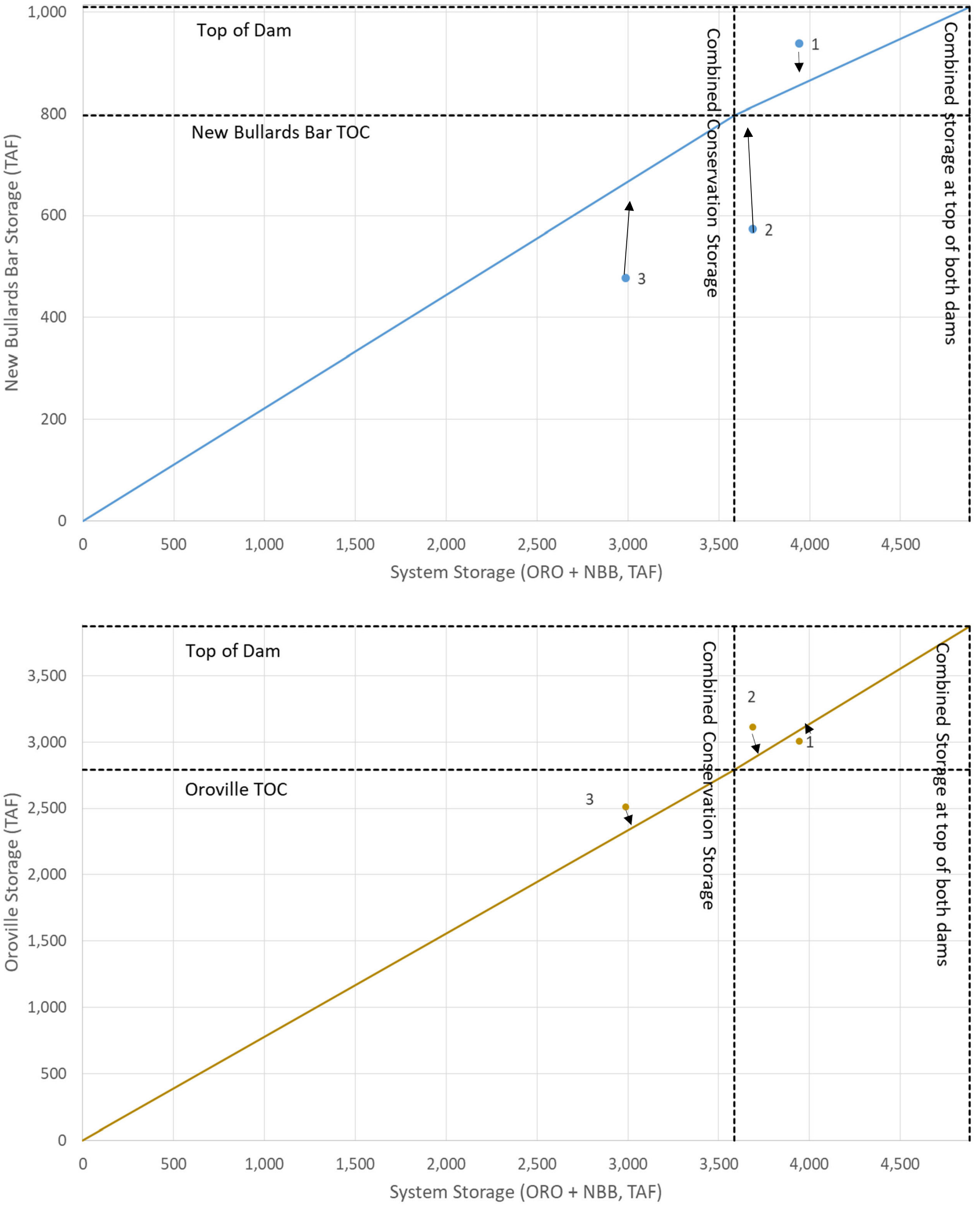


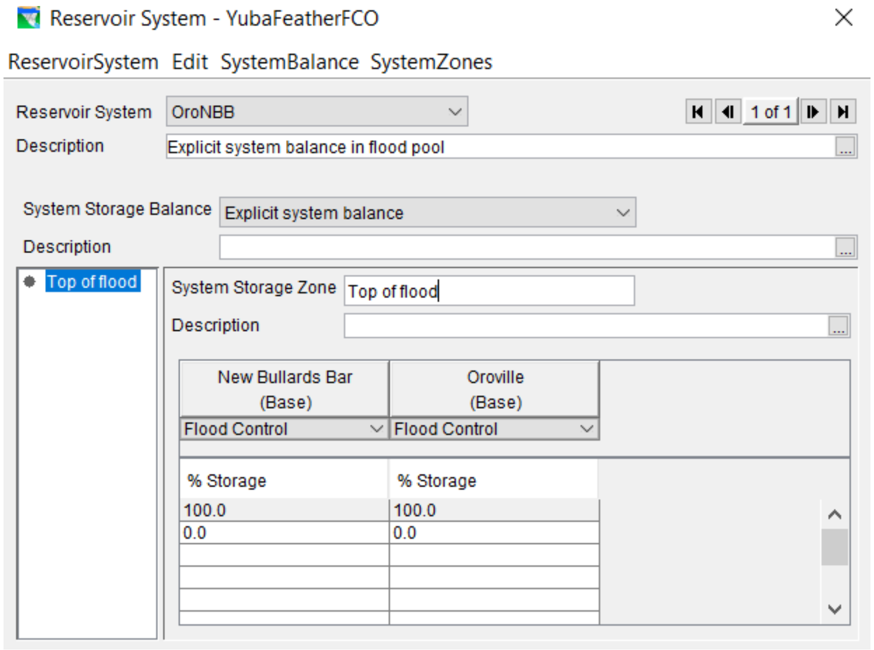
Figure J-1. *Example HEC-ResSim implicit storage balance for (a) New Bullards Bar and (b) Oroville.* The horizontal axis represents the combined system storage by the end of the time period, and the vertical axis represents each reservoir's storage by the end of the time period. Examples 1, 2, and 3 are shown with dots plotted against the system storage balance. The arrows show the direction of the decision to release or store.

Table J-1. *Example HEC-ResSim implicit storage balance scenarios*

Example	Preliminary end of period storage before balancing	Storage balance release decision
Example 1:	New Bullards Bar will reach 66% of the volume from its	*The software would prioritize decreasing the pool at New Bullards*
Both reservoirs	TOC to the top of the dam. Oroville will reach 20% of	*Bar. When both reservoirs are above their defined TOC, the implicit*
encroached	the volume from its TOC to the top of the dam. Inflows	*storage balance attempts to maintain the same percentage of total*
above the TOC	exceed outflows, but emergency releases are not	*storage from the TOC to the top of the dam at each respective*
	required. The downstream rule at the confluence is	*reservoir. The reservoir that is more encroached (New Bullards Bar)*
	limiting releases.	*is prioritized.*
Example 2:	Oroville will reach 30% of the volume from its TOC to	*The software would prioritize decreasing the pool at Oroville. If one*
Only one	the top of the dam. New Bullards Bar will still be below	*reservoir is below its defined TOC and the other is encroached into*
reservoir	its TOC. Inflows exceed outflows, but emergency	*its flood pool, the implicit storage balance limits the release from*
encroached	releases are not required. The downstream rule at the	*the reservoir that is below its TOC, and assigns priority to releases*
above the TOC	confluence is limiting releases.	*from the reservoir which is encroached.*
Example 3:	Oroville will fill 90% of the volume from empty to its	*In this situation, the software would prioritize increasing the pool at*
Neither	TOC. New Bullards Bar will fill 60% of the volume from	*New Bullards Bar. When both reservoirs are below their defined*
reservoir is	empty to its TOC. Inflows exceed outflows, but	*TOC, both reservoirs are allowed to fill, while meeting all higher*
encroached	emergency releases are not required. The downstream	*priority minimum release rules.*
above the TOC	rule at the confluence is limiting releases.	

J.5 Explicit Storage Balance

The explicit storage balance allows the user to specify a balance for more than two zones (recall that implicit storage balance considers only storage below TOC and storage above TOC). For example, the balance can be refined to consider the relative sizes of flood pools. **Figure J-2** shows a screenshot of the explicit balance configuration in HEC-ResSim.



Reservoir System: OroNBB

Description: Explicit system balance in flood pool

System Storage Balance: Explicit system balance

Description:

Top of flood

System Storage Zone: Top of flood

Description:

New Bullards Bar (Base)	Oroville (Base)
Flood Control	Flood Control
% Storage	% Storage
100.0	100.0
0.0	0.0

Figure J-2. *Screenshot of Explicit Storage Balance Configuration*

Figure J-3 shows an example explicit storage balance between the flood pools at Oroville and New Bullards Bar. Similar to Figure J-1, the blue and brown lines show the storage that would need to simultaneously occur at both reservoirs to maintain the same percentage use of the volume between the dashed lines.

In this example balance, the flood management pools would be prioritized equally based on percentage encroachment. Practically, however, this means that releases for specific storages at New Bullards Bar above the TOC would not be prioritized as highly as the implicit case and New Bullards Bar would therefore fill more quickly than in the implicit case. The converse is true for Oroville.

In addition, the explicit storage balance allows the option to maintain unequal proportional use of defined system's zones. The user may specify additional inflection points so that one reservoir fills slower than the other. For example, the user may specify that when Oroville has encroached into 80% of its flood pool, New Bullards Bar must only be 30% percent encroached. Figure J-4 shows this example balance as compared to the implicit storage balance.

J.6 Configuration of Current F-CO HEC-ResSim Model

The current F-CO model is configured with an explicit storage balance so that the reservoirs draw down proportionally when each is within its main flood pool (the balance shown on Figure J-2 and Figure J-3).

Additional inflection points and pools (such as the surcharge pool) are not explicitly defined, but refinements could be made to define these additional inflection points (the balance shown on Figure J-5).

After the explicit storage balance release is calculated, rules that are at a higher priority than the common downstream rule are applied. In any given time step that the reservoir is operating for downstream constraints, outlet capacity, rate of increase limitations, rate of decrease limitations, or releases according to either dam's ESRD, this may supersede releases that would balance the two reservoirs. As a result, the reservoirs are not always balanced (just as a reservoir may not always be at its guide curve).

J.7 Options for Modifying the Storage Balance Configuration

In practice, operators may not target keeping the reservoirs the same percent full. Using the explicit storage balance options, refinements could be made to prioritize filling one reservoir's flood pool faster than the other reservoir's flood pool.

The available storage-balance options currently only consider the current storage of the reservoirs, and inflows and releases in the current time step. Incorporating information about future inflows or releases into storage balance computations into the F-CO model could further refine how releases are prioritized. This could be accomplished by defining a forecasted TOC or forecast-based TOC for both reservoirs.

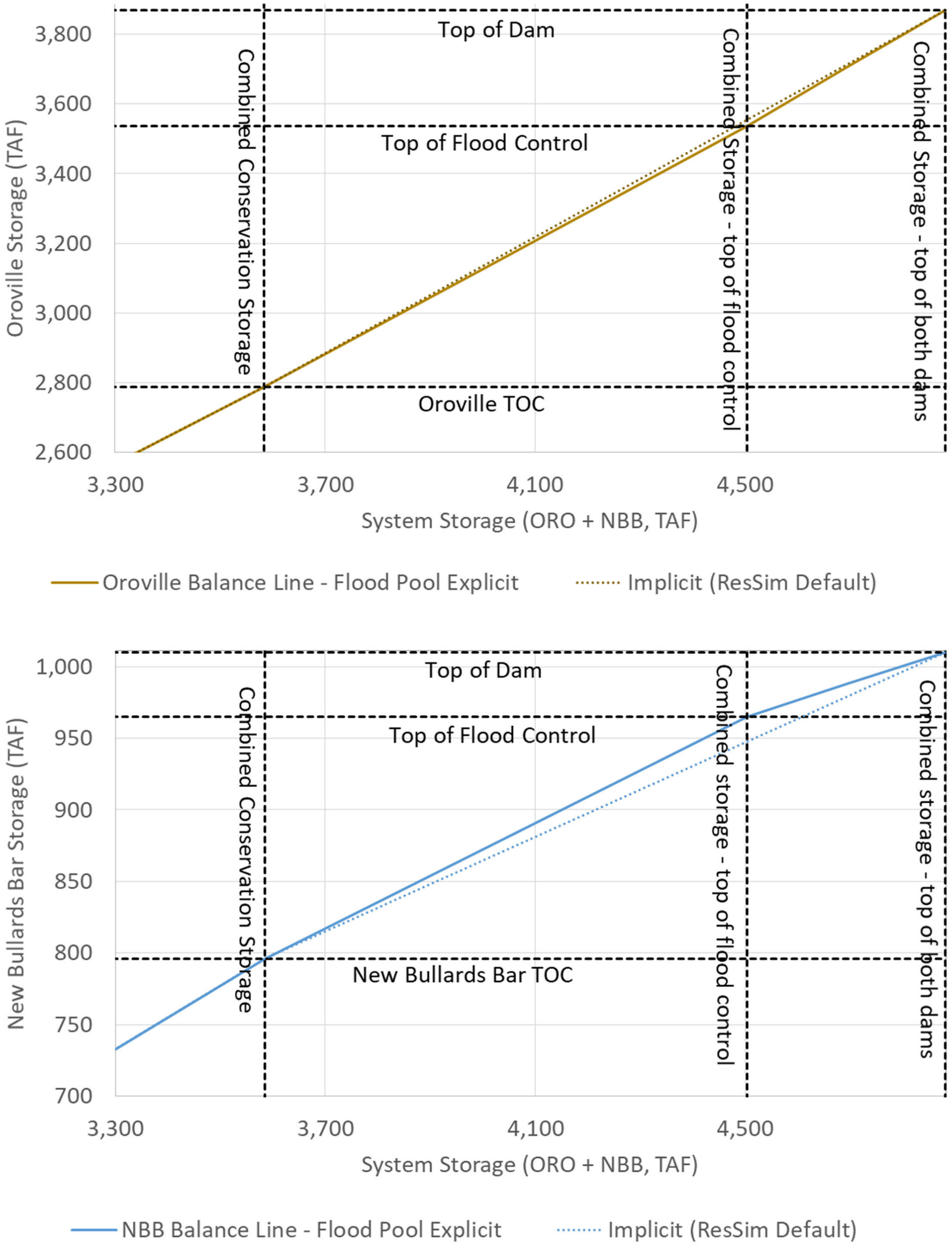


Figure J-3. *Example HEC-ResSim explicit storage balance between the flood pools at (a) Oroville and (b) NBB.* The horizontal axis represents the combined system storage by the end of the time period, and the vertical axis represents each reservoir's storage by the end of the time period. The dotted line shows how the program implicit default setting compares.

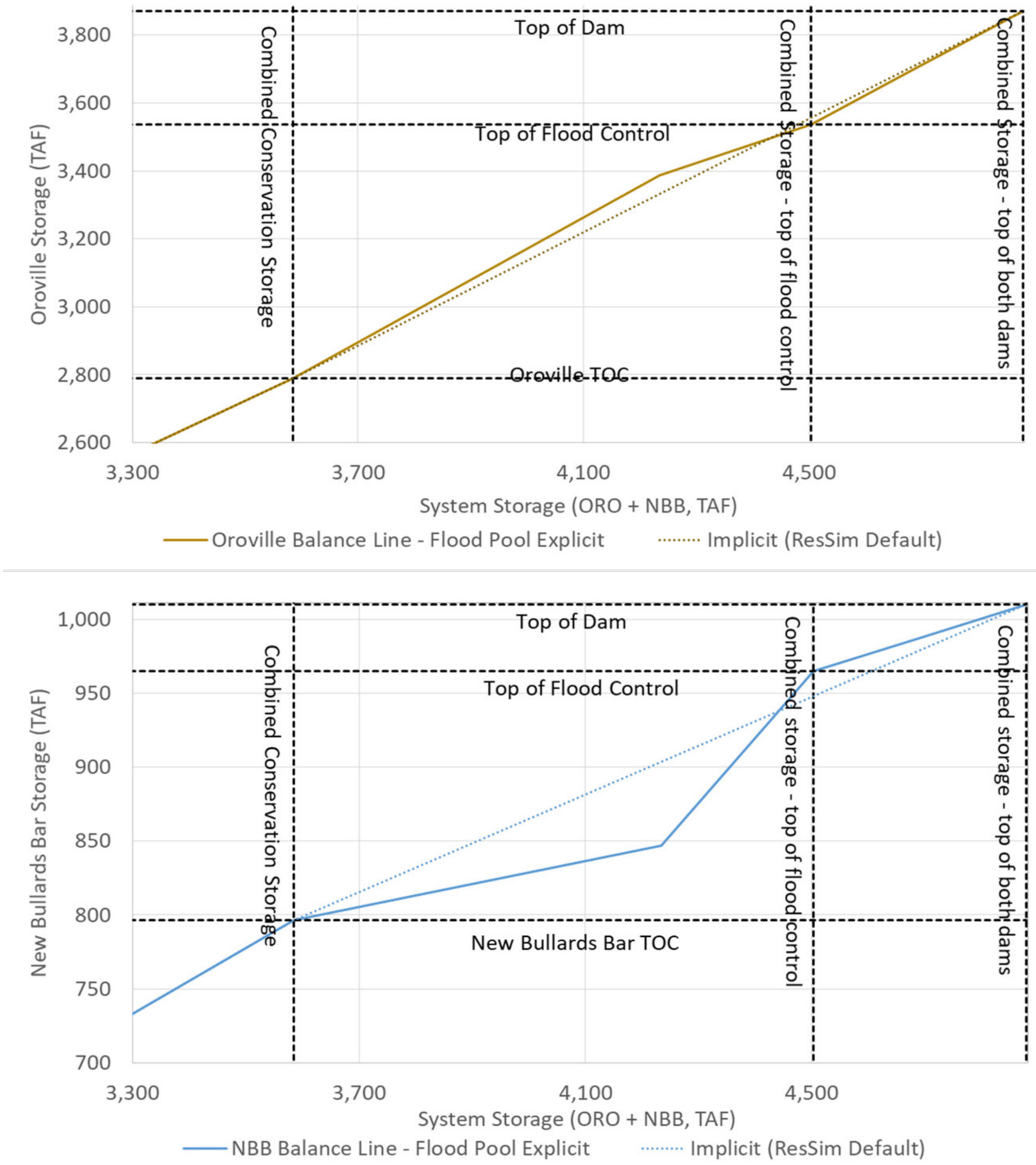
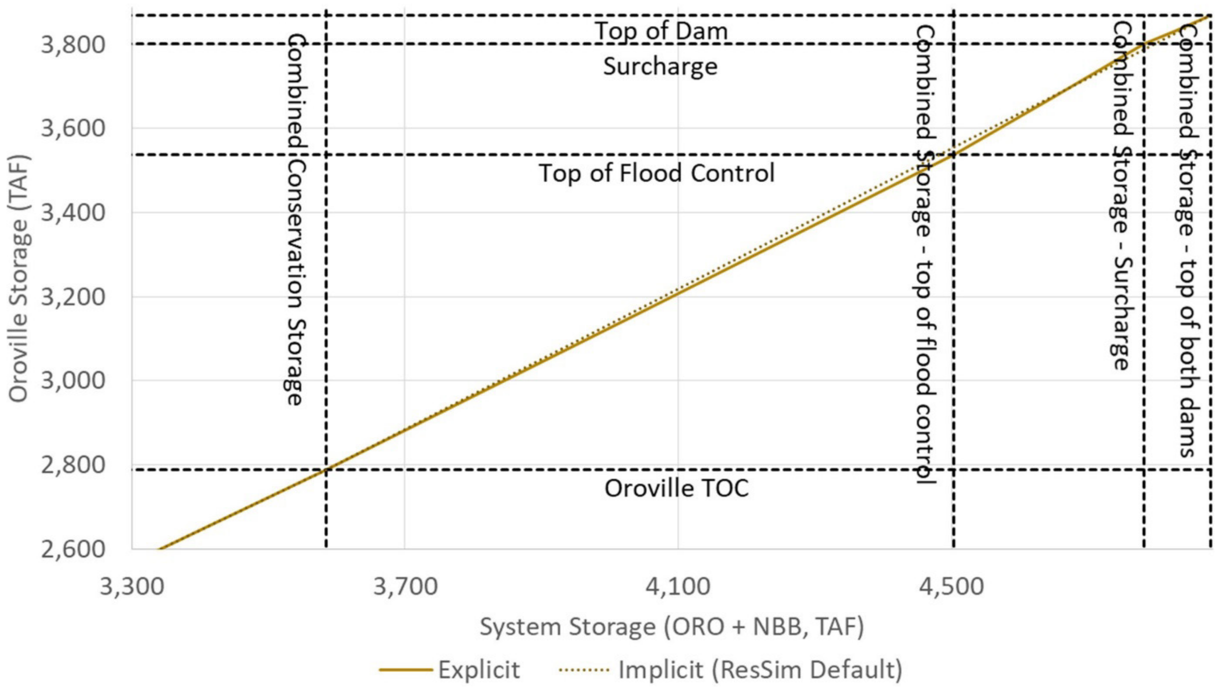


Figure J-4. *Example HEC-ResSim explicit storage balance between the flood pools at (a) Oroville and (b) NBB.* In this hypothetical balance, NBB is filled slower compared to Oroville. The horizontal axis represents the combined system storage by the end of the time period, and the vertical axis represents each reservoir's storage by the end of the time period. The dotted line shows how the program implicit default setting compares.



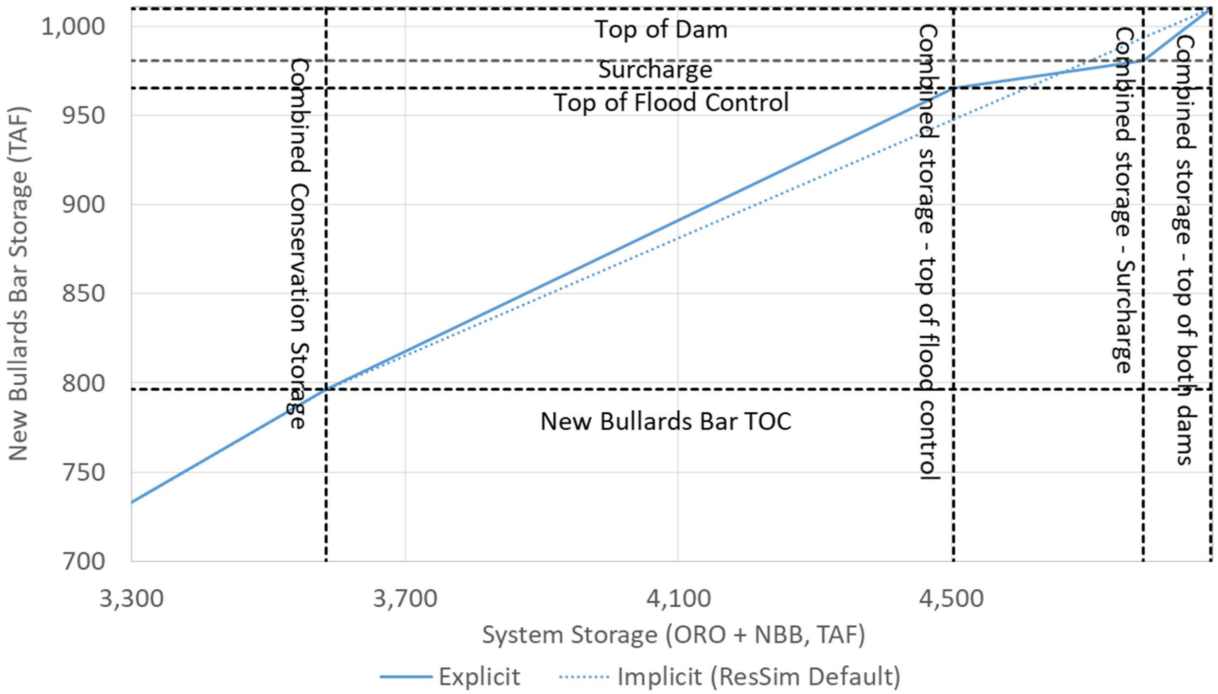


Figure J-5. *Example HEC-ResSim explicit storage balance for the flood pools and surcharge pools at (a) Oroville and (b) NBB.* The horizontal axis represents the combined system storage by the end of the time period, and the vertical axis represents each reservoir's storage by the end of the time period. The dotted line shows how the program implicit default setting compares.

J.8 References

U.S. Army Corps of Engineers, 1970. Report on Reservoir Regulation for Flood Control. Oroville Dam and Reservoir, Feather River, CA. Sacramento District, August 1970.

U.S. Army Corps of Engineers, 1972. Reservoir Regulation for Flood Control, New Bullards Bar Reservoir, North Yuba River, CA Appendix V to Master Manual of Reservoir Regulation. Sacramento District, June 1972.

U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC) 2010. HEC-ResSim Reservoir System Simulation. User's manual. Version 3.1, November 2010.

Appendix K—F-CO Activation Frequency (Section 4)

MEMORANDUM

DATE:	November 3, 2021
TO:	Yuba-Feather FIRO Water Resources Engineering Team
PREPARED BY:	Olivia Alexander, EIT
REVIEWED BY:	Ben Tustison, PE
SUBJECT:	Forecast-Coordinated Operations Activation Frequency

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K.1 Purpose

The purpose of this analysis is to estimate the frequency of Forecast-Coordinated Operations (F-CO) activation in the Yuba-Feather (YF) system. The New Bullards Bar (NBB) and Oroville reservoir operations were modeled with the MBK Python model baseline conditions, meaning the Atmospheric River Control (ARC) Spillway and Forecast Informed Reservoir Operations (FIRO) were not utilized. The following The Water Control Manual (WCM) constraints were included in the operational rules:

- 180,000 cfs on Yuba River at Marysville
- 150,000 cfs on Feather River at Gridley
- 180,000 cfs on Feather River at Yuba City

The WCM constraints of 300,000 cfs on the Feather River below Yuba River and 320,000 cfs on the Feather River below Bear River were removed from the operational rules. This was done to estimate the most frequent flood event where the downstream flow reached, but was not limited by, the constraint, or when F-CO would require activation.

K.2 Methods

The model was first run with Central Valley Hydrology Study (CVHS) based hydrology for the 1956, 1965, 1986, and 1997 events. Realistically, the coordination of New Bullards Bar and Oroville operations will be informed by event forecasts, so instead of using CVHS hydrology as initially modeled, scaled California Nevada River Forecast Center (CNRFC) ensemble hindcasts for 1986 and 1997 from the 2015 dataset were used as the input hydrology. The ensemble hindcasts contain 61 members representing variability in the forecast. Four non-exceedance probabilities (NEP), 99, 95, 75, and 50 percent, were selected to summarize the range in the forecast. The NEPs chosen were used to rank and identify a forecast ensemble member based on five day inflow volume, as shown in Figure K-1. Since ensemble forecasts have only recently been made available in the YF system, the actual ensemble member(s) preferred by operators to make decisions has not been identified, therefore these four NEPs are used to represent a range of options in this study.

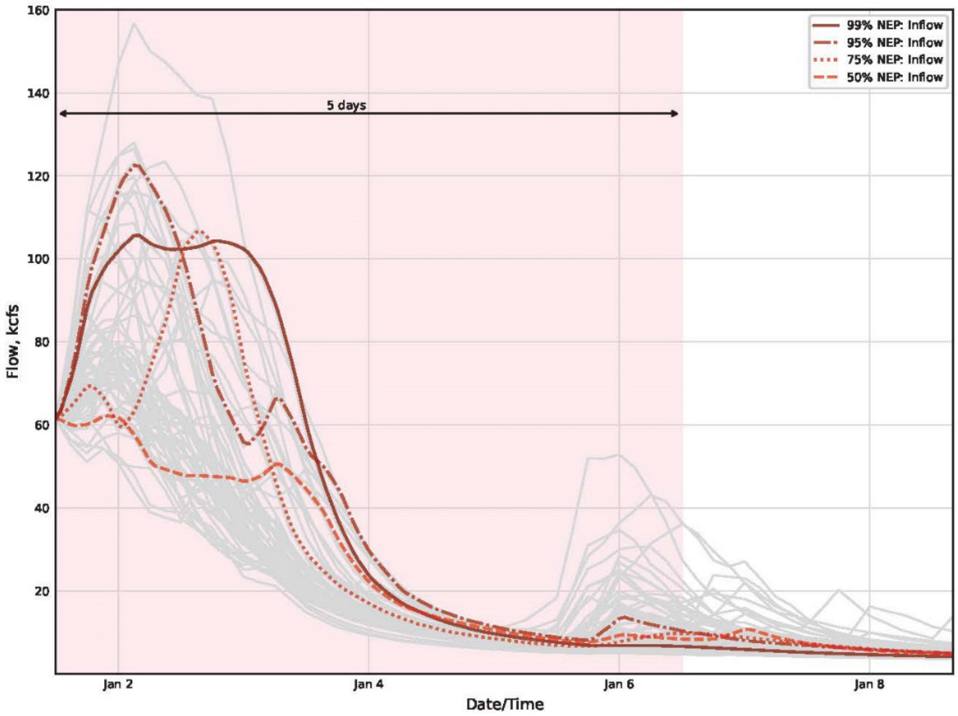


Figure K-1. *Example hindcast ensemble members and representative 99%, 95%, 75%, and 50% NEPs*

For each event, 1986 and 1997, six hindcasts issued on the days leading up to and including the event peak were run as the model hydrology. Figure K-2 and Figure K-3 show the evolution of the storm event through the six days.

The six hindcasts and four NEPs were run for scale factors ranging 10 to 130 percent for the 1986 event and 10 to 100 percent for the 1997 event. A visual representation of these parameters is shown in Figure K-4.

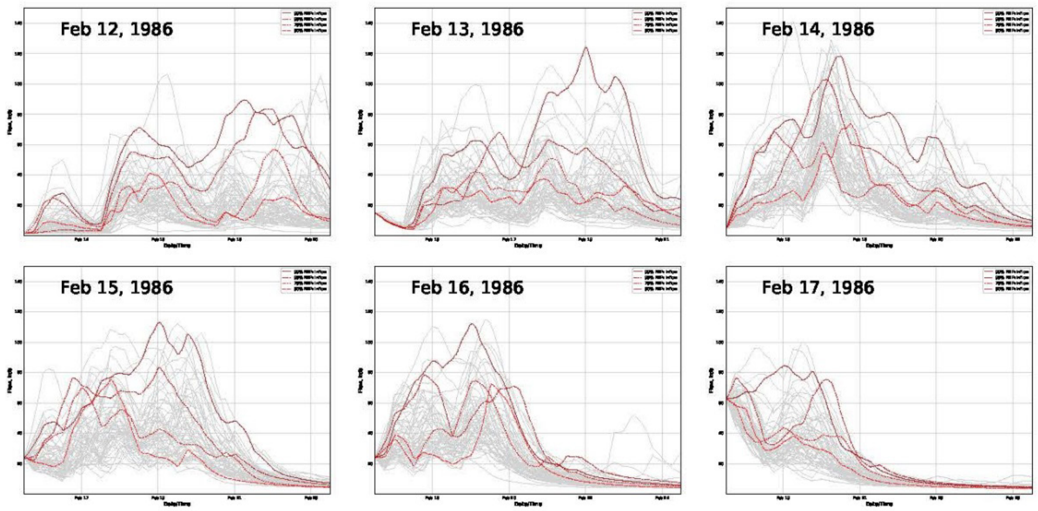


Figure K-2. *Six NBB inflow hindcasts for 1986 event*

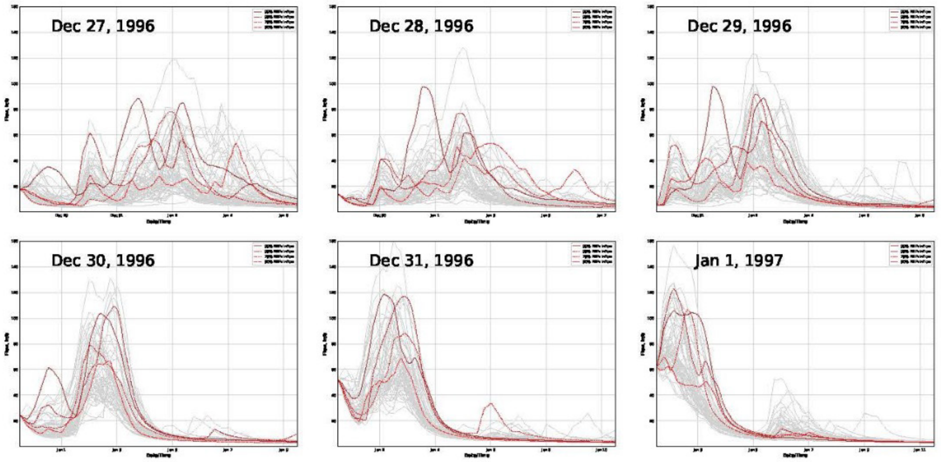


Figure K-3. *Six NBB inflow hindcasts for 1997 event*

1986 hindcasts	1997 hindcasts
2/12/86	12/27/96
2/13/86	12/28/96
2/14/86	12/29/96
2/15/86	12/30/96
2/16/86	12/31/96
2/17/86	1/1/97

X

Non-exceedance probability
99%
95%
75%
50%

X

1986 scale factors	1997 scale factors
10%	10%
20%	20%
40%	40%
60%	60%
80%	80%
85%	85%
90%	90%
95%	95%
100%	100%
105%	
110%	
115%	
120%	
125%	
130%	

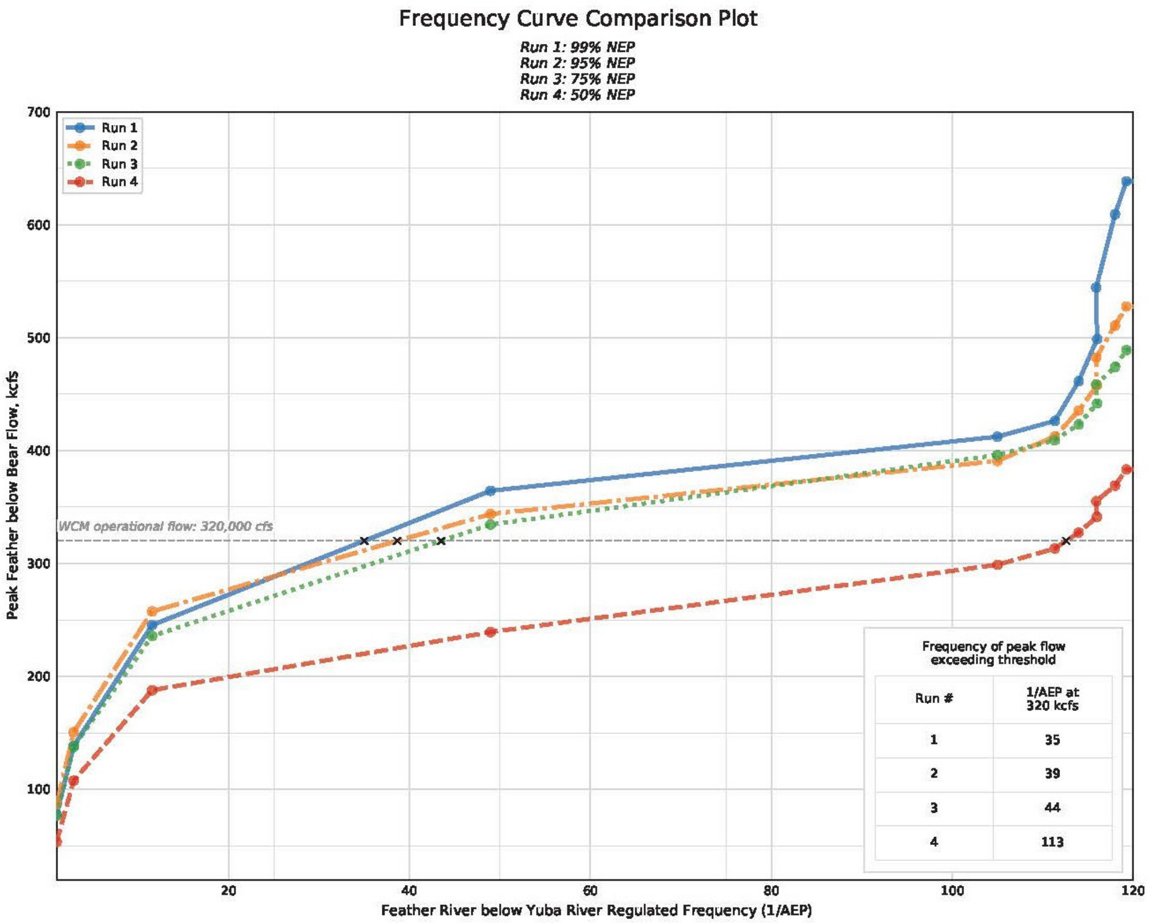
Figure K-4. *Summary of modeled dates, NEPs, and scale factors*

The following steps were then performed to summarize and analyze the results from the modeling:

- Scale hindcasts in order to model large enough event that crosses downstream thresholds
- Use scaled event operations to calculate frequency curves downstream for each forecast date
- Identify frequency at which threshold is reached (F-CO activation)

K.3 Results

An example plot of the 1997 event frequency (in inverse annual exceedance probability (1/AEP)) of exceeding 320 kcfs on the Feather River below Bear River is shown in Figure K-5. The regulated flow-frequency on the Feather River below Yuba River was used to represent the system. All four NEPs are plotted to show the variability in the ensemble forecasts.



Frequency of peak flow exceeding threshold

Run #	1/AEP at 320 kcfs
1	35
2	39
3	44
4	113

Figure K-5. *Frequency of baseline event exceeding 320 kcfs threshold on the Feather River below Bear River for hindcast on Jan. 1, 1997*

The most frequent event that crosses the threshold out of the six, daily-issued hindcast alternatives was selected to approximate the frequency where the two primary reservoirs must be coordinated to avoid exceeding each downstream flow threshold. The frequency of each event reaching the downstream threshold for each of the four NEPs and six forecast dates is summarized in Table K-1 and Table K-2.

Table K-1 shows the frequency of the event that reaches the 300,000 cfs constraint, and Table 2 shows the event that reaches the 320,000 cfs constraint.

Table K-1. *Frequency of Feather River below Yuba flow reaching 300 kcfs*

Non-Exceedance Probability	Frequency (1/AEP) of event that reaches 300 kcfs on Feather River below Yuba for forecast dates	
	12/27/96 – 1/1/97	**2/12/86 - 2/17/86**
99%	38	15
95%	35	24

Non-Exceedance Probability	Frequency (1/AEP) of event that reaches 300 kcfs on Feather River below Yuba for forecast dates	
75%	47	83
50%	113	70

Table K-2. *Frequency of Feather River below Bear flow reaching 320 kcfs*

Non-Exceedance Probability	Frequency (1/AEP) of event that reaches 320 kcfs on Feather River below Bear for forecast dates	
	12/27/96 – 1/1/97	**2/12/86 - 2/17/86**
99%	35	14
95%	32	20
75%	44	83
50%	113	56

K.4 Conclusion

New Bullards Bar and Oroville must attempt to jointly meet the downstream constraints on the Feather River below Yuba River and below Bear River. This analysis shows that in general, the 320,000 cfs constraint is exceeded for a more frequent event than the 300,000 cfs constraint, there- fore the Feather below Bear constraint is more limiting than the Feather below Yuba constraint. Depending on the timing of the forecast and which NEP is selected by operators as the basis for forecast-informed releases, F-CO could be activated for events with an estimated frequency range of 1-in-14 to 1-in-113 years.

Appendix L—FIRO Impacts on Water Supply Impacts (Section 4)

One of the conditions of employing FIRO approaches to Oroville (ORO) and New Bullards Bar (NBB) reservoirs is to show that water supply reliability is not compromised in the pursuit of improved flood risk management outcomes. They key issue here is whether there is a substantial risk of *not* refilling the conservation pool after an extreme event triggers a pre-release of stored water. For there to be an end-of-flood season reduction in storage three conditions must be present.

1. A significant over-forecast of inflow volume triggers a pre-release into conservation storage.
2. The over-forecast is associated with the last significant runoff event of the flood season.
3. A much below normal snowpack leads to spring volumes that are unable to refill the reservoirs.

Figure L-1 depicts a hypothetical case where all three conditions are met resulting in a lower end-of-flood season storage.

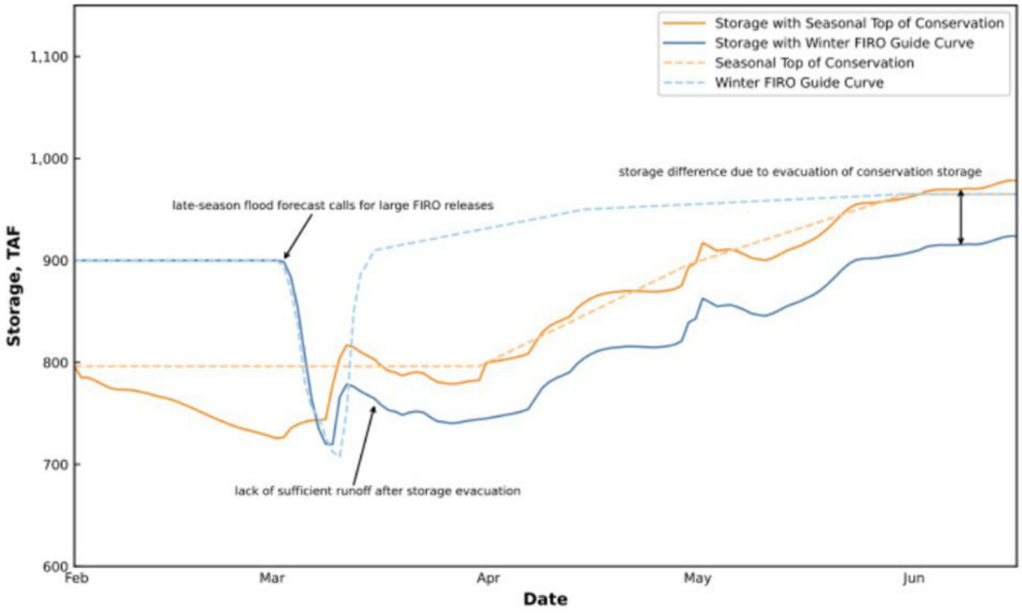


Figure L-1. *Hypothetical conditions where using the FIRO alternative would lead to reduced end-of-flood season reservoir storage.*

The Water Resources Engineering (WRE) team found this be challenging through direct methods because (1) non-flood control releases from both projects are difficult to agree on, and (2) there remains substantial uncertainty on how the spring refill curves may be adjusted as a function of both the FIRO and general WCM update work.

As a result, the WRE team adopted an indirect assessment for the prescriptive FIRO approaches where volume triggers are employed (PVA Alternative 2) and a period-of-record analysis with stated assumptions regarding (1) and (2) above for the iterative (EFO-type) approaches (PVA Alternative 3).

L.1 Indirect Assessment for PVA Alternative 2

The indirect approach used here is composed of three elements.

1. The frequency of observed trigger volumes
2. The frequency of forecast trigger volumes
3. The reliability associated with forecasts of trigger volume and greater

From these three elements, the team can made statements about the likelihood that the prescriptive approach may negatively impact water supply reliability. Table L-1 shows the trigger volumes for the prescriptive approaches developed for ORO and NBB.

Table L-1. *Forecast volume triggers for the prescriptive FIRO approaches.*

Reservoir	1-Day Volume	3-Day Volume	5-Day Volume	7-Day Volume
Oroville	222 KAF	530 KAF	N/A	694 KAF
New Bullards Bar	100 KAF	100 KAF	100 KAF	100 KAF

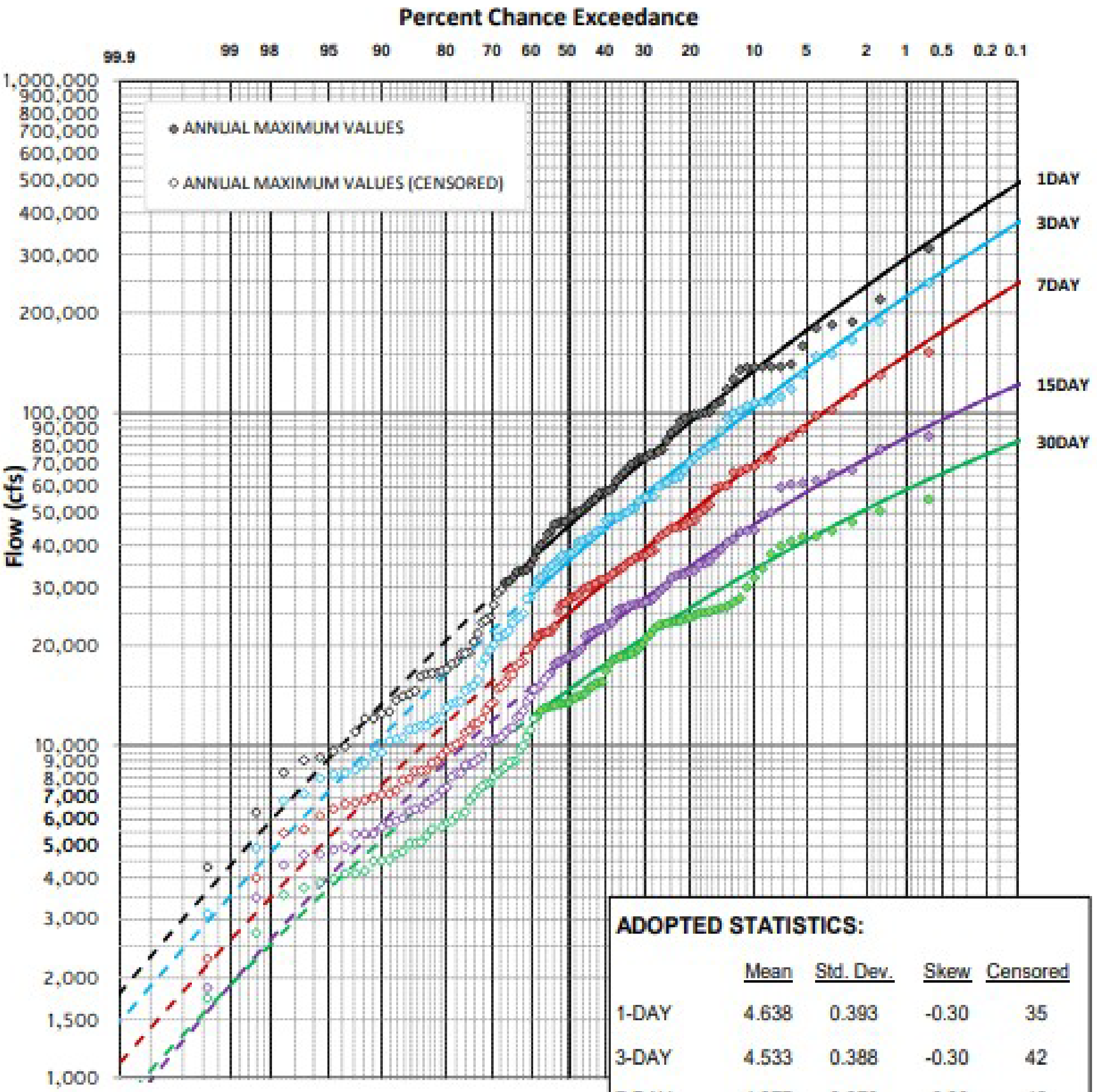
Table L-2 shows the frequency of these trigger volumes derived from the frequency curves shown in Figure L-2 and Figure L-3.

Table L-2. *Historical frequency (return period) of trigger volumes for the prescriptive approaches.*

Reservoir	1-Day Volume	3-Day Volume	5-Day Volume	7-Day Volume
Oroville	~12-year	~8-year	N/A	~11-year
New Bullards Bar	~19-year	~4-year	~3-year	~2-year

Note that the frequency of the trigger volumes for ORO are consistent (roughly 10-year) whereas the frequency of the single trigger volume of 100 TAF drops as the event duration increases.

Figure L-4 shows the frequency with which CNRFC HEFS-based hindcasts from 1985 through 2010 indicated inflows equal to or greater than the volume triggers shown in Table L-1 by month. Note that forecast inflows are much less likely to exceed the volume triggers for ORO. And even at the ~2-year return period volume of 100 KAF over 7-days, only 7% of February forecasts exceeded the volume trigger for NBB. Forecast for shorter durations were significantly less common.



ADOPTED STATISTICS:

	Mean	Std. Dev.	Skew	Censored
1-DAY	4.638	0.393	-0.30	35
3-DAY	4.533	0.388	-0.30	42
7-DAY	4.377	0.378	-0.30	42
15-DAY	4.235	0.355	-0.51	48
30-DAY	4.139	0.321	-0.50	44

NOTES:

1. Median plotting positions.
2. Estimated drainage area: 3,639 sq. mi.
3. Estimated average basin elevation: 4,965 ft.
4. Period of Record: 1902-2008.
5. Expected Moments Algorithm, Multiple Grubbs-Beck Test.
6. Station skew adopted: 15-day.
7. Skew manually adjusted: 1-, 3-, 7-, & 30-day.
8. Standard deviation manually adjusted: 30-day.
9. Adjustments made for system & at-site consistency.

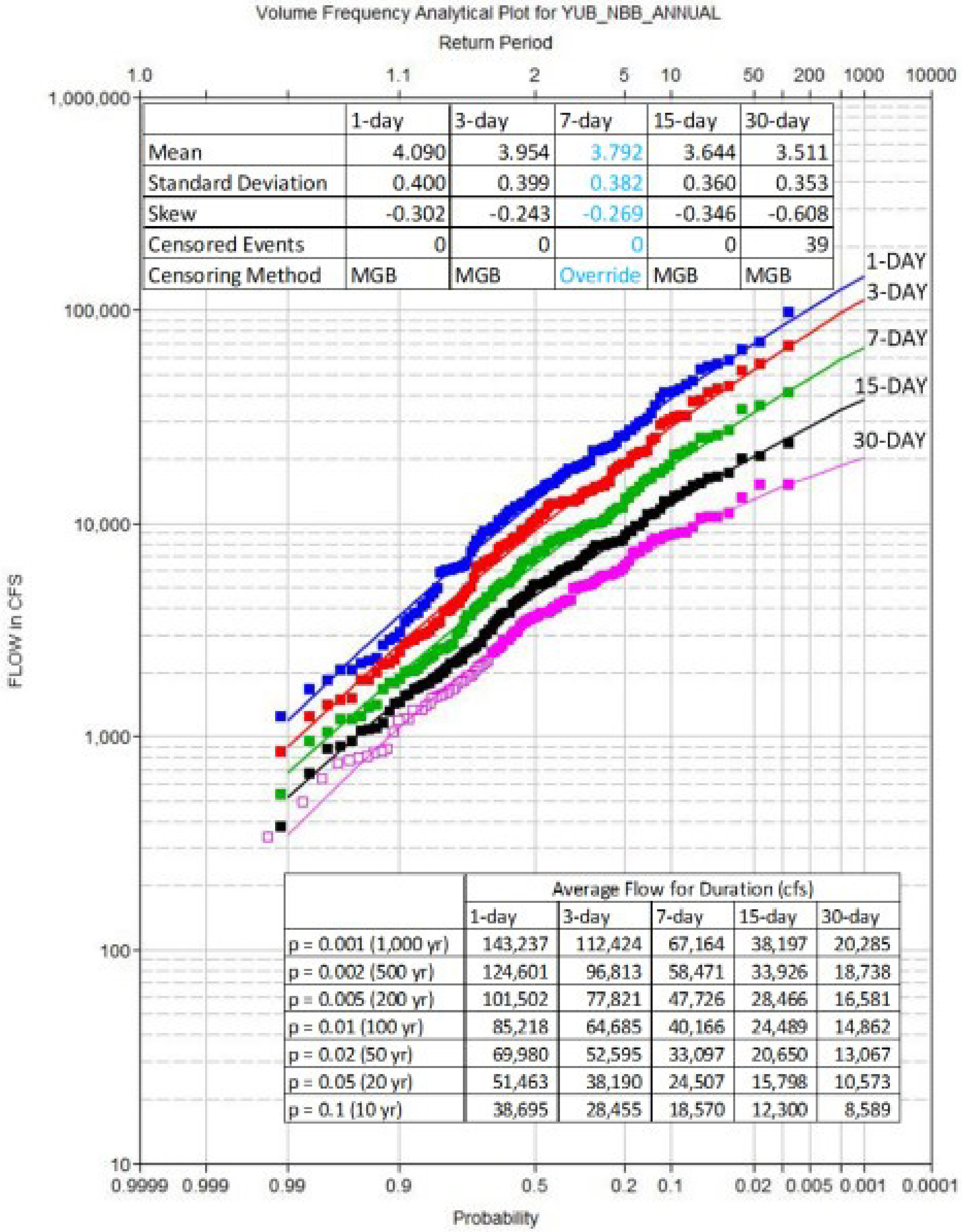
CENTRAL VALLEY HYDROLOGY STUDY
SACRAMENTO BASIN, CALIFORNIA

RAIN-FLOOD FREQUENCY CURVES
UNREGULATED CONDITION
ANALYSIS POINT FTH-ORO
FEATHER RIVER DOWNSTREAM OF OROVILLE DAM

U.S ARMY CORPS OF ENGINEERS
SACRAMENTO DISTRICT

11-Jun-2014

Figure L-2. *Unregulated rain-flood frequency curves for the Feather River below Oroville Dam.*



	1-day	3-day	7-day	15-day	30-day
Mean	4.090	3.954	3.792	3.644	3.511
Standard Deviation	0.400	0.399	0.382	0.360	0.353
Skew	-0.302	-0.243	-0.269	-0.346	-0.608
Censored Events	0	0	0	0	39
Censoring Method	MGB	MGB	Override	MGB	MGB

	Average Flow for Duration (cfs)				
	1-day	3-day	7-day	15-day	30-day
p = 0.001 (1,000 yr)	143,237	112,424	67,164	38,197	20,285
p = 0.002 (500 yr)	124,601	96,813	58,471	33,926	18,738
p = 0.005 (200 yr)	101,502	77,821	47,726	28,466	16,581
p = 0.01 (100 yr)	85,218	64,685	40,166	24,489	14,862
p = 0.02 (50 yr)	69,980	52,595	33,097	20,650	13,067
p = 0.05 (20 yr)	51,463	38,190	24,507	15,798	10,573
p = 0.1 (10 yr)	38,695	28,455	18,570	12,300	8,589

Figure L-3. *Adopted unregulated volume-frequency curves for point YB-NBB (period of record 1902-2018). Historical events are shown using Hirsch/Stedinger plotting positions. Events removed as outliers are indicated with hollow markers. Blue text represents values adjusted manually. HDR.*

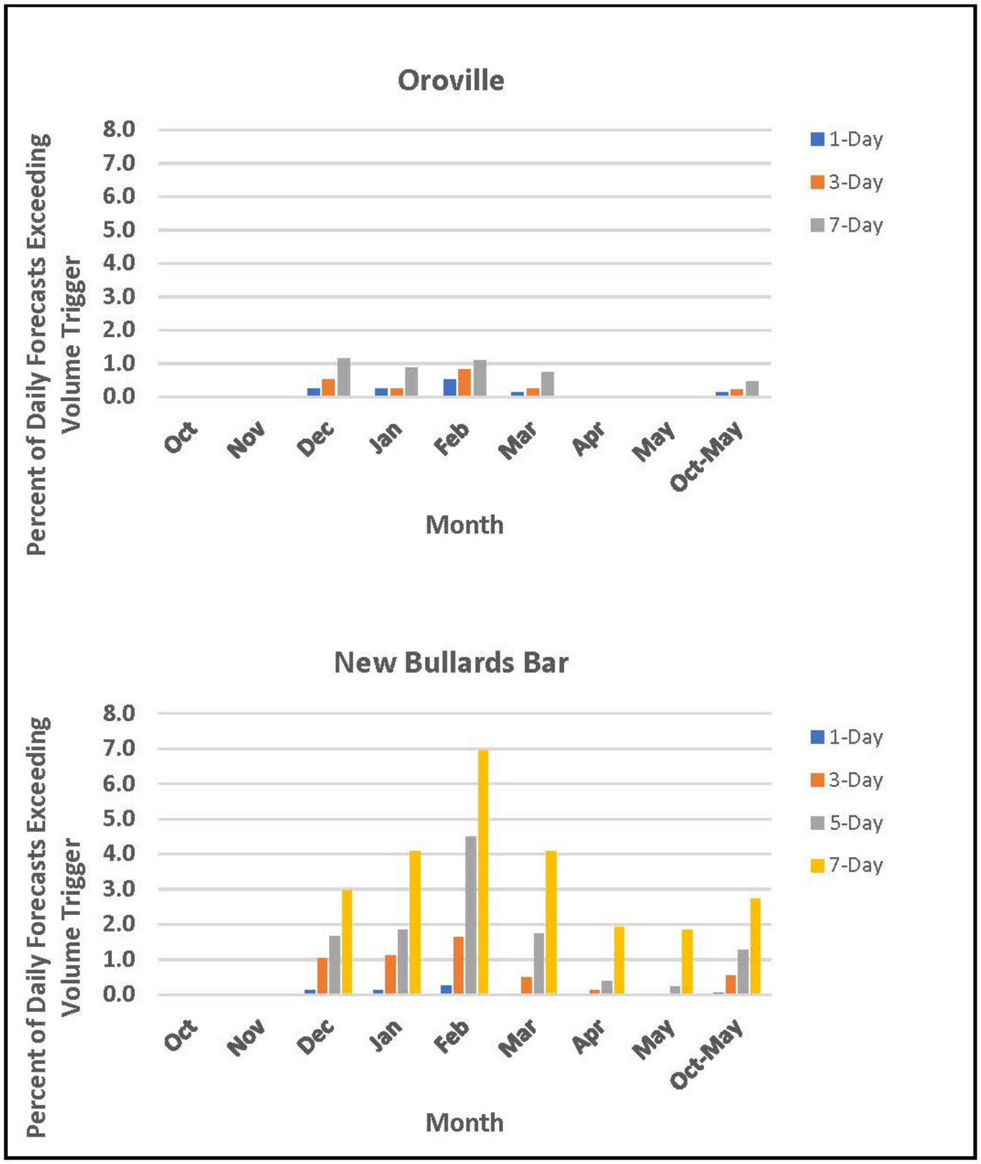
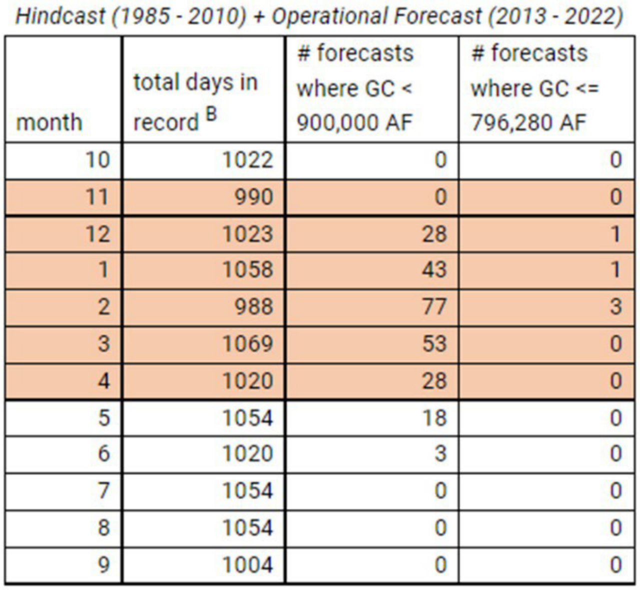


Figure L-4. *Percent of daily inflow forecasts exceeding the volume triggers shown in* ***Table L-1*** *for ORO and NBB.*

The figures and tables above show that the activation associated with the triggers for the prescriptive approaches are quite rare for ORO and certainly not an every-year occurrence for NBB. While higher at NBB, a 1986-2022 period of record calculation of the FIRO guide curve TOC for NBB (based on forecast inflows) showed that pre-releases into the conservation storage were only called for in February 1986 and January 1997. Table L-3 shows the number of days the NBB FIRO guide curve fell below 900,000 AF and 796,280 AF associated with the existing winter flood control pool. Drops into the conservation space (total of 5 days over 37 winter seasons) were less than 100 TAF, which was more than recaptured during the events that followed. Other triggered events for NBB as depicted in Figure L-4 simply result in a reduction of the encroachment into the traditional flood pool (900 TAF).

Table L-3. *Number of days where the NBB FIRO guide curve called for < 900,000 AF and 796,280 AF during the 1985 – 2022 period.*



Hindcast (1985 - 2010) + Operational Forecast (2013 - 2022)

month	total days in record B	# forecasts where GC < 900,000 AF	# forecasts where GC <= 796,280 AF
10	1022	0	0
11	990	0	0
12	1023	28	1
1	1058	43	1
2	988	77	3
3	1069	53	0
4	1020	28	0
5	1054	18	0
6	1020	3	0
7	1054	0	0
8	1054	0	0
9	1004	0	0

And finally, we can look at the reliability of inflow volume forecasts to assess the likelihood of significant over-forecasts that trigger pre-releases. Figure L-6 and Figure L-7 provide insight into the forecast reliability associated the 25% exceedance probability inflow volume used in the prescriptive approach for both reservoirs. Figure L-5 provides interpretive assistance using the 3-Day inflow case from ORO. Here the zones of over-forecast and under-forecast are identified as above and below the 1:1 line respectively.

False alarms (what we're concerned with for water supply reliability) are found in the upper left quadrant and their significance increases as you move from right to left.

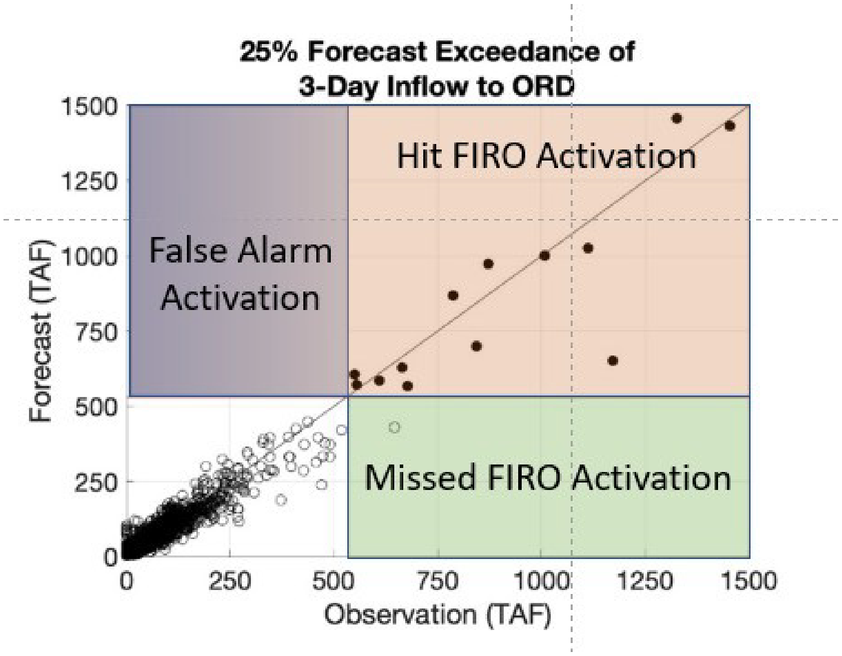


__Figure L-5.__ Interpretive guidance for Figures 6 and 7.

The number of forecast-observation pairs above the trigger volume is clearly higher for NBB as suggested in Table L-2 and Figure L-4. For both reservoirs, the 1-day 25% exceedance probability forecast appears to be reasonably unbiased. For longer durations of 3- to 7-days, an increasing negative bias is present. This suggests that these longer/larger inflow forecasts tend to under-estimate the observations in the domain of the triggering volumes.

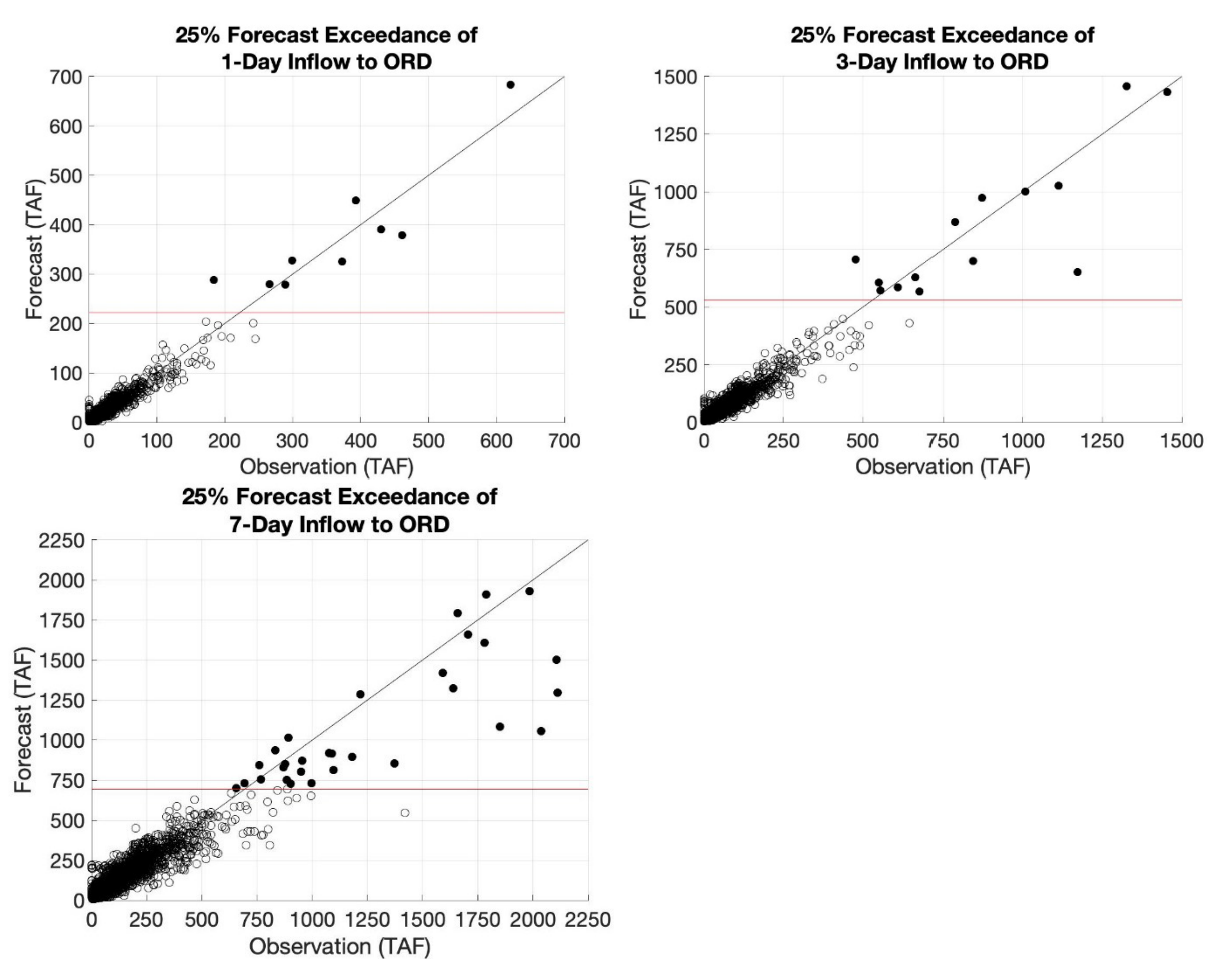


Figure L-6. *Scatter plots of 25% exceedance probability forecasts of Oroville inflow for durations of 1-, 3-, and 7-days. From CNRFC HEFS hindcasts (1985-2010).*

Water supply reliability may be compromised by large triggering inflow volumes that are significantly high-biased. For example, a forecast inflow might trigger a pre-release of conservation storage that would not be recovered during the observed period. This is depicted in Figure L-1. Figure L-6 and Figure L-7 suggest that it is much more likely that the 25% exceedance probability forecast under-estimates the inflow associated with pre-release events and therefore negative impacts on water supply reliability should be exceptionally rare. Further, for a false alarm activation to impact water supply storage into the dry season, it would have to be associated with (1) the last significant runoff event of the winter and (2) under conditions of an exceptionally low snowpack that limits the capacity of the watershed to refill the reservoirs with snowmelt.

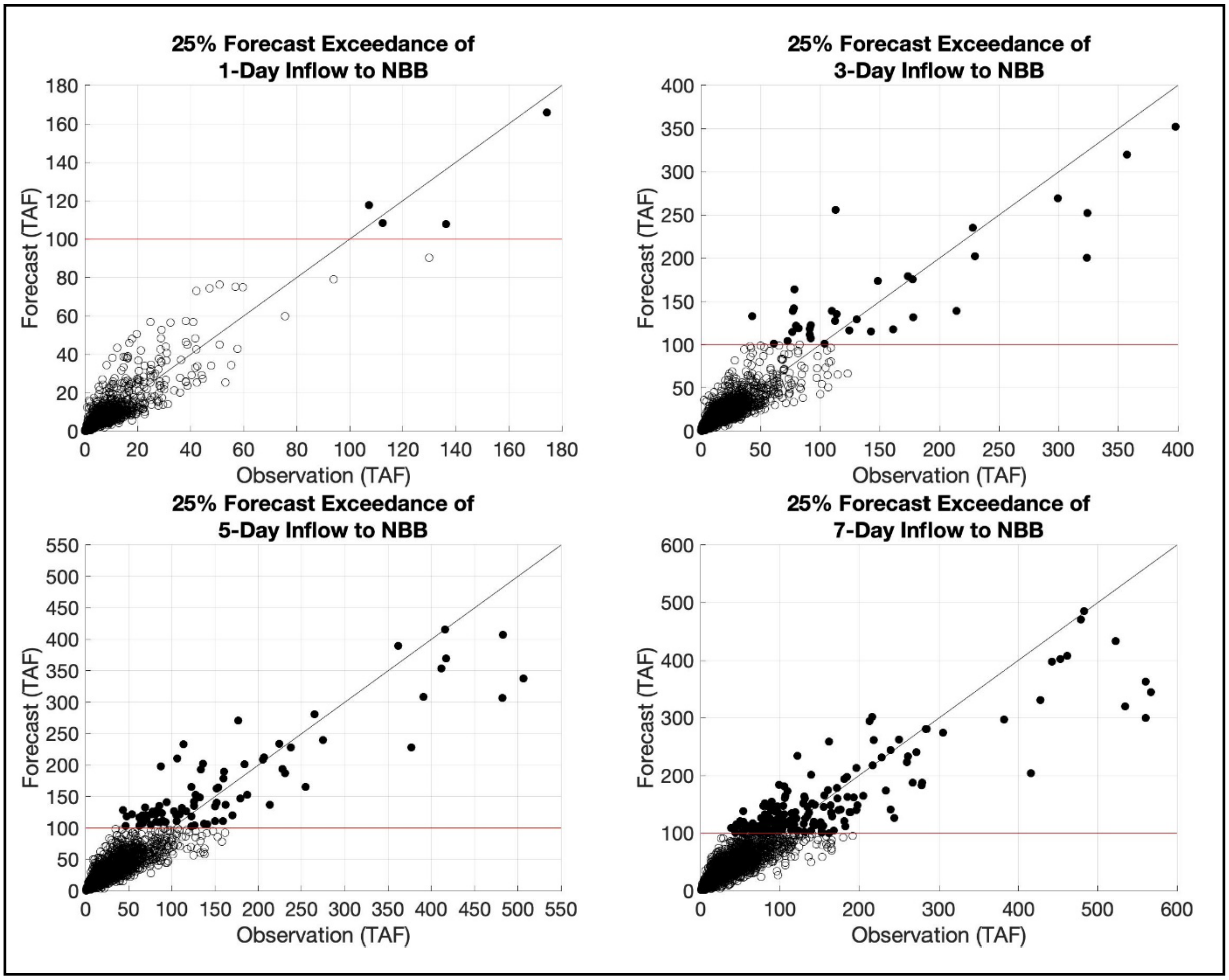
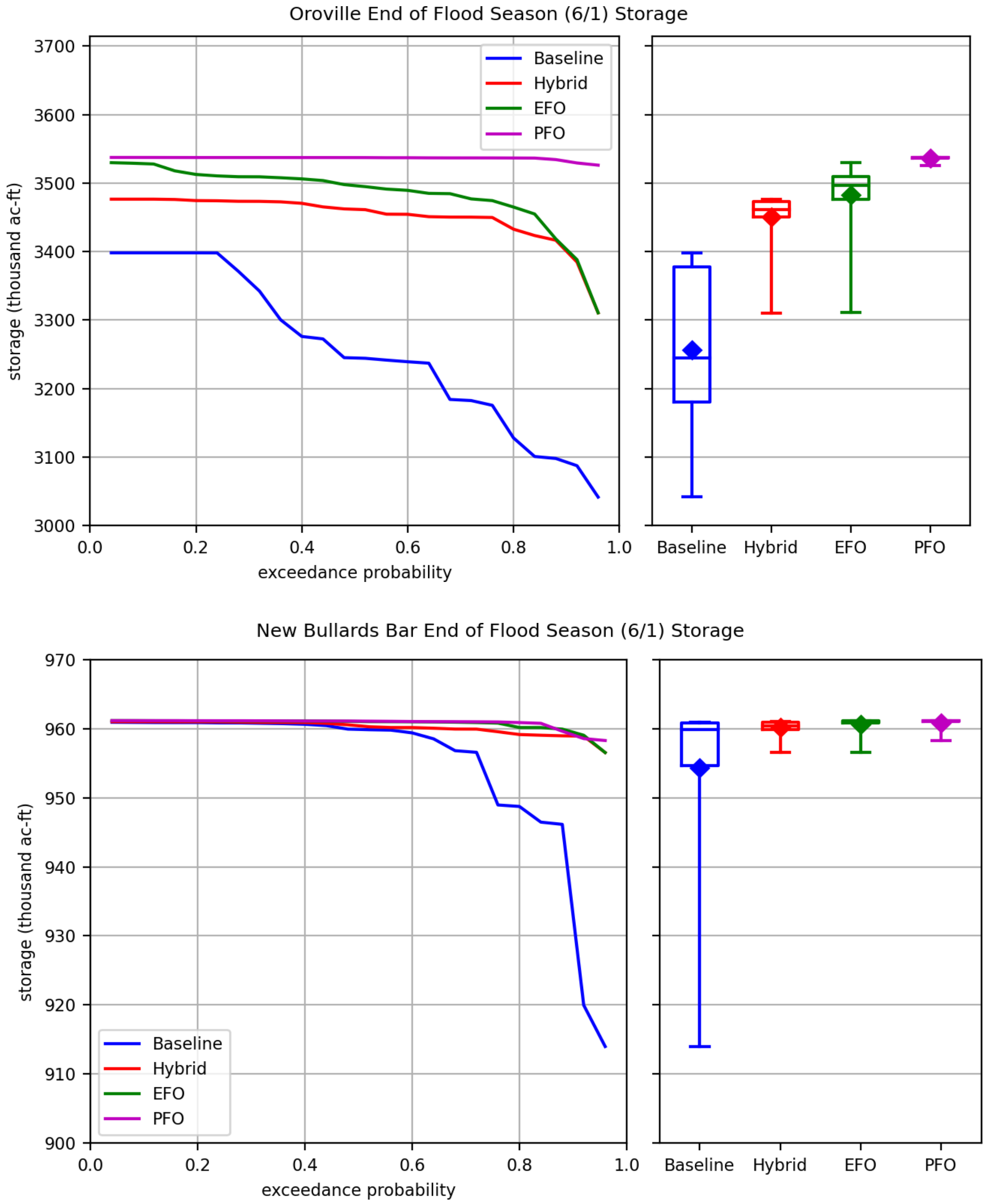


Figure L-7. Scatter plots of 25% exceedance probability forecasts of New Bullards Bar inflow for durations of 1-, 3-, 5-, and 7-days. From CNRFC HEFS hindcasts (1985-2010).

L.2 Direct Assessment for PVA Alternative 3

To assess the potential risk of the over-release of stored water with the Alternative 3 (Hybrid Ensemble Forecast Operations) alternatives (described elsewhere in the PVA and supporting appendixes) in advance of a flood event that could impact storage recovery and water supply, these alternatives were simulated for each year of the hindcast period at a daily time step using observed hydrology and hindcasts from 1985 through 2010 provided by the CNRFC. Baseline operations (consistent with the water control manuals) and perfect forecast operations (PFO) were also simulated to provide a basis of comparison of model results. These simulations were completed for the flood control season (November 1 to June 1) for each year of the hindcast with beginning storage levels set at the top of conservation for Baseline, the top of the FIRO encroachment pool for Alternative 3, and the top of the flood pool for PFO. These simulations did not include any rules for water supply operations (no water supply releases) to maximize storage levels during the flood control season, and thereby maximizing the frequency that FIRO pre-releases would be made. Given that this approach does not include any water supply operations to continually draw down storage through the flood control season, any over release of water made during an event will likely be recovered by subsequent storms. Therefore, this approach most accurately assesses the risk of over releasing water for the last significant storm of the season for each year of the hindcast period.

Figure L-8. *Frequency of end of flood season storage for ORO (top) and NBB (bottom) as a function of WCP alternative.*



End of flood season (June 1) storage levels for the period of record simulations were evaluated to assess potential risk of over-release with the Hybrid EFO alternative (Figure L-8). Results of Hybrid EFO relative to Baseline for both ORO and NBB show a significant increase in end of flood season storage suggesting that modeled releases would positively impact end of flood season storage and in turn water supply reliability.

L.3 Conclusions

The indirect assessment of prescriptive (PVA Alternative 2) and direct assessment of iterative (PVA Alternative 3) FIRO approaches strongly suggest that water supply reliability will not be negatively impacted by FIRO. In fact, there is evidence to suggest that the opposite is true. The level of evidence provided here is viewed as sufficient for the purpose of the PVA. For the FVA, it is recommended that the FIRO approaches undergo full period-of-record simulation with reasonable estimates of non-flood control releases and consistent starting storages for each water year. That evaluation should also capture any proposed changes to the spring refill curves for the two reservoirs.

Appendix M—Meteorological Analysis, Assessment, and Research (Section 6)

M.1 Additional information and imagery for AR characteristics and precipitation mechanisms

The precipitation in a landfalling AR in the Yuba-Feather watersheds may also be influenced by several meteorological processes that vary from one event to the next related to additional mesoscale and microphysical processes. These processes, among others, may include:

1. Water vapor flux altitude (Ralph et al. 2013, Hecht and Cordeira 2017; Ricciotti and Cordeira 2022).

2. Precipitation shadowing from the upstream topography of the Coastal Ranges and precipitation enhancement due to water vapor flux through terrain gaps (e.g., Neiman et al. 2004).

3. Development of a mesoscale frontal wave (e.g., Martin et al., 2019, Michaelis et al., 2021)

4. Development of a Sierra Barrier Jet (e.g., Ralph et al. 2003; Neiman et al. 2002, 2013; Hughes et al. 2014; Rutz et al. 2014; White et al. 2015; Lamjiri et al. 2018).

5. Development of a narrow cold frontal rainband (NCFR; e.g., Ralph et al. 2011; Cannon et al. 2020) or regions of enhanced convergence that can lead to intense precipitation within a landfalling AR.

6. Variability in the altitude of the freezing level and rain/snow transition (Henn et al. 2020; Sumargo et al. 2020).

7. Variability in cloud microphysics such as the seeding of orographic precipitation from higher-altitude precipitation (e.g., Browning 1980; Hill 1983; Neiman et al. 2002; Ralph et al. 2003; Creamean et al. 2013).

Additional details on these processes have been provided below:

1. Water vapor flux altitude (Ralph et al. 2013, Hecht and Cordeira 2017; Ricciotti and Cordeira 2022)

   Both Ralph et al. (2013) and Hecht and Cordeira (2017) also investigate the effect of water vapor flux altitude in precipitation production over the coastal Russian River watershed. While Ricciotti and Cordeira (2022) note that 850-hPa and 925-hPa water vapor flux magnitude and direction do also improve the relationships with watershed MAP across southern California watersheds (i.e., an improvement over IVT magnitude and direction), the effect is minimal across the Upper Yuba and North Fork Feather watersheds. The IVT or lower tropospheric water vapor flux are both appropriate meso-synoptic-scale ingredients that influence a large majority of the variance in daily precipitation across the Upper Yuba and Feather River watersheds.

2. Precipitation shadowing from the upstream topography of the Coastal Ranges and precipitation enhancement due to water vapor flux through terrain gaps (e.g., Neiman et al. 2004)

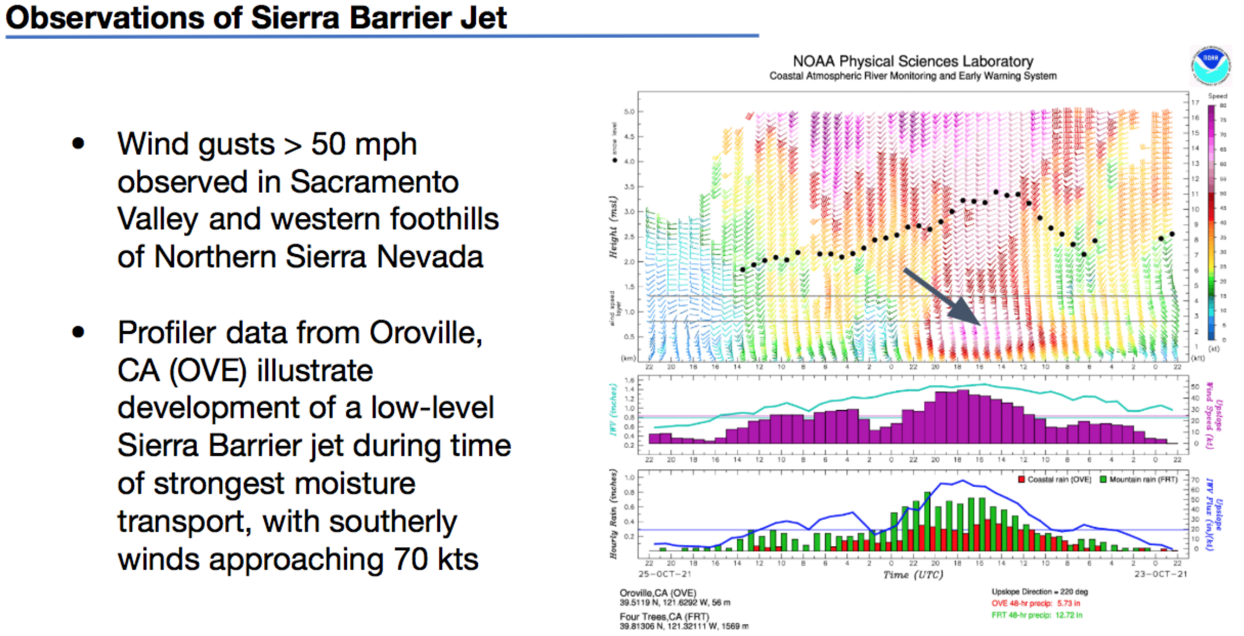
   The physiography of northern California is conducive to both precipitation shadowing from the upstream topography of the Coastal Ranges and precipitation enhancement due to water vapor flux through terrain gaps (e.g., Ralph et al. 2003; Neiman et al. 2002, 2013; Hughes et al. 2014; Rutz et al. 2014; White et al. 2015; Lamjiri et al. 2018). Of particular interest to the Yuba-Feather watersheds are landfalling ARs near San Francisco with west-southwest IVT directions that are able to transport water vapor into the Central Valley through the San Francisco and Petaluma Gaps in the Coastal Ranges.

3. Development of a mesoscale frontal wave (e.g., Martin et al., 2019, Michaelis et al., 2021)

   A mesoscale frontal wave is the development of a secondary cyclone or “wave” along a landfalling AR that can prolong the duration of and inhibit the southward propagation of a landfalling AR, thereby extending and enhancing its ability to produce hazardous weather. FIRO sponsored research has produced several papers (Martin et al. 2019, Michaelis et al, 2021, Hecht et al. 2022) regarding frontal waves, secondary cyclones, ARs and the forecast challenges that occur when these phenomena interact. Research conducted by CW3E Collaborator, Dr. Andrew Martin, has drawn on 10+ winter seasons of AR activity in the Northeastern Pacific to conclude that when a secondary cyclone develops on a landfalling AR, the AR scale can significantly increase. Notably, the AR Scales of those events with mesoscale frontal waves were higher (more intense and longer duration) than those without mesoscale frontal waves. Recall, the series of ARs that caused the Lake Oroville Dam spillway crisis in February 2017 included multiple developing secondary cyclones and frontal waves, and several of the most recent landfalling ARs also included mesoscale frontal waves.

4. Development of a Sierra Barrier Jet (e.g., Ralph et al. 2003; Neiman et al. 2002, 2013; Hughes et al. 2014; Rutz et al. 2014; White et al. 2015; Lamjiri et al. 2018)

   Landfalling ARs in this region favor the subsequent development of enhanced lower tropospheric (~1 km) flow from the south-southeast associated with a Sierra Barrier Jet (SBJ; e.g., Kingsmill et al. 2013; Neiman et al. 2013; Ralph et al. 2016) that was prominently observed during a landfalling AR during October 2021 (Fig. 6-3-2). Previous work identified that 45 of 50 days with extreme daily precipitation (wettest 50 days during 2002-2011) in the Northern Sierra 8-station Precipitation Index covering the headwaters of the Sacramento River, inclusive of the Yuba-Feather watersheds, were associated with a SBJ on the day of precipitation (Ralph et al. 2016). 41 of 50 (82%) were associated with both a landfalling AR and SBJ. The SBJ modulates precipitation across the west slope of the Sierra Nevada, inclusive of the Yuba-Feather watersheds, during a majority of landfalling ARs that produce the region’s most extreme precipitation. Note that the topography of the Yuba-Feather watersheds exposes the western portion of the Feather watershed (the North Fork), above Oroville, to orographic enhanced precipitation during a more southerly oriented flow along a SBJ.



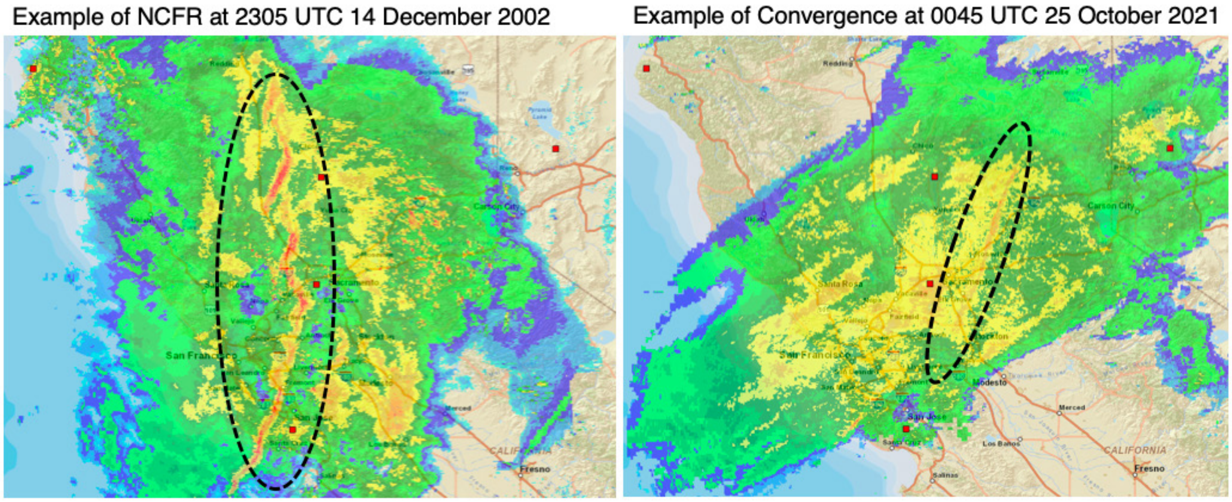
Observations of Sierra Barrier Jet

- Wind gusts > 50 mph observed in Sacramento Valley and western foothills of Northern Sierra Nevada
- Profiler data from Oroville, CA (OVE) illustrate development of a low-level Sierra Barrier jet during time of strongest moisture transport, with southerly winds approaching 70 kts

Figure M-1. *Example of the formation of a Sierra Barrier Jet (SBJ) during the landfalling of an AR in coastal northern California in late October 2021 with annotations provided by CW3E.*

5. Development of a narrow cold frontal rainband (NCFR; e.g., Ralph et al. 2011; Cannon et al. 2020) or regions of enhanced convergence that can lead to intense precipitation within a landfalling AR.

NCFRs or related regions of enhanced precipitation produce short-duration high-intensity rainfall that may be associated with flash floods and debris flows, especially in post-fire landscapes where lower-threshold precipitation rates may more easily trigger them such as in Southern California during the extremely destructive 2018 Montecito event (Oakley et al. 2018). Despite their occurrence in Northern California (Fig. A6-2), there is no established record of NCFRs or similar features over the region. However, a recent climatology of NCFRs has been created for Southern California (de Orla-Barile et al. 2021) and climatologies of NCFRs do exist elsewhere around the world. Construction of such a climatology in Northern California, as motivated and described by de Orla-Barile et al. (2021) is a labor-intensive process given that automated methods for their detection in radar data is limited by radar elevation and topographic blocking (Thompson 2001; Maddox et al. 2002; National Research Council 2005). These limitations are exacerbated by regional NCFR characteristics. Notably, the relatively shallow convective precipitation signal (typically <3 km in height; Hobbs and Biswas 1979; Hobbs et al. 1978), gap and core structure (Jorgensen et al. 2003; Cannon et al., 2020;), and topographic interactions (Neiman et al. 2004) collectively degrade the ability of the regional radar network to identify NCFRs. Accurate precipitation forecasts of landfalling ARs over the Upper Yuba and Feather watersheds must capture these short-duration high-intensity periods of rainfall, and their frequency and predictability have not been studied across northern California.



Example of NCFR at 2305 UTC 14 December 2002

Example of Convergence at 0045 UTC 25 October 2021

Figure M-2. *Examples of a NCFR and region of enhanced convergence in Northern California on 14 December 2002 and on 25 October 2021 during the landfall of high-impact ARs.*

6. Variability in the altitude of the freezing level and rain/snow transition (Henn et al. 2020; Sumargo et al. 2020);

   The atmospheric freezing level (i.e., altitude of the 0-degree celsius isotherm) and the snow level (i.e., altitude at which frozen hydrometeors fully transition to rain) govern precipitation type during storms and subsequent hydrologic responses (Osborne 2021). The freezing levels exist at the top of the vertical layer where hydrometeors melt and snow levels exist on average 192-207 meters (630-680 feet) below in coastal California (White et al. 2002; Henn et al. 2020). California cool season snow levels typically occur between 1000 and 3500 m MSL with medians near 1500 m MSL (Hatchett et al. 2017; Henn et al. 2020), encompassing a majority of the Yuba-Feather watersheds. Recent high-impact precipitation events in February 2017 (i.e., the Oroville Spillway incident; Hollins et al. 2018; White et al. 2019; Vano et al. 2019), February 2019 (i.e., the Valentine's Day Event; Hatchett et al. 2020; Hecht et al. 2022), and October 2021 all occurred in association with landfalling ARs that contained large changes in snow level within these events. Of particular interest to FIRO viability in the Yuba-Feather watersheds are studies demonstrating poor skill in model forecasts of the height of the freezing level with errors at lead times beyond 1-2 days exceeding the basin hypsometry (Henn et al. 2020). The practical consideration herein is precipitation type and streamflow forecasting; however, there is also an exponential relationship between temperature and air's capacity for water vapor (i.e., the Clausius-Clapeyron) that portends higher precipitation rates for higher freezing (snow) levels. Henn et al. (2020) found that warm ARs have the highest precipitation rates and the most negative forecast bias in the height of the freezing level (i.e., forecasts were too low/cold by ~250 meters or >800 feet on average at Lake Oroville for storms with the highest precipitation rates).

7. Variability in cloud microphysics such as the seeding of orographic precipitation from higher-altitude precipitation (e.g., Browning 1980; Hill 1983; Neiman et al. 2002; Ralph et al. 2003; Creamean et al. 2013).

CW3E is investigating the role of cloud microphysics and orographic precipitation within FIRO in collaboration with Dr. Andrew Martin at Portland State University who helped pioneer the development of the West-WRF model. These efforts include studies focused on cloud processes during orographic precipitation that support self-induced critical layers and leeside mountain windstorms using aircraft observations and modeling experiments. This study is emerging from the West-WRF "OP3" (orographic precipitation processes and prediction) research group activities regarding orographic cloud processes in WRF. Additional collaborative activities of note with Dr. Martin includes examining secondary ice production as a link between aerosols and precipitation efficiency in mixed-phase clouds. Specifically, this work seeks to investigate the development of new microphysics model parameterizations of secondary ice production in West-WRF, the verification of West-WRF simulated cloud properties using DOE aircraft data, and study of the impact of secondary ice processes on precipitation efficiency during orographic storms in the Sierra Nevada.

M.2 Additional information and imagery for Case Studies

M.2.1 Imagery for 2019 Valentine's Day Case Study

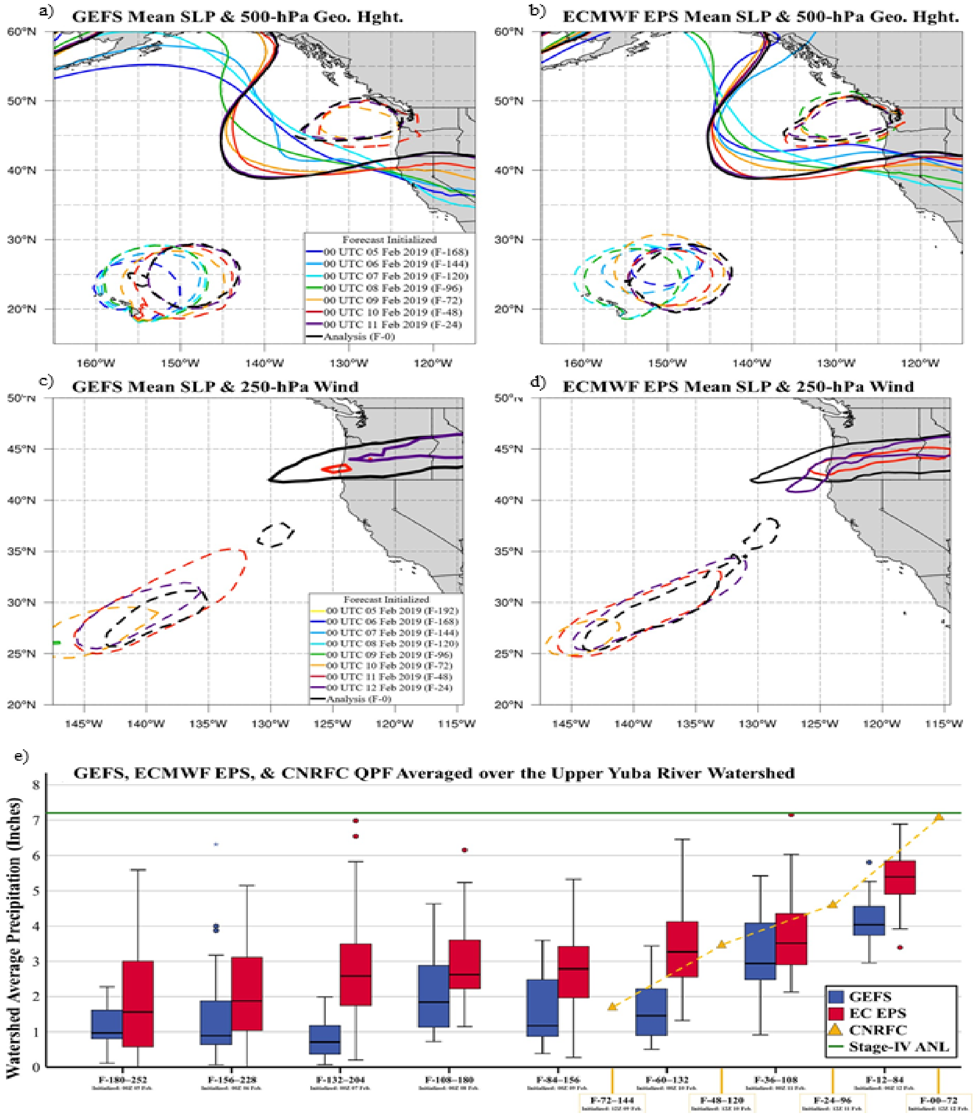


Figure M-3. *(a),(b) Ensemble-mean 500-hPa geopotential height (solid; 550-dam contour) and SLP (dashed; 1,004-hPa contour) for the (a) GEFS and (b) EPS forecasts initialized every 24 h from 0000 UTC 5 Feb 2019 (F-168) through the valid time of 0000 UTC 12 Feb 2019 (F-0). (a),(b) Ensemble-mean 250-hPa wind speed (solid; 130-kt contour) and SLP (dashed; 996 hPa) for the (a) GEFS and (b) EPS forecasts initialized every 24 h from 0000 UTC 5 Feb 2019 (F-192) through the valid time of 0000 UTC 13 Feb 2019 (F-0). (e) Watershed-averaged ensemble 72-h precipitation forecasts by the GEFS (blue) and EPS (red) initialized every 24 h from 0000 UTC 5 Feb (F-180 to F-252) to 0000 UTC 12 Feb 2019 (F-12 to F-84) valid from 1200 UTC 12 Feb through 1200 UTC 15 Feb 2019 for the Upper Yuba River Watershed. Image from Hecht et al. (2022).*

M.2.2 Imagery for January 2021 Case Study

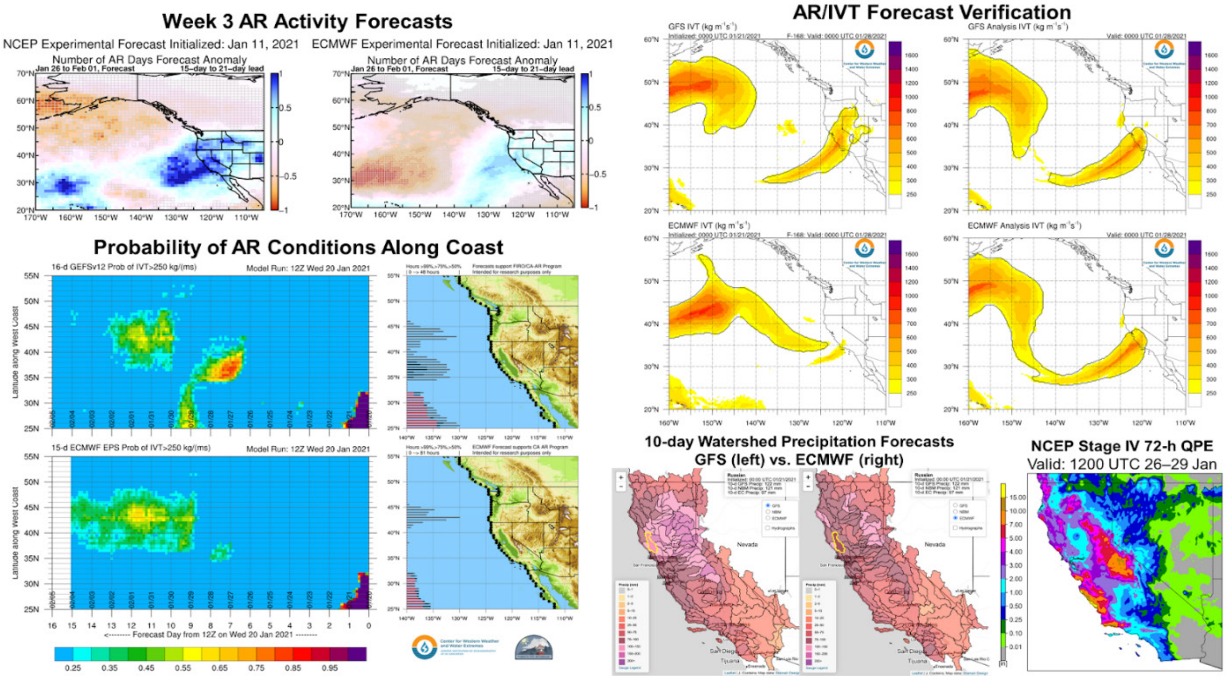


Figure M-4. *Multi-model and multi-scale assessment of forecasts prior to the late January 2021 landfalling AR event. Top left: Week-3 AR activity assessment; bottom left: AR Landfall Tool assessment of the likelihood of AR conditions along the coast; top right: 7-day forecasts of IVT magnitude by the GFS and ECMWF models with their respective analyses; and bottom right: 10-day watershed average precipitation forecast by the GFS and ECMWF models with the respective analysis.*

M.2.3 Additional information and imagery for Forecast Diagnostics and Sources for Uncertainty (AR Recon)

CW3E leads the Atmospheric River Reconnaissance (AR Recon) program to address sources of uncertainty within ARs over the Northeast Pacific. The overall goal of AR Recon is to support water management decisions and flood forecasting by using targeted airborne and buoy observations over the Northeast Pacific to improve analysis and forecasts of landfalling ARs and their impacts on the U.S. West Coast at lead times of 0-5 days. Innovations in targeting methods, data assimilation and regional forecast skill improvements are pursued through collaborative, cross-disciplinary, science-based strategies. AR Recon activities are guided by an international steering committee of senior experts from leading operational global numerical weather prediction (NWP) centers and research institutions. AR Recon was developed as a Research and Operations Partnership (RAOP) and is currently designated as an operational requirement and mission in the National Winter Season Operations Plan (NWSOP) (OFCM 2019, 2020; Ralph et al., 2020). AR Recon real-time operations sample essential atmospheric structures, notably ARs and their dynamics, as the primary target (Fig. A6-5). CW3E has developed a suite of forecast tools available to create targeted forecast briefings, during which IOP selection and planning takes place. Various initial condition sensitivity tools complement the foundational physical questions addressed by the AR Recon sampling strategy, as they provide information on optimal locations where additional observations could be most useful to minimize forecast errors or uncertainties.

AR Recon observations, which include targeted dropsonde data, drifting buoys that measure surface pressure and sea surface temperature, and innovative observing platforms such as Airborne Radio Occultation (ARO; Haase et al., 2021), fill documented gaps in the traditional observation system (Zheng et al., 2021a). These gaps occur within and around ARs due to their associated deep clouds and represent some of the leading sources of uncertainty for the prediction of extreme events over the western U.S. (Lavers et al., 2018; Reynolds et al., 2019; Demirdjian et al., 2020; Lavers et al., 2020). Dropsonde and buoy observations are transmitted in real-time to the Global Telecommunications System (GTS) to be assimilated in operational NWP systems. That capacity is currently being built up for ARO. Studies using AR Recon data have already shown the positive impact on forecasts (e.g., Stone et al., 2020; Zheng et al., 2021b). Furthermore, AR Recon data have enabled advances in the understanding of physical processes (e.g., essential atmospheric structures; Wilson et al. 2022) that modulate AR characteristics such as intensity (Hatchett et al., 2020; Cannon et al., 2020; Norris et al., 2020; Demirdjian et al., 2020; Cobb et al., 2021). The regular AR Recon season happens during January - March; AR Recon flights provided additional data for the January 2021 storm described above. The impact of the additional data on the forecast skill is currently being investigated.

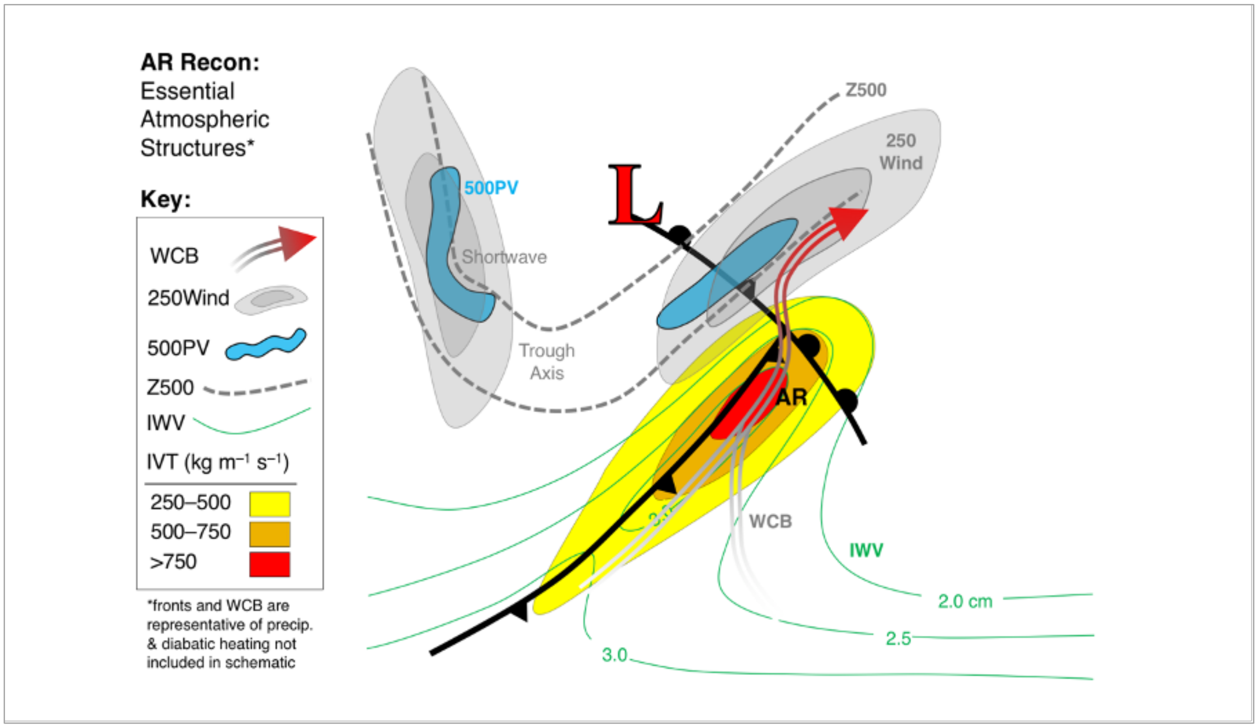


__Figure M-5.__ Schematic of physical targets known as "essential atmospheric structures" identified during AR Recon as key regions typically responsible for ensemble-based and adjoint-derived forecast model uncertainties. Image from Wilson et al. (2022)

M.3 Full report on West-WRF development and configuration

CW3E has developed an optimized version of the Weather Research and Forecasting model (WRF, Skamarock et al. 2008; Powers et al. 2017), named West-WRF, that is run in near-real-time (NRT) forecast mode in support of decision making and scientific research of extreme weather events over the Western U.S. (Ralph et al. 2016; Cordeira et al. 2017). The 2021-2022 (WY2022) NRT features several additions and improvements upon previous NRT simulations, for both technical and scientific purposes.

Four sets of West-WRF NRT simulations are being run for WY2022. The first, the deterministic forecast based on the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) hereafter referred to as "NRT-GFS", is new for WY2022 as it was updated from a frozen configuration last season. The three remaining sets of simulations were run last season - a deterministic simulation based on the European Centre for Medium Range Weather Forecasts (ECMWF) HRES ("NRT-ECMWF"), a frozen (since WY2020) GFS-based deterministic simulation that is used for machine learning purposes ("NRT-ML"), and an ensemble ("NRT-ENS"). NRT-GFS, NRT-ECMWF, and NRT-ENS all use WRF version 4.3.1, where NRT-ML uses version 4.1.2. Daily initializations of all simulations are done using 00 UTC initial conditions for the period 1 December through 31 March. The deterministic simulations have a forecast horizon of 10 days for the 9-km domain and 5 days for the 3-km domain (shown below), and the ensemble extends out to 7 days. Full output from the deterministic simulations is available hourly, and select two-dimensional variables are available every 15 minutes. For the ensemble, full output is available every three hours, and select two-dimensional variables are available every 15 minutes. All simulations are run on the *Comet* supercomputer at the San Diego Supercomputer Center, using the rocoto workflow system.

Several significant changes were made to all but the NRT-ML simulations including expanded domain, vertical resolution, and physical parameterizations.t. The West-WRF NRT has a 9-km outer domain spanning the northeast Pacific and Western U.S., and a 3-km domain focused on U.S West Coast states. The 3-km domain was expanded northward to include all of the U.S. West Coast for WY2022 (Fig. A6-6). This expansion is beneficial to capture the precipitation field from ARs making landfall in Northern California and less subject to domain boundary interference as ARs propagate north to south. The NRT-ML simulations use a slightly different 9-km domain (rotated 10 degrees longitude westward) and a smaller 3-km domain. The NRT-ML simulation configuration has been frozen for three seasons now to ensure consistency with the neural network training dataset.

The vertical resolution in the NRT-GFS and NRT-ECMWF configurations were increased from 60 to 100 vertical levels while the NRT-ENS used 60 levels, all with a 10-hPa model top. The vertical level distribution was adjusted from the default WRF configuration this season, to provide greater vertical resolution throughout the lower troposphere where key AR-related physical processes occur. Figure M-2 illustrates the difference in vertical grid spacing between the old and new configurations for 100 vertical levels, showing the improved vertical grid spacing in the new configuration to about 8-km above ground level (AGL). Improvements in the 60 vertical level configuration are similar with enhanced resolution achieved in the lower atmosphere (not shown).

The initialization of the snowpack in the West-WRF NRT simulations was improved this season by implementing a daily 4-km snow product produced by the University of Arizona (Broxton et al. 2016; Zeng et al. 2018; Broxton et al. 2019). The UA Snow product combines thousands of point-based snow water equivalent (SWE) observations from SNOpack TELemetry (SNOTEL) and Cooperative Observer Program (COOP) sites with the PRISM temperature and precipitation estimates (Daly et al. 2008). Initial conditions are updated using the latest available UA snow field (interpolated to the West-WRF domains) and any additional accumulated snowfall between the time of the latest UA snow field and the initialization time using the previous day's West-WRF forecast. Software to modify input files with the UA snow fields was provided by Jorge Arevalo and Xubin Zeng at the University of Arizona.

Several adjustments were made to the West-WRF parameterization schemes, including the Thompson microphysics scheme (Thompson et al. 2008). Research by CW3E staff, in collaboration with Greg Thompson (JCSDA), identified several adjustments to the cloud droplet concentration and autoconversion parameters that were warranted for better representation of west coast precipitation, based on several test simulations. Hydrometeor terminal fall speed variables were added to the West-WRF output files for additional microphysics diagnostics. The Noah-Multiphysics (Noah-MP) land surface scheme has also been implemented, in place of the Noah scheme used in previous seasons. Noah-MP (Niu et al. 2011) introduces several improvements over the original Noah LSM, including a separate vegetation canopy layer from the surface, an improved snow layer model, and multi-parameterization options. Optimal settings for the representation of west coast precipitation in both microphysics and land surface parameterization schemes remain areas of current research at CW3E.

Logistical improvements were made to the West-WRF NRT system, including a rewrite of most workflow scripts, on-the-fly processing of all tasks (which saves 1-1.5 hours of processing time), and improved reliability of model I/O (using asynchronous I/O and PNetCDF in place of split output files).

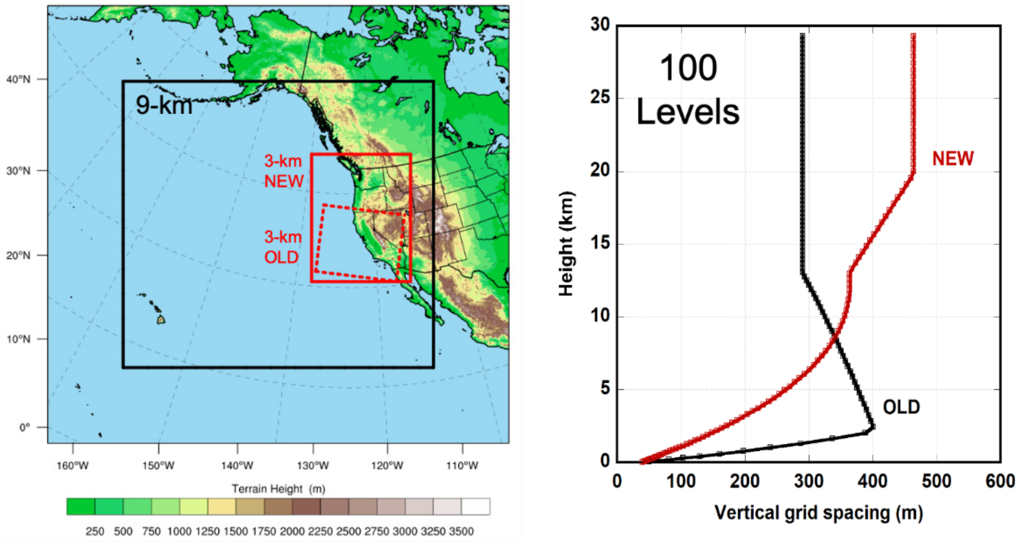


Figure M-6. *West-WRF NRT WY2021-2022 domains, with terrain height (shaded, m) and vertical level grid spacing as a function of height (red) compared to the previous configuration (black).*

CW3E began running an operational West-WRF NRT ensemble in 2020-2021 winter season. Ensemble forecasts offer several advantages over deterministic forecasts; over time, the mean of the forecast ensemble is generally more accurate than any individual ensemble member. The spread of ensemble predictions provides an indication of the flow-dependent uncertainty of the forecast, and most importantly, the probability distribution function (PDF) of the ensemble can identify the likelihood of extreme events. CW3E expanded the size of the West-WRF NRT ensemble from 48 members in WY-2021 to 200 members in WY2022. This expansion provides improved statistical sampling of the key sources of uncertainty that negatively impact numerical weather prediction (e.g., initial conditions and physics parameterizations). The larger ensemble also results in improved forecast skill of the ensemble mean, and a greater likelihood of predicting the timing and magnitude of extreme AR events that lead to flooding and debris flows. Multiple sources of perturbations are introduced into the ensemble, including initial and boundary conditions, parameterization schemes ("multi-physics"), and stochastic kinetic energy backscatter (SKEB).

The 200-member West-WRF NRT ensemble has two sets of initial and boundary conditions, split between 120 ensemble members that use ECMWF, and 80 members that use the Global Ensemble Forecast System (GEFS). The ensemble is sampled across 51 members from the ECMWF global ensemble and 31 members of the GEFS global ensemble, where input ensemble members are duplicated two to three times. Along with varying meteorological input conditions, ensemble spread is also introduced through SKEB and multi-physics. A conceptual diagram of the ensemble is shown in the appendix. The parameterization schemes used in the multi-physics configuration are chosen based on both previous experience of the CW3E West-WRF modeling group, and for operational considerations. The model parameterization schemes utilized for the West-WRF NRT are shown in the appendix. Cumulus and microphysics schemes are sampled the most since they tend to have the greatest impact on precipitation forecasting on the U.S. West Coast (Jeworrek et al. 2021).

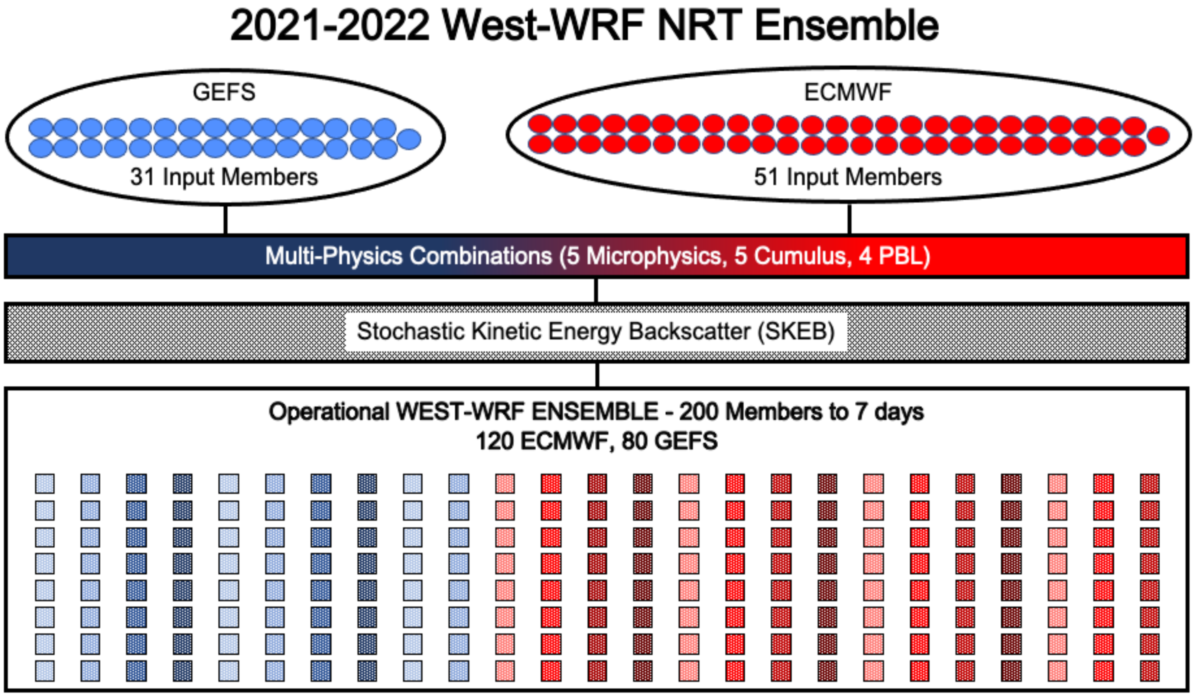


Figure M-7. *Schematic of the West-WRF NRT 200-member ensemble.*

Phys. Category	Dim.	Scheme 1	Scheme 2	Scheme 3	Scheme 4	Scheme 5
Boundary Layer	4	YSU	MYJ	MYNN2.5	ACM2	
Cumulus	5	GF	Tiedtke	KF	BMJ	KSAS
Microphysics	5	Thompson	Morrison	Lin	WSM6	WDM6
Land Surface	1	Noah MP				
Surface layer	1	PBL depend.				
LW Radiation	1	RTMG				
SW Radiation	1	RTMG				

Figure M-8. *Physical parameterization schemes used in the multi-physics configuration of the West-WRF NRT ensemble.*

M.4 Additional information and imagery for Decision Support Tools

Following the development of an "AR Portal" in support of CalWater 2015 (Cordeira et al. 2017), CW3E has expanded its forecast tools and visualizations in support of research and operational partnerships including AR Recon and FIRO. These forecast tools span spatial scales from regional (e.g., the North Pacific) to local (e.g., watersheds) and temporal scales from weeks (e.g., subseasonal) to sub-daily (e.g., 15-minute to hourly) leveraging a suite of global and regional models from operational centers such as the NCEP global forecast system, ECMWF model, and the CW3E- developed West-WRF model tailored to precipitation prediction in California. From these forecast data, CW3E has developed tools to enhance situational awareness associated with landfalling ARs (e.g., the AR Landfall Tool; Cordeira et al. 2017 and Cordeira and Ralph 2021) and watershed-scale precipitation.

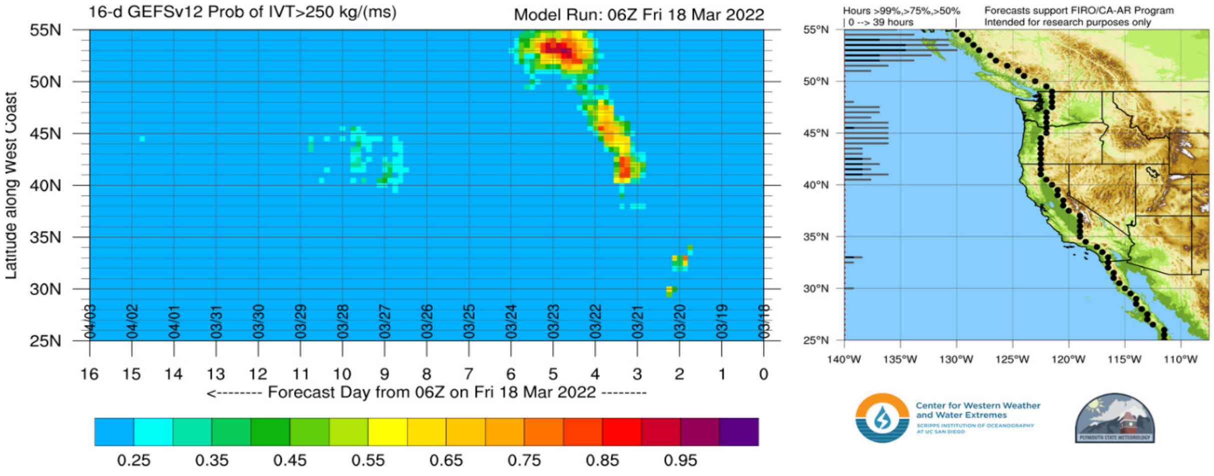


Figure M-9. *AR Landfall Tool (Cordeira et al. 2017; Cordeira and Ralph 2021) modified for a Foothills transect to better highlight the likelihood of landfalling ARs along the west slope of the Pacific Crest, including the Upper Yuba and Feather River watersheds.*

M.5 Full report on machine learning predictive capabilities

CW3E is focused on developing creative, novel approaches for skillful forecasts to support FIRO at the Yuba-Feather watersheds. One such avenue is applying machine learning (ML) algorithms for the development of predictive models and decision support tools. The most recent phase of this effort relevant to FIRO focuses on probabilistic predictions of IVT, short-range prediction of precipitation using innovative deep learning (DL) techniques, and convolutional neural networks to capture spatial precipitation patterns. These include:

- Chapman et al. (2022) studied DL postprocessing methods to obtain reliable and accurate probabilistic forecasts of IVT. Using a 34-year reforecast *(Steinhoff et al. 2022)*, based on the CW3E West-WRF mesoscale model of North American West Coast IVT, the 0–120-h probabilistic forecasts for IVT under AR conditions are tested. These predictions are compared with the GEFS model and the GEFS calibrated with a neural network. The findings (cf. Fig. A6-10) show that the DL methods compete with or outperform the calibrated GEFS system at lead times from 0 to 48 h and again from 72 to 120 h for AR vapor transport events. In addition, DL methods generate reliable, skillful forecasts which can be leveraged to learn if AR conditions are probable for a watershed.
- Hayatbini et al. (2022) focused on post-processing NWP predictions to improve the accuracy of short-range rainfall prediction. A dual-branch setup using a U-Net feature extractor is developed. It is trained end-to-end to first classify a rain/no-rain (R/NR) label for each grid location, or pixel, and then regress a rainfall amount for each rain pixel. In the study, CW3E's 34-years reforecast is used as input whereas PRISM dataset is used as ground truth. To demonstrate the generalizability of the methodology, four water years with different climate conditions are left out as test years and the prior year of each are used for validation purposes. Significant improvements are achieved in both R/NR classification and rainfall rate quantification (including mean squared error and bias reduction over the test periods) for the proposed framework compared to West-WRF.
- Badrinath et al. (2022) proposed to identify and reduce biases affecting predictions of a dynamical model using a ML method based on spatial convolution to capture complex spatial precipitation patterns. The method is based on a dual model approach using modified U-Net convolutional neural networks (CNN) regressors and classifiers to post-process daily accumulated precipitation over the US west coast. In this study, CW3E's 34-year high resolution deterministic West-WRF precipitation reforecast is used as training data for the U-Net CNN. The data is split into 4 test years that encompass characteristic West-Coast precipitation regimes. On the unseen 4-year data set, the trained CNN yields a 12.9-15.9% reduction in root-mean-square-error (RMSE) and 2.7-3.4% improvement in Pearson correlation (PC) over West-WRF for lead times of 1-4 days. Effectively, CNN adds more than a day of predictive skill when compared to West-WRF. CNN outperforms the other existing methods for the prediction of extreme events, highlighting a promising path forward for improving precipitation forecasts.

CW3E will continue to explore and develop novel AI/ML methods to improve AR, ridge and precipitation forecasts and aid in the improvement of AR forecast lead times. Specifically, we seek to run experimental ML algorithms in near real time during the water year for deterministic and probabilistic prediction of IVT and precipitation in the U.S. West.

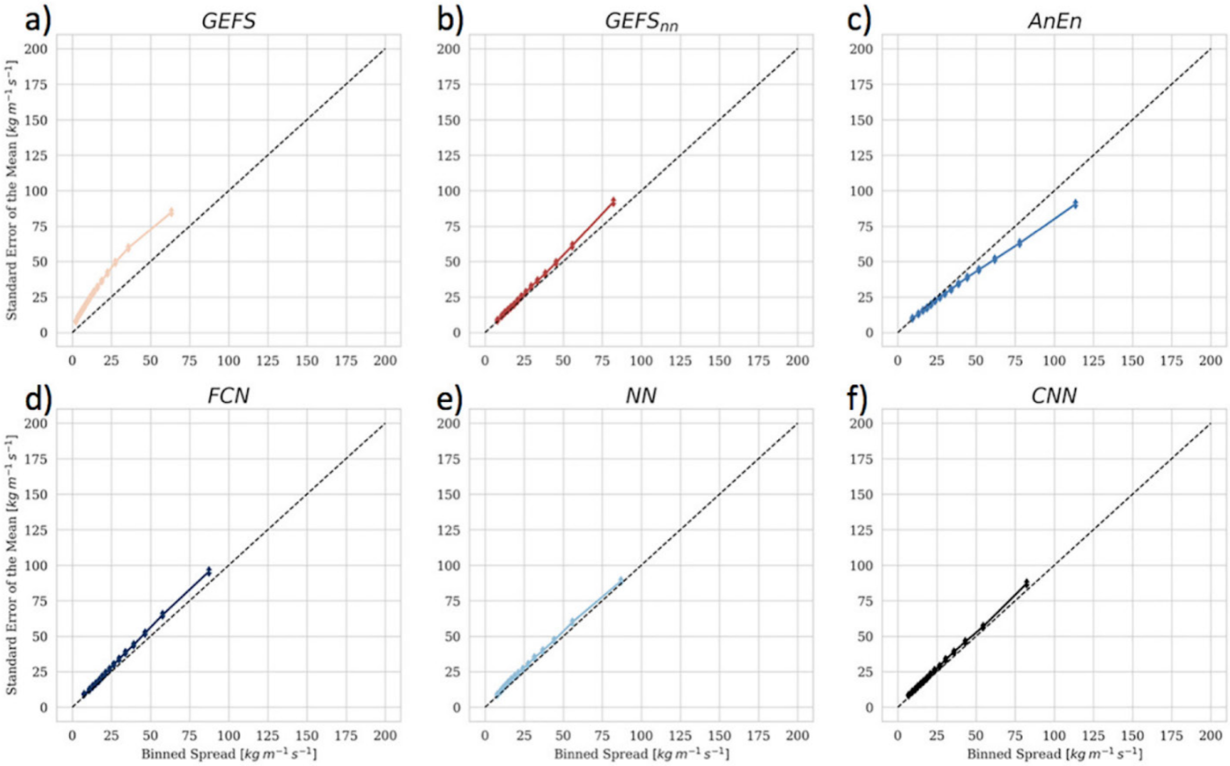


Figure M-10. *Probabilistic IVT prediction with Machine Learning. (top) Coastal evaluation locations and climatological (December– March 1984–2019) IVT (color fill; kg m^{-1} s^{-1}). (right) Binned spread–skill plots for the deep learning models (CNN, NN) compared to other prediction systems. Please note that the 1:1 dotted line indicates a perfect spread–skill line.*

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Appendix N—Hydrology (Section 6)

N.1 CNRFC Hydrology Modeling Overview

CNRFC streamflow forecasts are operationally available for the Feather-Yuba system as both use physically based models that attempt to capture the full physics of watershed behavior. CNRFC model applications are “semi-lumped” as opposed to an interconnected grid network. Watersheds with large elevation ranges are typically modeled in two to three elevation bands to better represent elevation-dependent processes, features, and conditions. CNRFC watershed models are run with a six-hour time step and riverine models are run with an hourly time step.

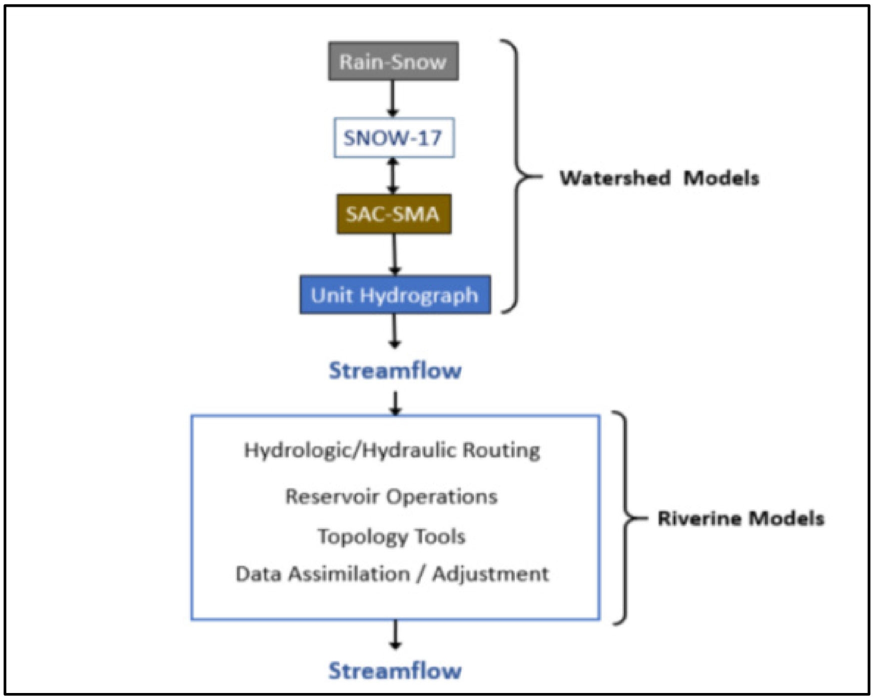


Figure N-1. *Watershed and riverine models deployed by the CNRFC within the CHPS framework*

The generalized process used to generate the 5-day deterministic forecasts is shown in Figure 3-15. Here, the CHPS hydrologic models are presented with new observations and updated meteorological forecasts with each forecast cycle. There is at least one forecast cycle per day (365 days/year), with two on weekdays in the winter and up to four during flood events. As well as needing the latest weather forecast, reliable streamflow forecasts depend on quality control of observations and the monitoring and tuning of model states. In conducting forecasting duties, hydrologists work their way through the model topology for each river basin, making the necessary adjustments to the observational data and model states to achieve (1) a good fit of the simulated streamflow to the observations during the last several days and (2) confidence in the streamflow forecast given the forecast meteorology. When complete, the forecasts are packaged into graphics and text products used to generate public watches and warnings and to help with resource management decisions (e.g., reservoir releases). Current and archived river forecasts can be found on the CNRFC website (www.cnrfc.noaa.gov).

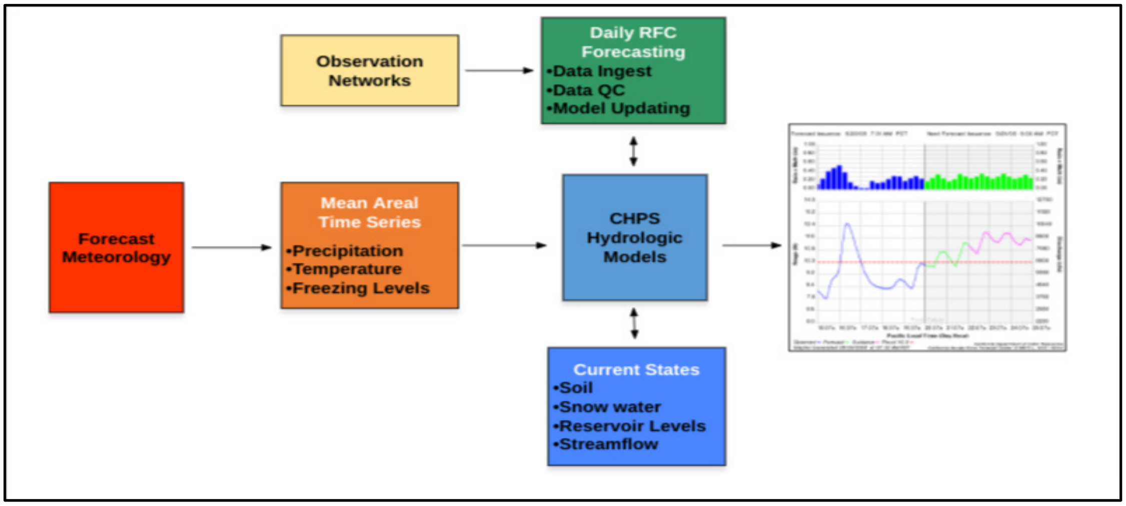


Figure N-2*. Generalized forecast process used by the CNRFC to generate five-day deterministic streamflow forecasts*

The CNRFC model topology for simulating and forecasting the Feathery-Yuba watershed are shown in Figure N-3 through Figure N-8. This is a highly regulated system, and the CNRFC attempts to model the regulation for the short range deterministic and ensemble (< 30 days) streamflow products. The reservoirs modeled are indicated by squares, and diversions are dashed lines. It should be noted that none of this regulation was accounted for in the hindcast effort but is implemented into the short range operational streamflow forecast products.

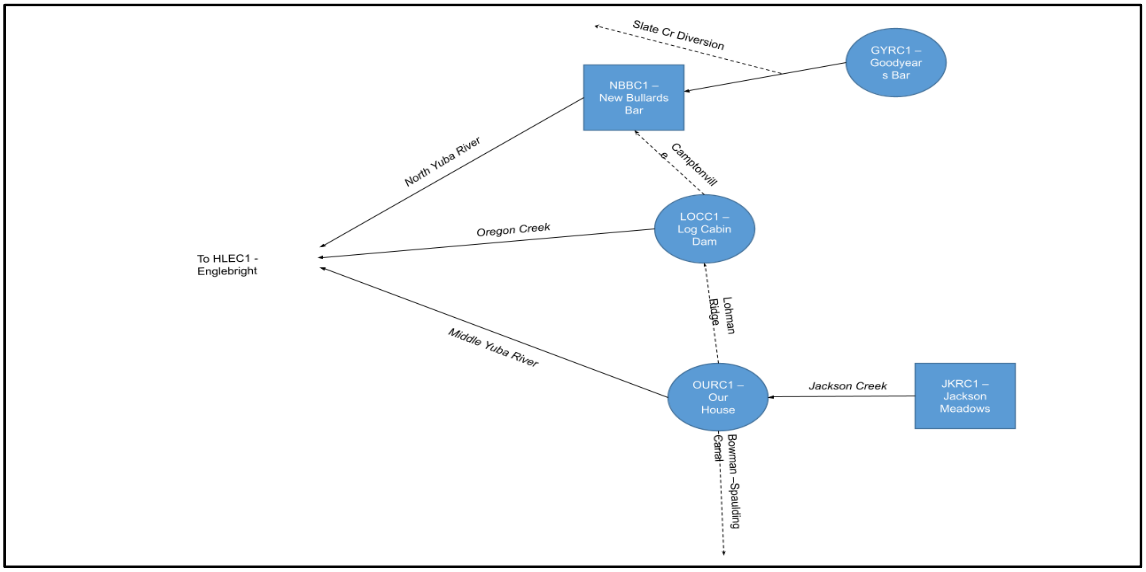


Figure N-3. *North and Middle Yuba River Topology*

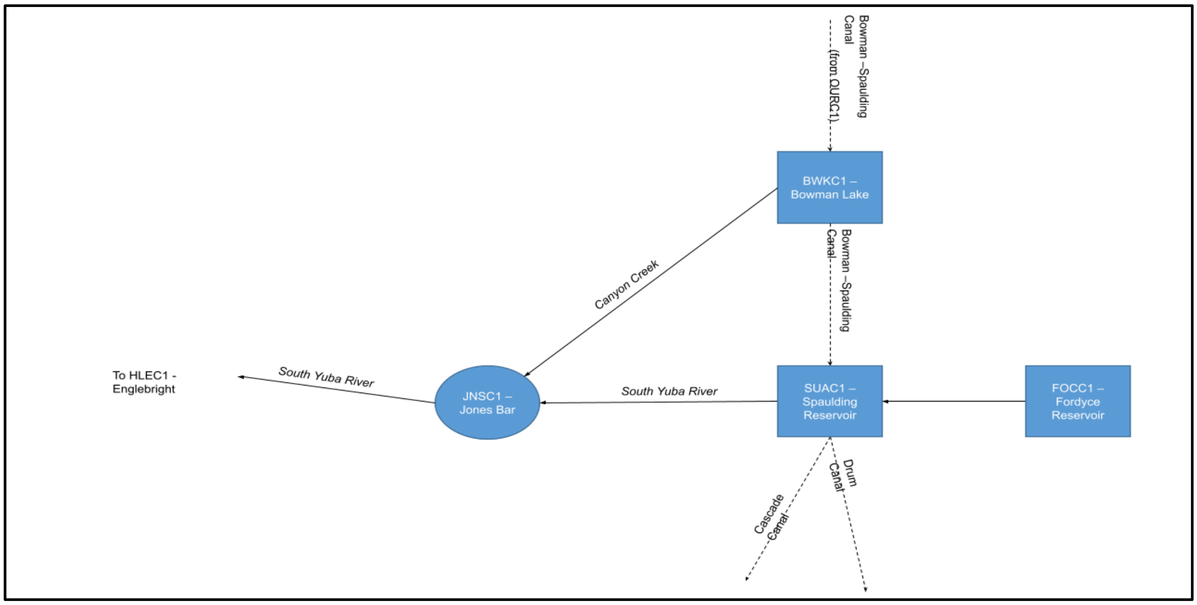


Figure N-4. South Yuba River Topology

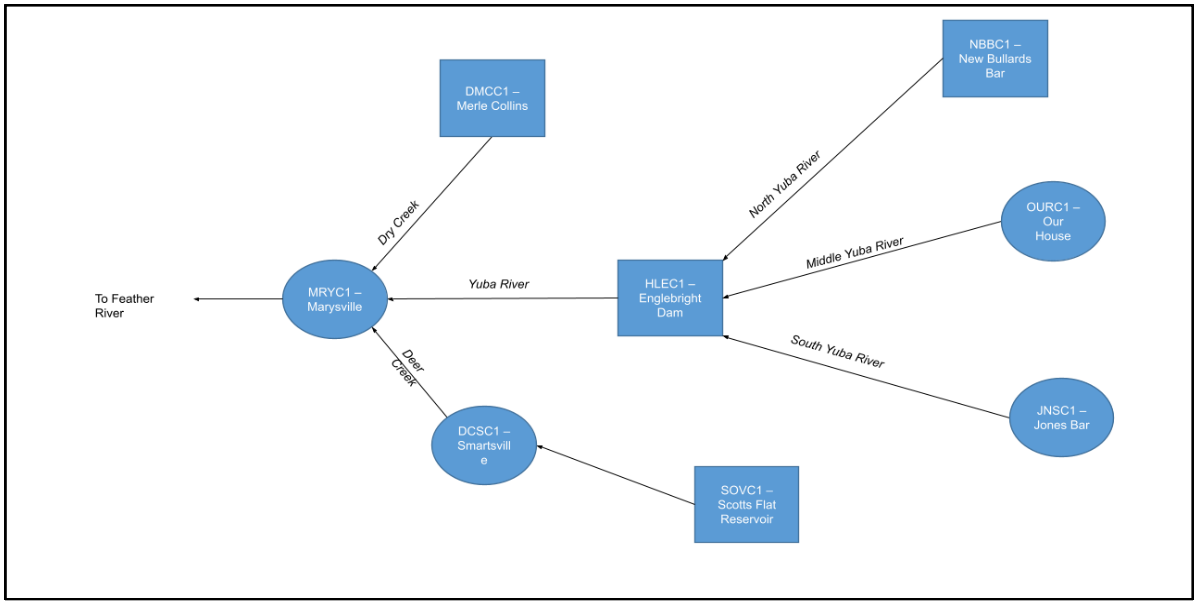


Figure N-5. Lower Yuba River Topology

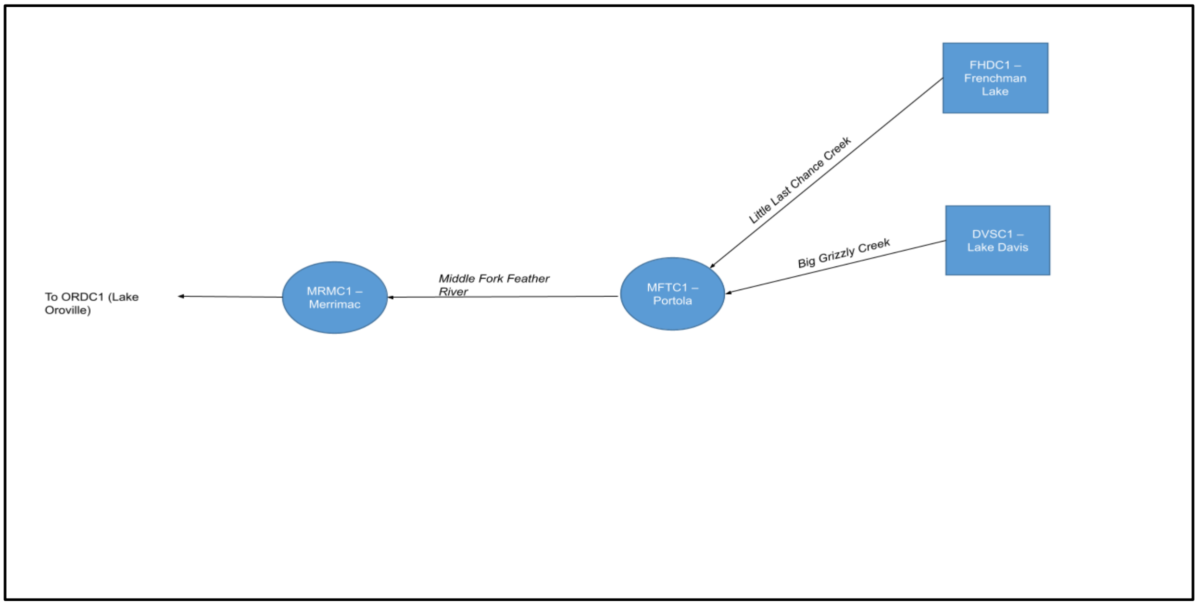


Figure N-6. *Middle Fork Feather River Topology*

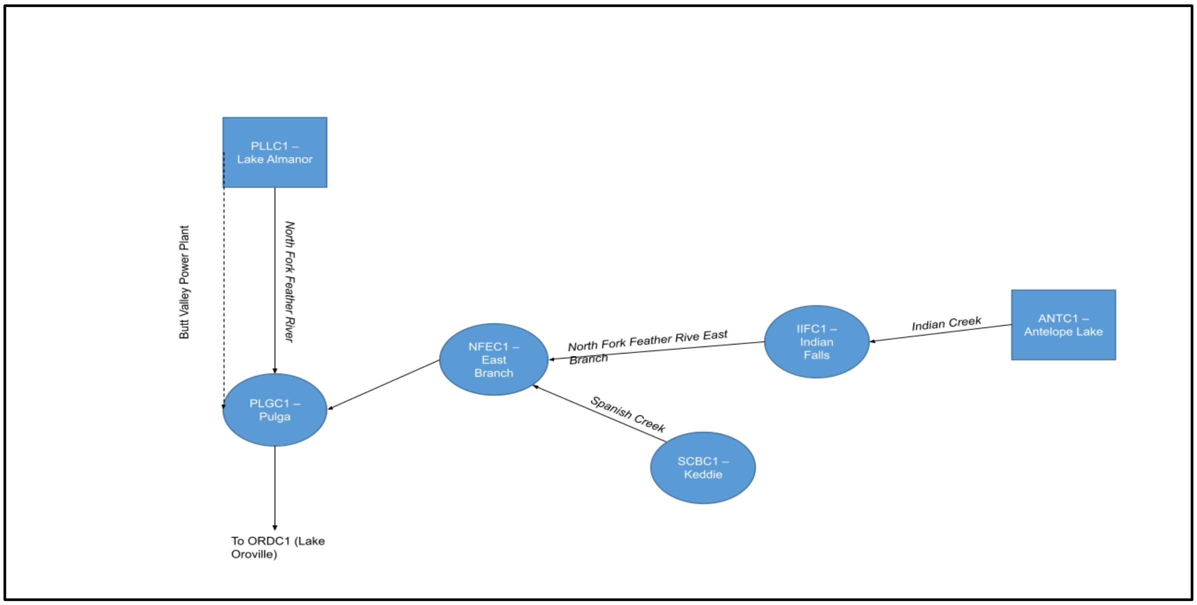


Figure N-7. *North Fork Feather River Topology*

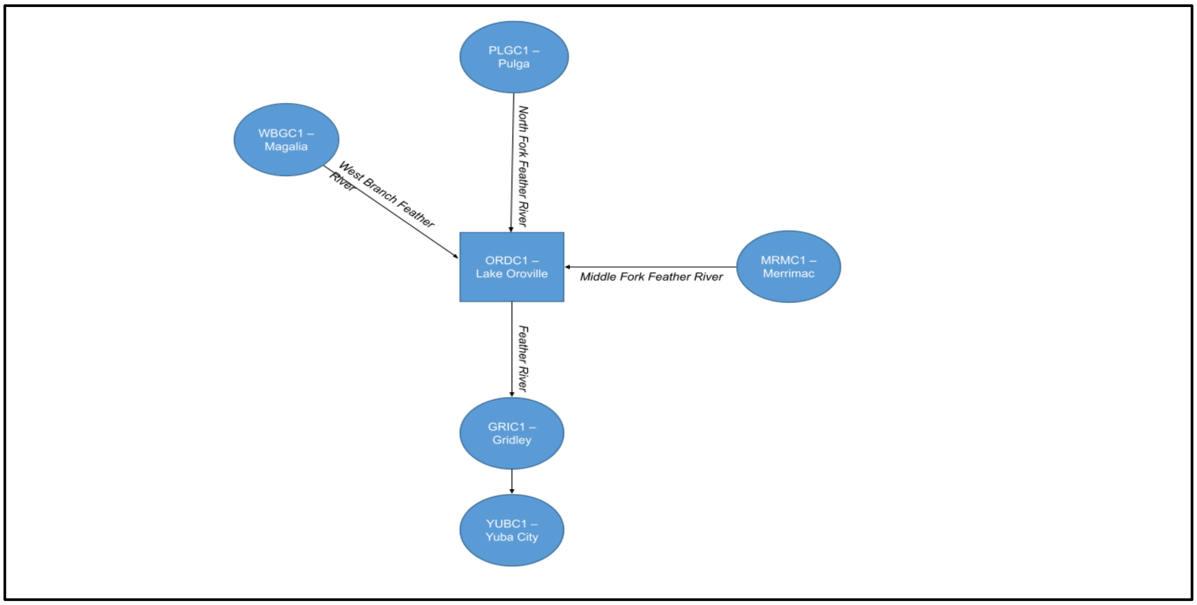


Figure N-8. *Lower Feather River Topology*

N.1.1 Hindcast Scaling Details

The dates and scale factors associated with the hindcast scaled events are in the following table:

Historical Event	Scale Window	Scale Factor Range
1986	2/15/1986@12:00GMT - 2/20/1986@6:00GMT	1.0 to 1.5 @ 0.1 increments
1997	12/29/1996@6:00GMT - 1/3/1997@0:00GMT	0.9 to 1.3 @ 0.1 increments
2006	12/27/2005@6:00GMT - 1/1/2006@0:00GMT	1.8 to 2.8 @ 0.2 increments

Appendix O—Yuba-Feather Monitoring Network Evaluation (Section 6)

The higher-level objectives of the network evaluation plan are discussed in Section 6.3. Below we have included the results of the initial evaluation that inform the observation section recommendations. The survey portions of the evaluation are to be completed as part of the FVA.

O.1 Existing Gaps in Data: Spatial and Temporal

O.1.1 Background

The monitoring network in the Yuba and Feather watersheds consists of several, independently operated meteorological and hydrological monitoring networks. Records of monitoring in these watersheds date back to the early 1900s with the development of the snow survey network and cooperative. The oldest telemetered precipitation monitoring stations date back to 1984, however there are several stations with manual entry dating back further. Many precipitation and snow stations came online in the early 1980's through advances in technology and monitoring initiatives. The network evaluation surveys, to be completes with FVA, will include additional information from key operators regarding the periods of record from their respective networks.

This initial assessment focuses on data available via the California Data Exchange Center (CDEC; cdec.water.ca.gov), however, determining what stations exist offline or on other platforms and the potential gaps they fill is also a priority for assessing monitoring efforts as we continue to evaluate their effectiveness.

The network evaluation focuses on the following observation types: Snow water equivalent (including snow surveys), snow level, precipitation amount, precipitation phase, soil moisture, and streamflow (Overview map: Fig. 6c.1-1). The spatial distribution of each observation type and the period of record of those stations are detailed in the 6c supplemental maps (6c. 6-1 - 6-4) and summarized in supplemental Table 6c. 6-3.

O.1.2 Spatial gaps: Elevation distribution

The elevational coverage of precipitation and soil moisture observations are summarized in figures 6c.1-2 and 6c.1-3 which show the hypsometric curve, the percent of land area below a specified elevation, and the number of stations per 250-m elevation band. These show a relatively even representation of elevation by the precipitation stations with 62% of stations existing between 1000m and 2250m (~80% of the watersheds' area). There are far fewer stations with soil moisture measurements (10 stations total) which are well-distributed across elevation; 80% of stations are between 1000m and 2250m.

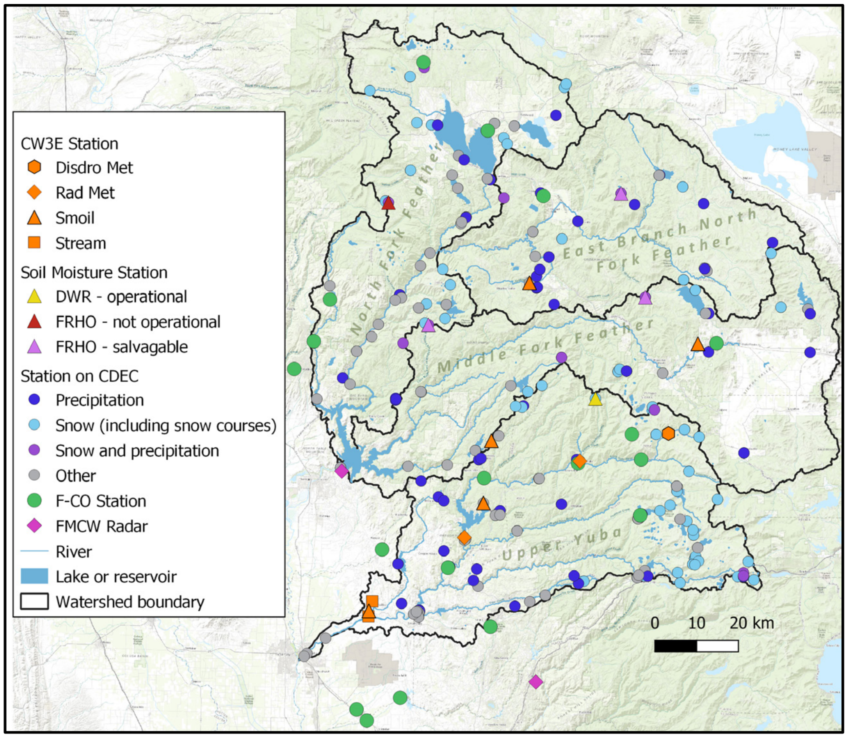


Figure O-1. *Map of monitoring station locations in the Yuba and Feather watersheds that are available online in near real time. Colors and symbols indicate observation type and network/availability.*

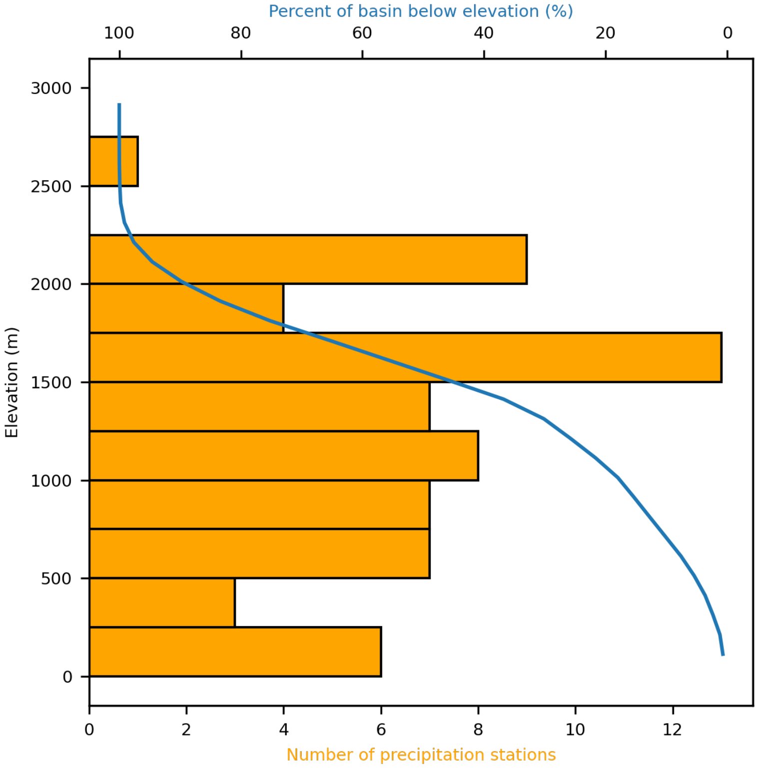


Figure O-2. *Hypsometric curve of the Yuba and Feather Watersheds showing number of real-time precipitation stations per 250-meter elevation interval.*

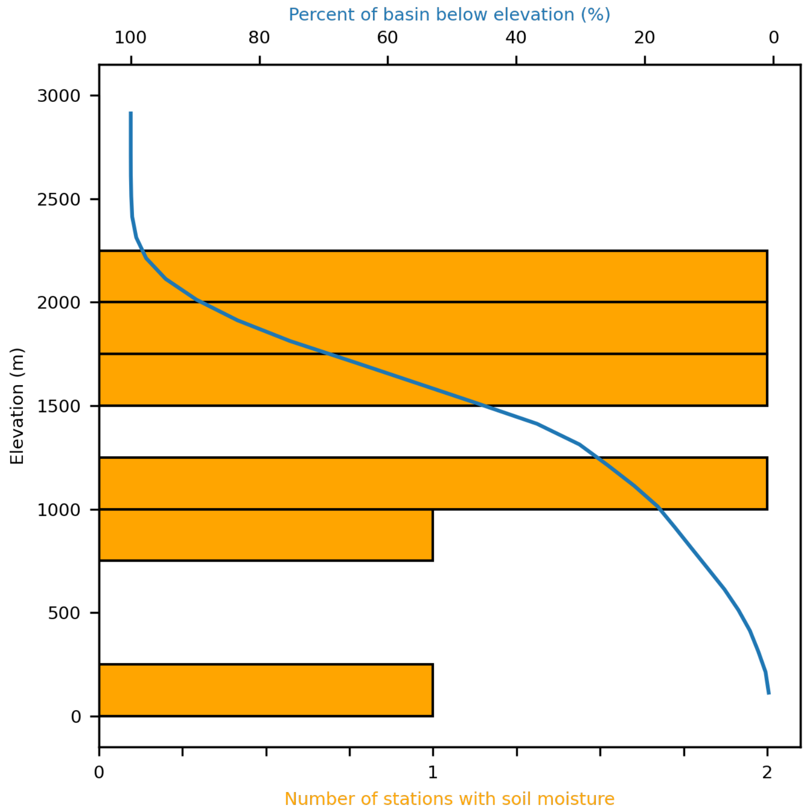


Figure O-3. *Hypsometric curve of the Yuba and Feather Watersheds showing number of real-time soil moisture stations per 250-meter elevation interval.*

O.1.3 Spatial gaps: Landscape characteristics

A K-means clustering analysis was performed to classify areas of the watershed into 6 classes with distinct characteristics (SAGA-GIS v7.1.0; Forgy, E. (1965) & Rubin, J. (1967)). The classification used elevation, aspect, and slope derived from a 3-m digital elevation model and resampled to match the 800-m resolution of the PRISM 30-year precipitation climatology for the watersheds (supplemental Table 6c. 6-1). All datasets were normalized prior to clustering to prevent bias in the results due to different ranges in each dataset. Soil type and landcover were excluded from the cluster analysis itself as the watershed is heavily forested and the categorical soil type information was compared after the fact primarily for the existing soil moisture observations.

The clusters (Fig. 6c.1-4; summarized in supplemental Table 6c. 6-2) were most distinguished by precipitation, ranging from 645 mm/yr (cluster 4) - 2050 mm/yr (cluster 5). West of the Sierra Crest, the clusters breakdown largely by elevation and precipitation, while east of the Sierra Crest, the clusters are more influenced by aspect. The clusters evenly represent basin area (12.6% (cluster 1) - 20.8% (cluster 6)).

Cluster 6, which experiences a 30-yr mean precipitation in the upper part of the range across clusters (1780 mm/yr), had the highest number of precipitation stations (16 stations; supplemental Table 6c. 6-3). The lowest number of precipitation stations was in cluster 2 (7 stations; supplemental Table 6c. 6-3) which experiences a mean annual precipitation in the middle of the range across clusters (1100 mm/yr) and is interspersed with cluster 3 grids (940 mm/yr mean) near many of these stations.

There are no soil moisture stations in cluster 2, however, adjacent clusters 3 and 4 do have soil moisture stations (supplemental Fig. 6c. 6-6). Though there are few soil moisture stations in the watershed, the existing stations represent most of the clusters as well as covering a range of gravelly loam and sandy loam soil types. However, due to the low total number of stations relative to the vast area of the watersheds, it is still strongly recommended that more stations with soil moisture are installed throughout the watersheds.

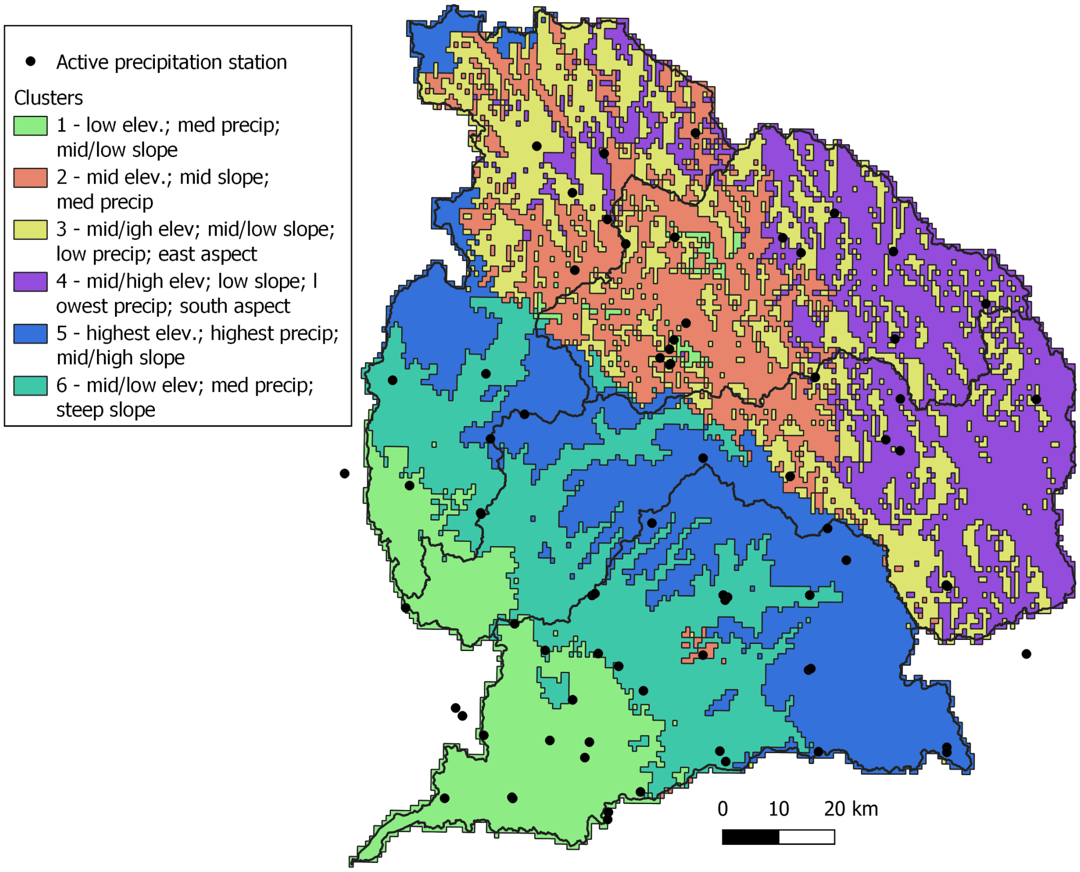


Figure O-4. *Map summarizing the clusters determined from K-means clustering of elevation, aspect, slope, and PRISM precipitation climatology at 30-m grid scale. Precipitation station locations are shown (black dots) for reference of station coverage.*

O.1.4 Precipitation decision support

The Yuba and Feather watersheds contain 3 of the 8 stations (see Fig. 6c.1-5) used in CA DWR's Northern Sierra 8-Station Precipitation Index (8SI), an important water supply indicator developed in 1920. The stations are well-distributed across the range of precipitation experienced climatologically.

The CNFRC uses one of the stations used in the 8SI as well as many stations available on CDEC and some stations from other networks (Fig. 6c.1-5). These stations are also well-distributed throughout the watersheds. It is recommended that we further investigate the reasons for exclusion of some stations from CNRFC's products.

The density of active precipitation stations was calculated using a kernel density estimation (QGIS Heatmap (kernel density estimation)). The densest areas of monitoring are in the East Branch of the North Fork Feather watershed near Quincy, CA and in the Yuba below New Bullards Bar (both areas have upwards of 8 stations per 30km^2 which includes manually entered data). These areas border the Sierra Crest, which has the highest precipitation climatologically. The lowest density monitoring areas are the northwest portion of the North Fork Feather, the western portion of the Middle Fork Feather near the Sierra Crest, and the easternmost portion of the Middle Fork Feather. Near Lassen Peak and Tásmam Koyóm (Humbug Valley) in the North Fork Feather are gaps recommended to be filled. The western portion of the Middle Fork includes mostly steep terrain in a mix of private forestry and National Forest land making it difficult to instrument. The easternmost port of the Middle Fork is largely irrigated, agricultural land and is the area with the lowest precipitation climatologically; however, these areas are still recommended to be monitored.

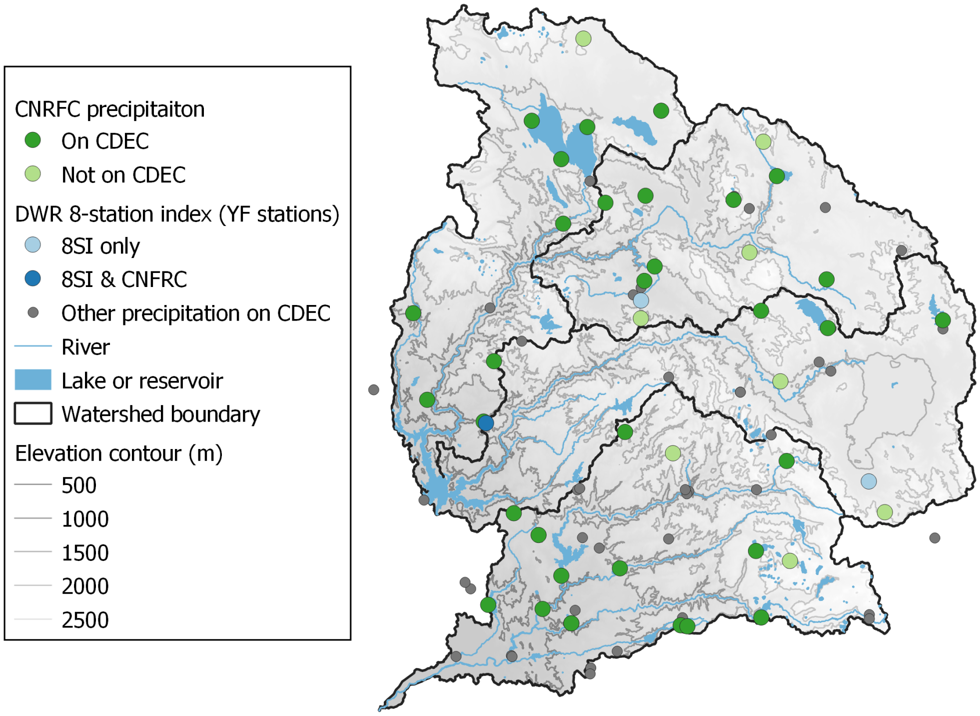


Figure O-5. *Map showing the locations of precipitation stations used by CNRFC (QPE products) and by DWR's Northern Sierra 8-Station Index.*

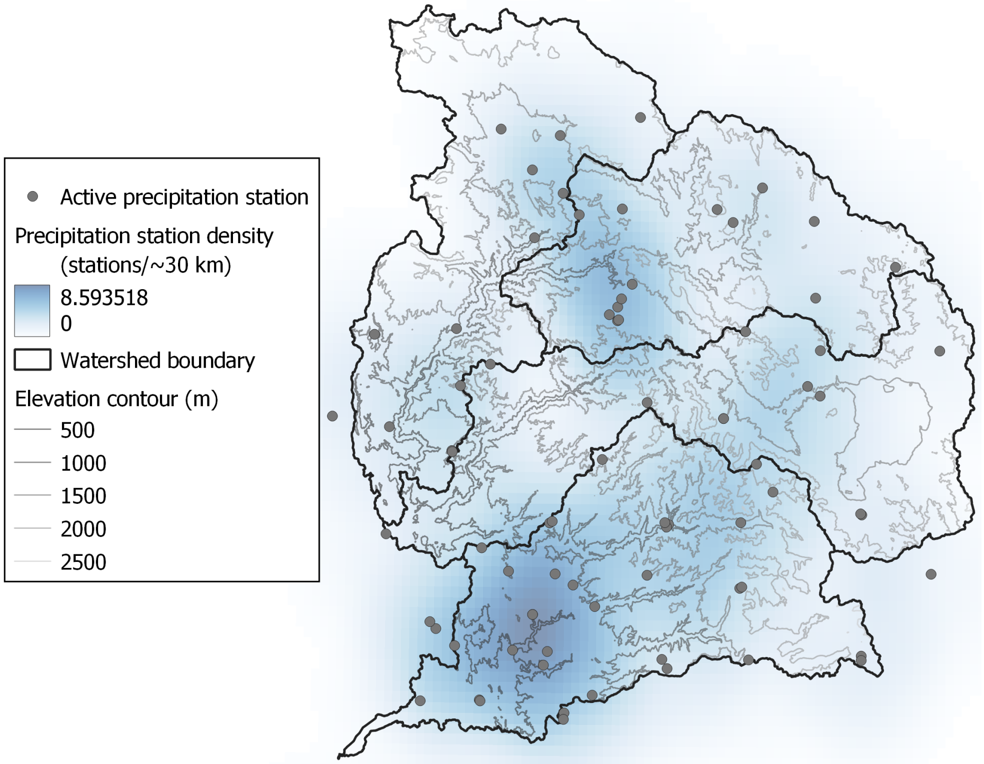


Figure O-6.*Map showing the locations of precipitation stations and the density of stations per 30 km^2 (higher density = darker blue).*

O.1.5 Precipitation time series correlation

Precipitation time series for the identified clusters were compared during 3 different AR events to determine how similar (or not) stations within each cluster were (summarized in supplemental Table 6c. 6-4). The clusters cover large areas of the basin and a combination of topography and storm track drive differences in precipitation timing and amount for a given area which likely explains why the correlations are not strong and vary widely between events. Further investigation into station performance and coverage is recommended in conjunction with verification section efforts.

O.1.6 QPF Error

Preliminary results from analysis on West-WRF QPF errors show a lack of model skill in the high elevation regions near the Sierra Crest (Fig. 6c. 1-7). This area has medium station density; however, the quality of precipitation information in the high elevations is affected by the type of gage used and whether the gage can account for frozen precipitation. It is recommended that gage type information be readily available and high elevation gages be replaced by robust, all-weather options. Additional analysis on model and forecast performance is recommended to confirm areas that require upgraded gages or additional instrumentation and to cover the Feather watershed. Further analysis is required to best quantify model errors and gaps related to soil moisture and other variables. 72-hr inflow verification and discharge observation evaluation are covered by the hydrology and verification sections.

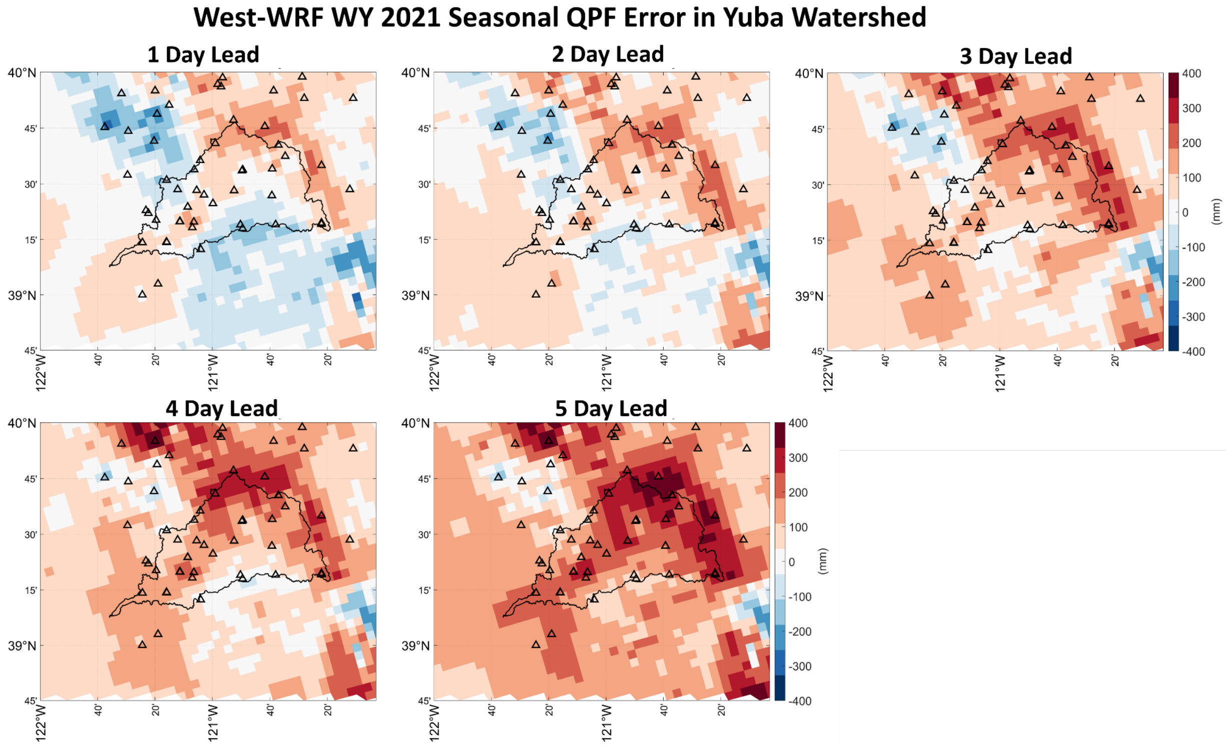


Figure O-7. *West-WRF QPF error (mm; more red = higher error) for 1–5-day lead times overlaid with precipitation station locations (hollow triangles) for the Yuba watershed.*

O.1.7 Additional observations of interest

Additional observation types have been flagged as priorities for evaluation through cross-team collaboration among PVA sections including snow albedo, precipitation phase from disdrometers, and snow level from radars. Currently there are no albedo measurements available in near real time for the Yuba and Feather, however, remote sensing products such as ASO do provide albedo data with high spatial coverage but low temporal frequency. Precipitation phase from disdrometers is a new measurement to the watersheds as of CW3E installations beginning in 2019 and the data quality are assessed in this evaluation but spatial coverage is not. Snow level data are available from the NOAA FMCW Radars: OVL (since 2012) and CFF (2008) and CW3E micro rain radars NBB and DLA since 2019. We evaluate the data quality and outages for the CW3E radars in this assessment and recommend further assessment of the FMCWs in future evaluations.

O.1.8 Temporal gaps: Resolution and period of record

15-minute data are the highest resolution available for near real time data on most online platforms and are preferred over hourly or coarser resolutions for evaluating precipitation processes and runoff generation. Due to telemetry limitations, data logger storage and age, and other factors, not all stations have data available at sub-hourly intervals. It is a priority to develop a network with high spatial coverage of 15-minute resolution data and long periods of record (10+ years).

The temporal resolution available for various observation types as well as the periods of record available for those observations are summarized in Table 6c.1-1. Periods of record for different observations are also visualized in the maps provided in the supplemental section of this report.

Table O-1. *Number of stations per observation type and temporal resolution and the average periods of record available on CDEC for those stations with near real time data available. Periods of record calculated relative to 2022.*

Observation type	Number of Stations with Event Data	Number of Stations with Hourly Data	Avg. Period of Record (years)
Precipitation	17	43	24
Snow water equivalent	11	15	29
Snow depth	5	5	14
Snow level	2	2	3
Precipitation type	2	0	2
Soil moisture	5	6	2
Streamflow	22	19	14

O.2 Issues with existing networks

Information regarding station outages and quantifying when stations are down is difficult to compile with existing resources. Some operators are able to backfill stations, which benefits the long-term usability of the data but obscures whether the data were available at the time of the event. Real time data are necessary for forecasts and decision support.

We have compiled the outage data for the CW3E Rad Met stations and compared it to the QPE of the nearest grid cell for the period of water year 2019 to June 2022. For the period of record of the DLA and NBB disdrometer data, most missing data occurred when it was not raining (DLA: 93.45%, NBB: 93.07%; Table 6c. 6-8) and sensor error indications were exclusively when it was not raining (DLA: 100%, NBB: No sensor error indications for period of record; Table 6c. 6-9). The MRRs were similarly error-free during rainy periods, with the largest percentage of missing data occurring when it was not raining (DLA: 93.16%, NBB: 90.22%; Table 6c. 6-6). Water year plots of missing data for the disdrometer and MRR at DLA and NBB show that missing data are often but not always a station-wide issue (Water 2021 example in Fig. 6c. 2-1 & Fig. 6c. 2-2). Further information from the evaluation of outages at DLA and NBB is provided in the supplemental figures and tables (Tables 6c. 6-5 - 6-9; Figures available upon request).

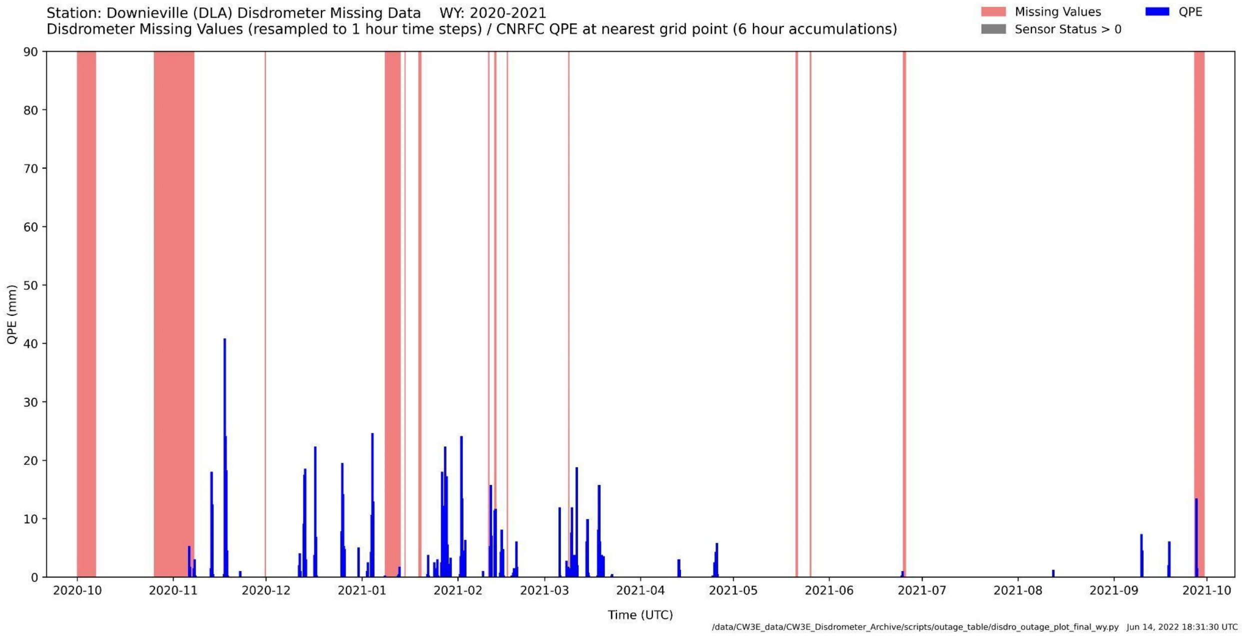


Figure O-8. *Missing disdrometer data (red shading) plotted over the time series of QPE (blue bars) from the grid cell nearest DLA for water year 2021.*

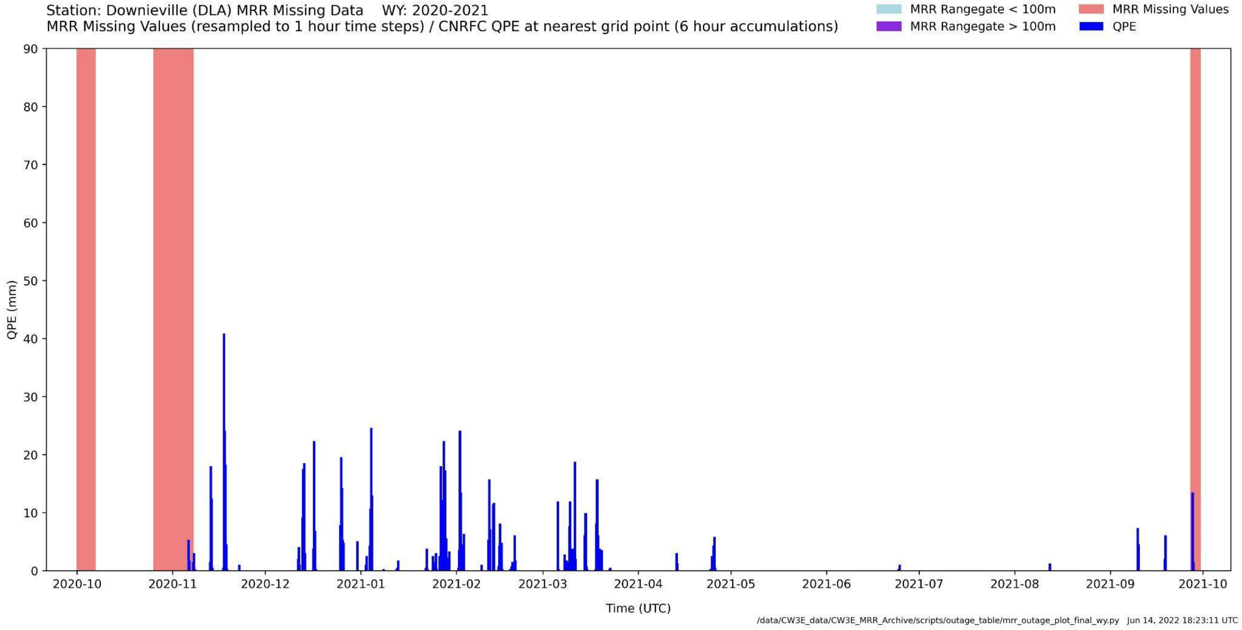


Figure O-9. *Missing MRR data (red shading) plotted over the time series of QPE (blue bars) from the grid cell nearest DLA for water year 2021.*

We will evaluate the CW3E surface meteorology and soil moisture station's outages for the FVA. To better quantify outage information from other operators and networks, the survey implemented for the FVA will assess metadata regarding outages, flagging, quality control, and backfill processes. We recommend that more clear flagging is made optional via CDEC to indicate backfilled content.

O.3 Improvements in data receipt and visualization

Data receipt and visualization will be assessed via surveys to be conducted for the FVA. The surveys will cover the following questions and topics:

- Are there any improvements needed in terms of data receipt and visualization?
    - How many stations are not hosted on CDEC?
        - Survey of all station networks in the region
        - Summary map or table depending on extent of stations not on CDEC
        - Include survey question for reasons stations are not on CDEC
    - What observation types would be beneficial to have on CDEC and in near real-time?
    - Survey questions for data visualization on CW3E website and on CDEC

The surveys will inform the recommendations of the FVA and will be available as a reference point for future evaluations of the network. A version of the survey will be distributed annually to track improvement on these subject areas.

O.4 Recent network enhancements and recommendations

The main section references the stations added by CW3E since 2019, tabulated below.

Continued network enhancements will be logged in future, annual evaluations.

Table O-2. *Observations added in support of FIRO objectives. * = not telemetered (as of July 2022). ^{S} = non-standard soil pit depths. ^{H} = Heated tipping bucket.*

Name	Watershed	Code	Latitude	Longitude	Elevation (m)	Station Type	Installation date
Skyline Harvest^{S}	Yuba	SKY	39.470969	-121.091673	833	SMOIL	Oct 2019
Northstar Meadow*	Yuba	NSM	39.605249	-121.071594	1235	SMOIL	Aug 2020
Lower Bathhouse (SFSU)^{H}	Yuba	LBH	39.624073	-120.577654	1680	Disdro Met	Oct 2020
Downieville^{H}	Yuba	DLA	39.5634	-120.8242	901	Rad Met	Oct 2019
New Bullards Bar Dam^{H}	Yuba	NBB	39.396359	-121.1437698	634	Rad Met	Dec 2019
Feather River College	Feather	FRC	39.945873	-120.969701	1044	SMOIL	Nov 2019
Marysville, Kibbe Road	Yuba	YUB	39.220808	121.482356	30	Launch	2019
Truckee radar	Martis Cr.	TRK	39.328435	120.122274	1789	MRR	Mar - June 2020
Browns Valley	Yuba	BVS	39.23586	-121.40621	71	SMOIL	Apr 2021

Name	Watershed	Code	Latitude	Longitude	Elevation (m)	Station Type	Installation date
School							
Portola	Feather	POR	39.8175	-120.4969	1509	SMOIL	Oct 2021
Sycamore Ranch*	Yuba	SYR	39.22389	-121.407016	46	Stream	Aug 2021
Little Dry Cr.*	Yuba	LDM	39.256644	-121.39706	65	Stream	Aug 2021

This iteration of the network evaluation highlights broader issues and gaps within the monitoring network, key findings include:

- Soil moisture data are lacking and many existing observations are not available in near real time. The soil moisture stations added by FIRO have increased the spatial and temporal coverage of soil moisture data available in near real time but some landscape characteristics are still not well-represented. Utility of soil moisture data requires a long period of record (3–6 years minimum; Ford et al., 2016) and is currently most useful for situational awareness and model validation.
- Precipitation stations have good spatial and temporal coverage and represent key identified landscape characteristics. Precipitation is also most useful and most readily integrable into runoff forecasts.
- All-weather precipitation gages (especially above approximately 5000 feet elevation) have the best accuracy for determining precipitation totals regardless of precipitation phase and metadata information is lacking for identifying gage types at high elevations.
- Current precipitation data quality at high elevation should be further investigated with regards to high QPF error in those regions.
- Point measurements of precipitation phase in mid-elevations (approximately 5000 feet) can validate freezing level forecasts by identifying the rain-snow transition elevation and more of these data would be useful in validation efforts.
- Snow level data, used for adjusting forecasts (nowcasting) and validating gridded datasets, would benefit from additional point measurements to add granularity.
- Precipitation phase and snow level data from CW3E stations had very little to no missing data during ARs. Further examination of outages is required to quantify error across other observation types during ARs.
- Data quality and reliability are a priority for many snow variables (snow water equivalent, albedo, density) for understanding snowmelt timing and magnitude.

We recommend the following be completed for the FVA and by future iterations of the network evaluation:

- Develop and implement the CNRFC Mountain Mapper tool to best leverage the precipitation (and ancillary) data collected from existing and newly deployed sensor networks

- Confirm and exhibit utility of newly available observation types (e.g., snow albedo, ASO, Rad Met data) to inform/validate forecasts in case studies
- Determine what monitoring stations exist offline and work with operators to make data available in near real time and more readily integratable into forecast, verification, and decision support tools
- Investigate the data quality of high elevation precipitation further and quantify the all-weather gages available to improve QPF errors
- Conduct and refine the network evaluation plan annually to accommodate partner recommendations and needs
- Plan network installation/enhancement to fill known gaps

Our recommendations are summarized further in Section 6.3 of the PVA.

O.5 References

Ford, T. W., Wang, Q., & Quiring, S. M. (2016). The observation record length necessary to generate robust soil moisture percentiles. *Journal of Applied Meteorology and Climatology*, 55(10), 2131–2149. https://doi.org/10.1175/JAMC-D-16-0143.1.

Forgy, E. (1965). Cluster analysis of multivariate data: efficiency vs. interpretability of classifications. *Biometrics* 21:768.

Rubin, J. (1967). Optimal classification into groups: an approach for solving the taxonomy problem. J. *Theoretical Biology*, 15:103-144.

O.6 Supplemental figures and tables

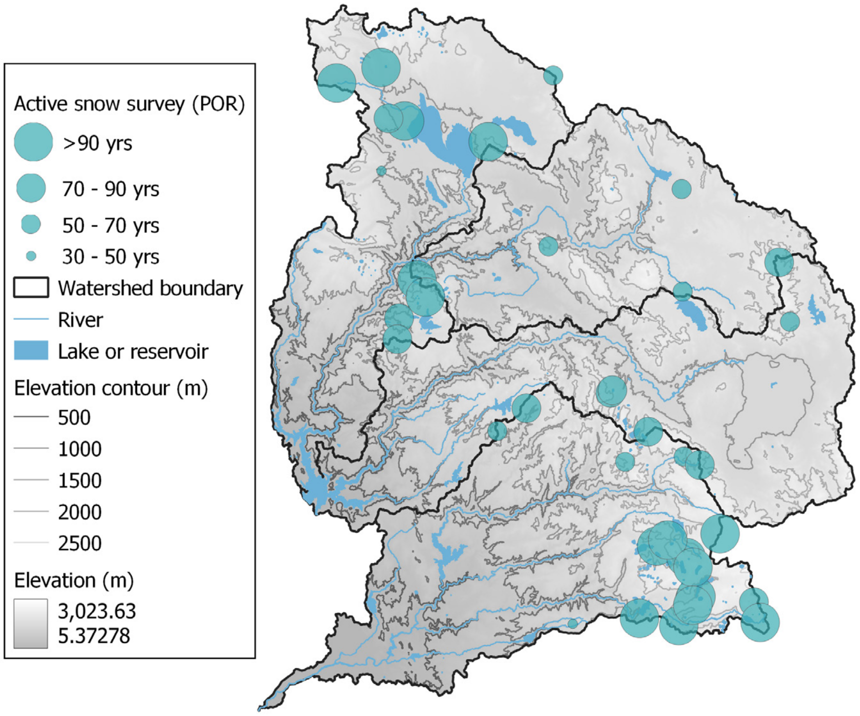


Figure O-10. *Map of period of record of active snow surveys (larger symbol = longer period of record).*

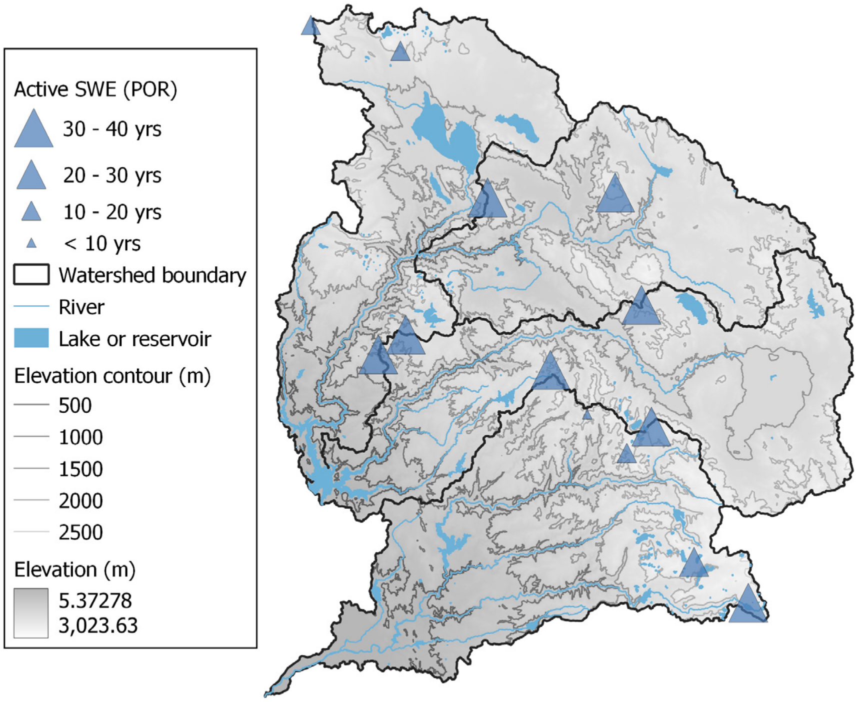


Figure O-11. *Map of period of record of active stations with snow water equivalent measurements in near real time (larger symbol = longer period of record).*

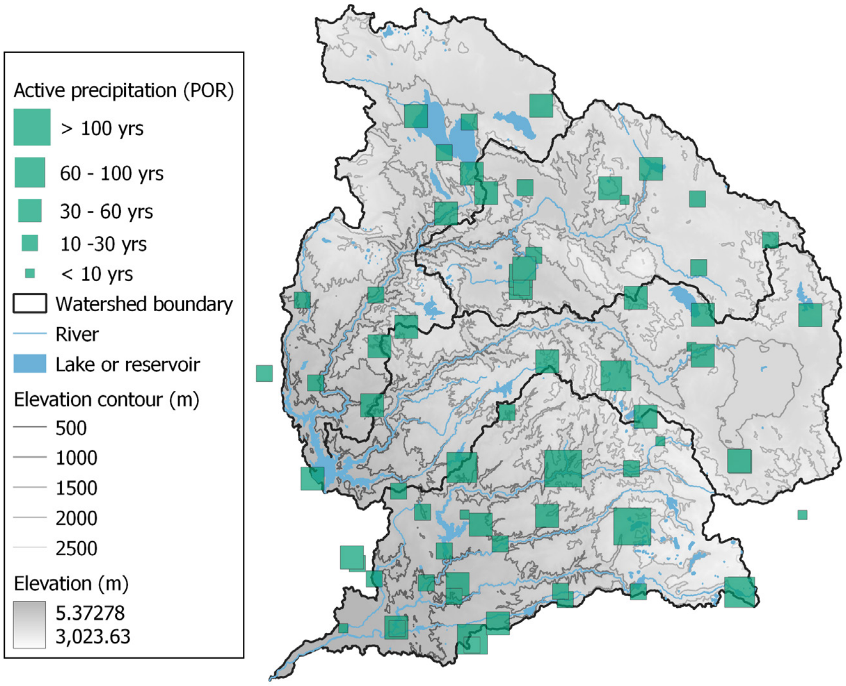


Figure O-12. *Map of period of record of active stations with precipitation measurements (manual entry and telemetered)(larger symbol = longer period of record).*

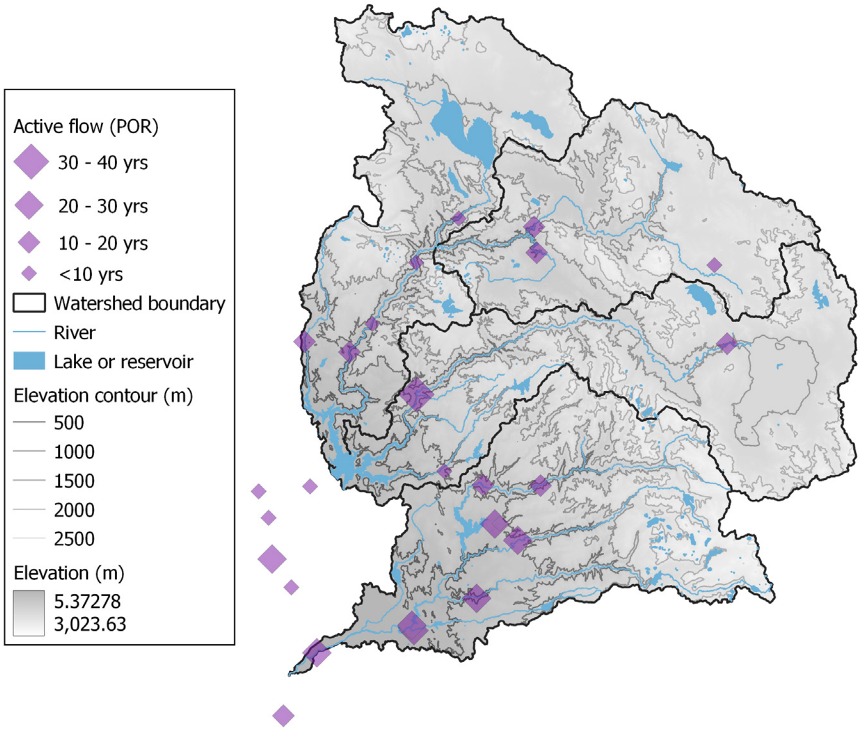


Figure O-13. *Map of period of record of active stations with discharge measurements available in near real time (larger symbol = longer period of record).*

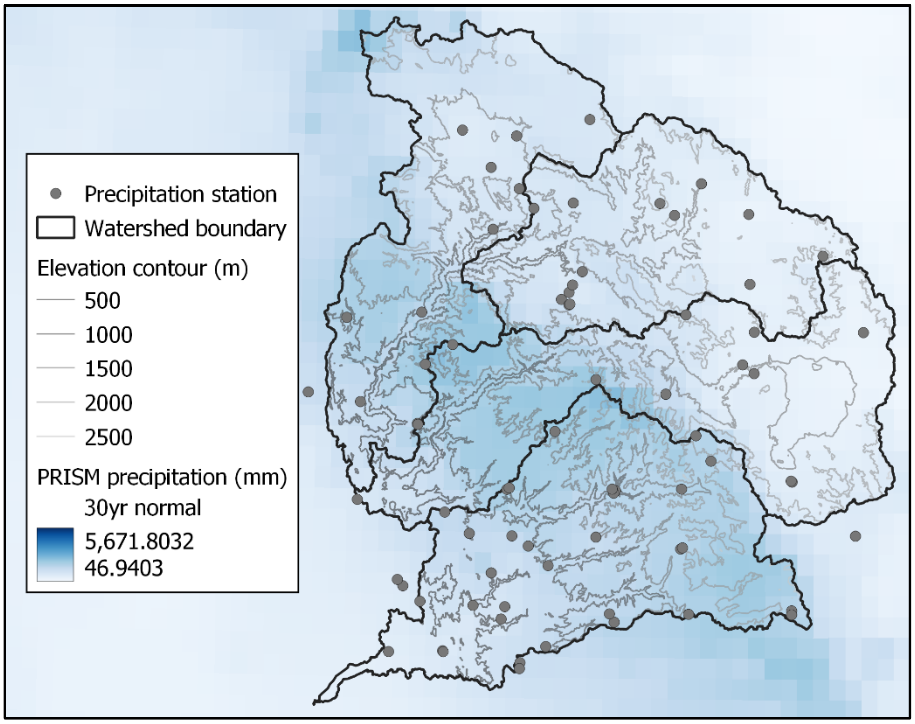


Figure O-14. *Map of active precipitation stations with PRISM precipitation climatology overlaid.*

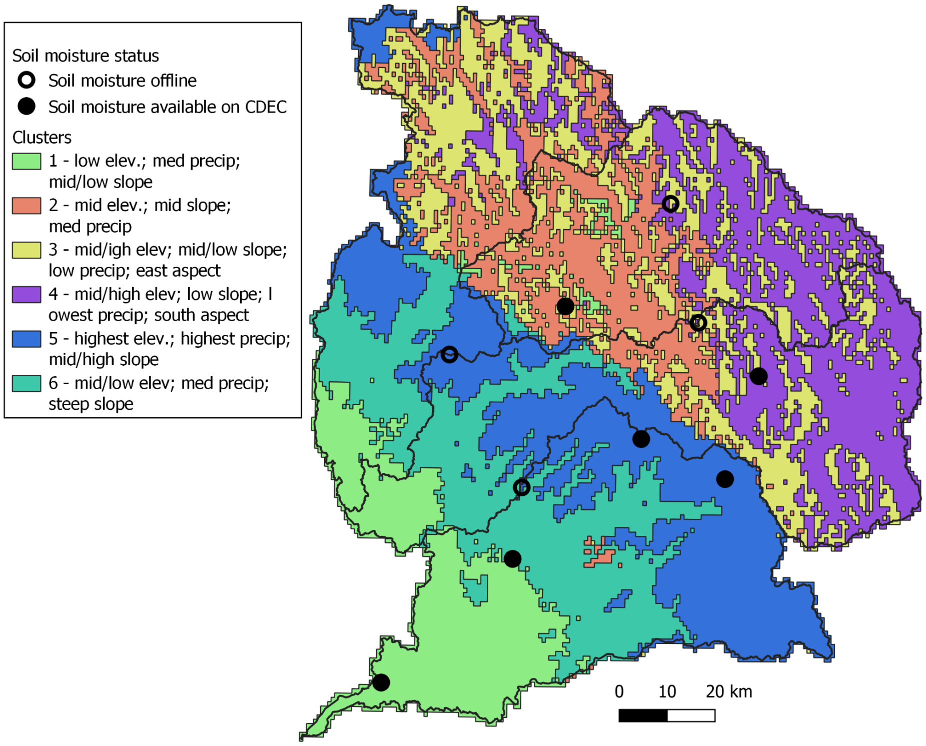


Figure O-15. *Map of clusters from cluster analysis with locations of soil moisture observations (filled = telemetered, hollow = offline).*

Table O-3. *Datasets included in the cluster analysis. Soil types were referenced but not used in the clusters.*

Variable	Resolution	Source
Total Annual Precip - 30 Year Norm	800m	PRISM
Digital Elevation Model (DEM)	3m	USGS
Slope	3m	Derived from DEM
Aspect	3m	Derived from DEM
NRCS Digital General Soil Map of U.S.	*6km*	*NRCS*

Table O-4. *Cluster characteristics.*

Cluster	% Basin area	Avg. Precip. (mm/yr)	Avg. Elev. (m)	Characteristics
1	12.6	1190	534	lowest elevation region; western-most, medium precip and lower slope
2	12.7	1100	1520	mid-elevation; mid-slope; med-low precip; eastern side
3	17.4	940	1680	mid/high elev; lower slope; med-low precip; mostly east facing
4	18.1	645	1760	mid/high elev; lower slope; lowest precip; mostly south facing
5	18.4	2050	1830	Highest elev; highest precip; mid-slope
6	20.8	1780	1120	mid/low elev: med precip; steep slope

Table O-5. *Station types and amounts per cluster from cluster analysis. These totals include stations of all temporal resolutions (event - monthly).*

Cluster #	Station type	# of stations	Percent of total station type
1	Precipitation	13	19%
	SWE	0	0%
	Snow survey	0	0%
	Soil Moisture	1	17%
2	Precipitation	7	10%
	SWE	2	15%
	Snow survey	5	13%

Cluster #	Station type	# of stations	Percent of total station type
	Soil Moisture	0	0%
3	Precipitation	15	21%
	SWE	1	8%
	Snow survey	7	18%
	Soil Moisture	1	17%
4	Precipitation	8	11%
	SWE	1	8%
	Snow survey	3	8%
	Soil Moisture	1	17%
5	Precipitation	11	16%
	SWE	9	69%
	Snow survey	22	58%
	Soil Moisture	2	33%
6	Precipitation	16	23%
	SWE	0	0%
	Snow survey	1	3%
	Soil Moisture	1	17%

Table O-6. *Correlation between precipitation time series by cluster for 3 ARs.*

Event	Cluster #	Range of correlation between stations	mean correlation between stations	# of stations used (15-min data)
Feb. 6th, 2017	1	-0.045 - 0.76	0.31	4
	2	0.27 - 0.78	0.47	4
	3	-0.099 - 0.95	0.25	8
	4	0.41 - 0.70	0.55	3
	5	0.12 - 0.83	0.6	7
	6	0.090 - 0.86	0.6	7

Event	Cluster #	Range of correlation between stations	mean correlation between stations	# of stations used (15-min data)
Feb. 14th, 2019	1	0.35 - 0.84	0.54	4
	2	0.17 - 0.56	0.41	4
	3	0.018 - 0.68	0.31	8
	4	0.44 - 0.51	0.48	3
	5	0.30 - 0.72	0.55	7
	6	0.10 - 0.82	0.44	7
Oct. 23rd, 2021	1	0.47 - 0.96	0.76	6
	2	0.55 - 0.75	0.66	3
	3	-0.048 - 0.99	0.52	8
	4	0.69 - 0.90	0.8	4
	5	0.56 - 0.98	0.76	7
	6	-0.19 - 0.96	0.48	8

Table O-7. *Number of total minutes vs. the number of missing minutes for DLA and NBB MRRs.*

Station	Total Minutes	Num Missing Minutes	% Missing Minutes
DLA	1340640	77610	5.79%
NBB	1291680	86870	6.73%

Table O-8. *Percent of missing minutes binned by QPE (ex. of all missing values, what % occurred when QPE=0, etc.) for DLA and NBB MRRs.*

Station	QPE=0mm	0-10mm	10-20mm	20-30mm	30-40mm	40-50mm	50-60mm
DLA	93.16%	5.42%	0.99%	0.42%	0.00%	0.00%	0.00%
NBB	90.22%	8.54%	1.24%	0.00%	0.00%	0.00%	0.00%

Table O-9. *Number of total time steps vs. the number of missing time steps for DLA and NBB disdrometers.*

Station	Total Time Steps	Num Missing Time Steps	% Missing Time Steps
DLA	5685120	448273	7.89%
NBB	7076160	198026	2.80%

Table O-10. *Percent of missing time steps binned by QPE (ex. of all missing values, what % occurred when QPE=0, etc.) for DLA and NBB disdrometers.*

Station	QPE=0mm	0-10mm	10-20mm	20-30mm	30-40mm	40-50mm	50-60mm
DLA	93.45%	5.75%	0.68%	0.08%	0.02%	0.01%	0.00%
NBB	93.07%	5.71%	1.16%	0.00%	0.05%	0.00%	0.00%

Table O-11. *Percent of sensor status 1–3-time steps binned by QPE (ex. of all sensor error values, what % occurred when QPE=0, etc.) for DLA and NBB disdrometers. NBB unavailable because no sensor errors occurred.*

Station	QPE=0mm	0-10mm	10-20mm	20-30mm	30-40mm	40-50mm	50-60mm
DLA	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
NBB	--	--	--	--	--	--	--

Appendix P—Weather and Water Forecast Verification: Comprehensive Review (Section 6)

Forecast verification of atmospheric river characteristics and impacts in the Yuba/Feather region

P.1 Introduction

The Yuba/Feather FIRO program is fundamentally grounded in the idea that utilization of high-quality forecast information could help to better make decisions about water storage and releases of reservoirs at Oroville and New Bullards Bar reservoirs without further increasing risk to public safety and resources. Thus, a thorough knowledge of the quality of the forecast information affecting runoff generation and inflows into the reservoirs is a critical step for potential FIRO implementation.

This section captures the forecast evaluation and verification of AR-related atmospheric and hydrologic characteristics relevant for FIRO in the Yuba/Feather watershed. Using a verification framework that takes into account decisions on the appropriate datasets, time scales, metrics, and tools appropriate for describing forecast skill under AR conditions, we evaluated forecasts over available periods of records for each model and observation source. The baseline skill describes to the best ability, the long-term predictability of AR and hydrologic characteristics aggregated over relevant time scales. Additionally, we provided examples of individual events or cases in which research directions for the FVA could be derived.

P.2 AR landfall error

Landfall position of an atmospheric river is a key indication for the onset and location of extreme precipitation in California. Landfall represents the “first stage” of forecast error as the AR plume propagates onshore and is one of the measures used to describe the large (synoptic) scale forecast predictability. The aim of this subtask is to provide a baseline assessment of landfall error of ARs impacting the Yuba/Feather region over several decades.

Landfall error was evaluated using integrated vapor transport (IVT) from 34 years (1985-2018) of West-WRF reforecasts. The reforecast is used in this case because the configuration of the models used to generate and initialize the forecasts are static; therefore, the forecast skill represents the AR predictability through time and not model improvements over time. The 1–5-day lead time forecasts were compared to the ECMWF v5 reanalysis (ERA5) throughout the cold season (December through March). ARs are defined as contiguous areas (objects) of IVT above a given threshold using the Method for Object-based Diagnostic Evaluation (MODE, Davis et al, 2009). ARs are subdivided by two sets of IVT thresholds; a threshold of 250 kg m^{-1} s^{-1}, which require objects to have a minimum length of 2000 km, and 500 kg m^{-1} s^{-1}, which require objects to have a minimum length of 1500 km (DeHaan et al, 2021). Note that the ARs that satisfy the 500 kg m^{-1} s^{-1} threshold generally also satisfy the conditions for the 250 kg m^{-1} s^{-1} threshold, and so the statistics computed for the higher threshold ARs also include the lower threshold ARs.

Landfall is defined when any part of the AR object is within a quarter degree of the coastline. The landfall position is defined as the latitude with the highest IVT (i.e., core of the AR). When both the reanalysis and the reforecast have a landfalling AR, the error in position is defined simply as the difference between the two. In order to focus on ARs that affect the Yuba/Feather water basin, the metrics presented here only consider ARs that make landfall between 35.5 and 38.5 degrees north (Ricciotti and Cordiera, 2022).

Figure P-1 shows a performance diagram (Roebber, 2009) for forecasted landfalling ARs, where a hit is defined as an instance where both the forecast and the reanalysis have landfalling AR objects. The probability of detection (POD) for landfalling ARs at the 250 kg m^{-1} s^{-1} threshold and 24-hour lead time is over 0.95, that is, 95% of the observed IVT objects were correctly matched to a forecast object at the time of landfall. The success ratio, or the fraction of correctly matched AR objects at the time of landfall to the total number of forecasted objects at 24-hr lead time, is approximately 0.9 (i.e., false alarm ratio of 0.1). Both of these metrics steadily fall with increasing lead time to a POD of 0.65 and success ratio of 0.8 at 168 hours. The metrics for the 500 kg m^{-1} s^{-1} threshold is lower than that of the 250 kg m^{-1} s^{-1} threshold at every lead time. The critical success index (CSI) is greater than 50% for all lead times using a threshold of 250 kg m^{-1} s^{-1}, whereas the CSI for the 500 kg m^{-1} s^{-1} threshold is 50% or greater only up to 96 hours lead time. This likely means that higher intensity ARs are contributing to a greater degradation in hit rate, given the overlap of 500 kg m^{-1} s^{-1} objects within the 250 kg m^{-1} s^{-1} threshold. While the difference in metrics between the two thresholds at 24-hour lead time is relatively small, the difference at 168 hour lead time is much larger, with the higher threshold having a POD of only 0.45 (i.e. only 45% match between forecast and observations) and a success ratio of less than 0.6. Note, at a 24-hour lead time over the 34-year record there are 186 landfalling ARs at the 250 kg m^{-1} s^{-1} threshold, while there are only 30 landfalling ARs at the 500 kg m^{-1} s^{-1} threshold in the selected latitude band. At 168-hour lead time the number of landfalling ARs at 500 kg m^{-1} s^{-1} is only 16. This suggests higher intensity ARs are likely under forecasted (i.e., miss) at long lead times.

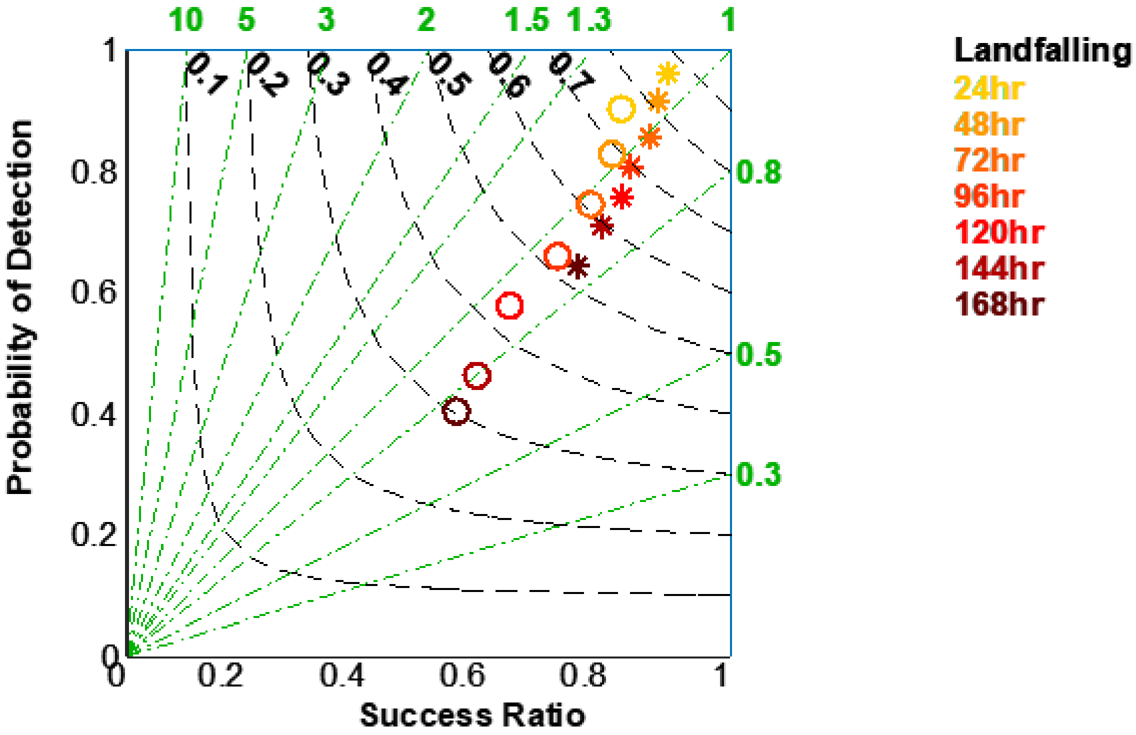


Figure P-1. *Performance diagram for existence of landfalling ARs for the 250 kg m^{-1} s^{-1} threshold (asterisks) and the 500 kg m^{-1} s^{-1} threshold (circles) at lead times from 24 hours to 168 hours. The green radial lines are the frequency bias, and the curved black lines are the threat score.*

When AR objects are correctly matched at the time of landfall (i.e. hit), the average position error for the ARs with a 250 kg m^{-1} s^{-1} threshold at a 24-hour lead time is 160 km, while the average error for the ARs with a 500 kg m^{-1} s^{-1} threshold at the same lead is 125 km (Figure P-2). At 144-hour lead time, the average errors have increased to 435 km and 345 km, respectively. As noted above, there are fewer ARs at the higher threshold, which leads to the larger confidence interval, shown in the shading. The difference between the contingency table metrics (shown in Figure P-1) and the landfall position error suggests that while the forecast is less likely to predict the existence of a stronger landfalling AR, if it does predict the existence of a stronger AR, it is more likely to correctly position that AR.

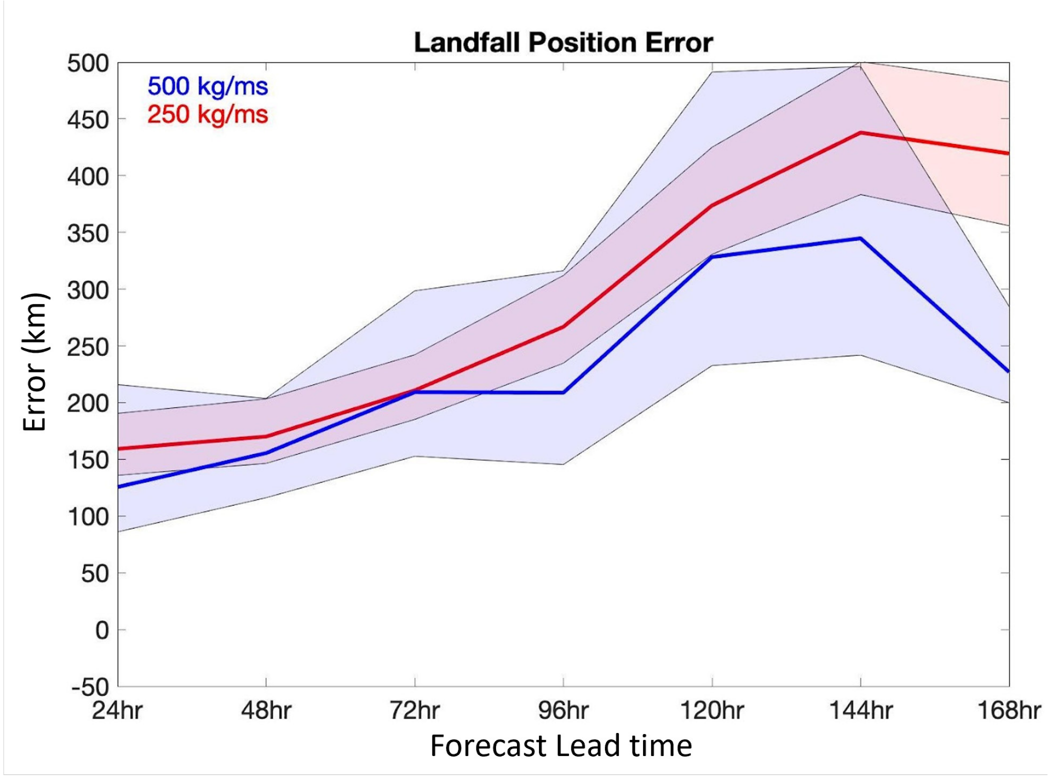


Figure P-2. *Average landfall position error for ARs at the 250 (red) and 500 (blue) kg* m^{-1} s^{-1} *thresholds. The shading indicates the 90% confidence interval computed with bootstrapping.*

P.2.1 72-hr mean areal precipitation error

The aim of this subtask is to provide a baseline assessment of precipitation forecasts in the Yuba/Feather region over several decades. The accumulation period of 72 hours encapsulates the mean AR duration in Northern California, and therefore more adequately represents event total precipitation, and is consistent with Central Valley Hydrology (Department of Water Resources, 2015) for hydrologic time scale impacts from precipitation. (See section 1.1.1.4).

Precipitation forecasts from the Global Ensemble Forecast System (GEFS) version 10 reforecast, hereafter GEFSv10, the GEFS version 12 reforecast, hereafter GEFSv12, and the West-WRF 3-km reforecast, hereafter WWRF are compared and skill is assessed within the cool season between December and the following March. For the GEFS models the ensemble mean is used as the predictor of the basin MAP. We compare the MAP as a method to understand the hydrologic implications particularly in these two mountainous watersheds (i.e., Feather, Yuba). This follows the methodology described by Brown et al. (2014), where the GEFS ensemble mean grid point(s) nearest the watershed of interest is used in a pre-processor Meteorological Ensemble Forecast Processor (MEFP) to force a set of hydrologic ensembles used in the Hydrologic Ensemble Forecast Service (HEFS). These hydrologic ensemble predictions are input to the Ensemble Forecast Operations (EFO) model (Delaney et al. 2020) for FIRO decision support.

The GEFSv10 ensemble mean was available on a 1° grid and processed using the 1° grid box(es) (red rectangle) centered nearest the individual watersheds as shown in Figure P-3. For the Yuba watershed, the 1° grids split the watershed. Thus, the MAP had to be calculated based on the percent area of the sub-basins falling within each grid box. Sub-basins are shown as cyan lines in Figure P-3. The GEFSv12 MAPs for each watershed were calculated by sub-basin by the CNRFC and provided to CW3E. The percent area of each sub-basin to the total watershed was also provided. From this information, the total watershed MAP was computed.

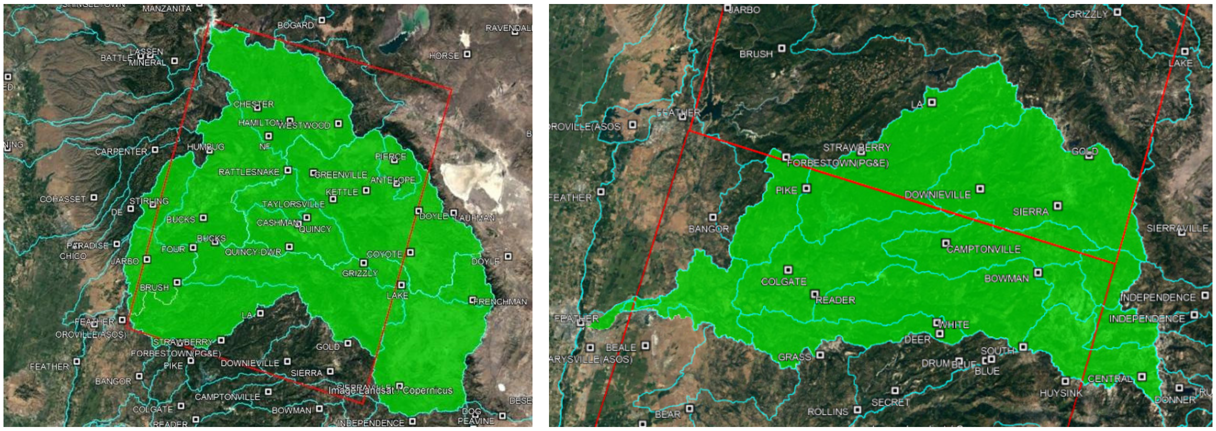


***Figure P-3**. Feather (left) and Yuba (right) basin watersheds shaded in green with the 1° GEFSv10 grid used outlined in red. See text for explanation of treatment of grid box averaging for the Yuba for GEFSv10. CNRFC reference gauges used for computing mean areal precipitation (MAP) are identified. Cyan lines are the CNRFC sub-basins for the GEFSv12 MAPs.*

The WWRF reforecasts are a dynamical downscaling of the GEFSv10 control run and studied to determine if there is value added in MAPs generated at high resolution as a more skillful input to the MEFP for HEFS execution (Cobb et al., in preparation). The WWRF data were processed using HUC8 shapefiles (shaded objects in Figure P-3) that define the watershed boundaries. All model grid points falling within the shapefiles are averaged for each 6-hr period matching the GEFSv10/12 to arrive at the basin MAP. The individual 6-hr forecasts available for each model (20 for WWRF and 64 for the GEFS runs) were combined into 3-day MAP forecasts for days 1-3 to days 14-16 for the GEFS, and days 1-3 to days 5-7 for WWRF.

The qualitative precipitation estimate (QPE) is derived by the CNRFC via quality-controlled gauge data mapped to a 4-km HRAP (Hydrologic Rainfall Analysis Project) grid using index gauges across the watershed. The HRAP is derived using the Mountain Mapper algorithm (Henkel and Peterson 1996) and the index gauges shown in Figure P-3. The algorithm is based on interpolation of the reference gauge information to non-gauge locations adjusting for orography using PRISM (Parameter-elevation Relationships on Independent Slopes Model; Daly et al. 1994). An MAP is computed by averaging the grid points within each of the sub-basins defined for the given watershed. Each sub-basin's MAP is weighted by its areal percentage of the entire watershed and then summed to arrive at the watershed MAP. The MAPs are in 6-hr intervals beginning at 12 UTC each day. These values have been error checked by the CNRFC. To arrive at 72-hr totals the individual 6-hr MAPs are summed from 00 UTC Day 1 to 00 UTC day 4, or 12 6-hr periods.

The precipitation forecasts were evaluated between December 1989 and March 2017. Note, each forecast model configuration is static; however, the forcing of the GEFS forecasts changes around 1999. The metrics evaluated were the coefficient of determination (R2), the root mean square error (RMSE), bias, the symmetric extremal dependence index (SEDI; Ferro and Stephenson 2011), and the Heidke skill score (HSS; Jolliffe and Stephenson 2011). The SEDI is a skill score used for extreme events. It can vary from 1 to -1, with 1 being perfect (hit rate of 1 and false alarm rate of 0), and negative values representing worse than random chance. The HSS varies from 1 to $-\infty$, with 1 being a perfect categorical forecast and negative values no better than chance. The 90th percentile 72-hr observed Dec–Mar MAP for the period of record (1989–2017) was used as a threshold for the SEDI and HSS metrics.

Figure P-4 and Figure P-5 show the results for the Feather and Yuba basins using the coefficient of determination (R2, columns), RMSE (filled markers), and bias (unfilled markers) for the two watersheds shown in Figure P-3 for the GEFSv12 (blue), WWRF (red), and GEFSv10 (green). Each metric for each model has 95% confidence intervals shown. For the Feather (Figure P-4), there is no statistical difference in the GEFS R2 values for any lead time. The WWRF shows a slight improvement for days 1-3. If one uses a value of R2 ≥ 0.5 as a threshold for reasonable association (Murphy 1995) (i.e., the forecasts explain ≥ 50% of the variance in observed 3-day MAP), then days 6-8 marks this threshold for both GEFSv10 and GEFSv12. The RMSE results indicate the WWRF has a higher RMSE for days 2-4 and days 3-5 compared to both GEFS runs, with the GEFSv12 RMSE trending higher than GEFSv10 beyond days 7-9. The difference however is not statistically significant. The bias results show all three models with a high bias through days 4-6, with WWRF indicating a statistically significant higher bias compared to both GEFS versions through days 3-5. After days 6-8, the GEFSv10 has a statistically significant negative bias. GEFSv12 shows little bias through days 14-16.

For the Yuba (Figure P-5), the results for R2 are very similar to the Feather both in model comparisons and where values drop below 0.5. For RMSE, the WWRF does show a statistically significant higher RMSE compared to GEFSv12 for days 2-4 and days 3-5, while the GEFSv12 trends slightly higher for RMSE compared to GEFSv10 beyond days 8-10 but with no statistical difference. There is however a significant difference in bias between the three models. WWRF and GEFSv12 both show a high bias through days 3-5 and days 7-9, respectively, with WWRF's high bias statistically higher compared to GEFSv12. GEFSv10 shows a statistically significant negative bias for all 3-day periods. This difference in bias is most likely a result of the resolution differences between the GEFSv10 (1°), GEFSv12 (0.25-0.50°), and WWRF (3 km). Both the Feather and Yuba make up some of the wettest watersheds in the Sierra Nevada, and these results are consistent with other studies showing that higher resolution numerical guidance over-estimates precipitation in the Sierra Nevada (Caldwell et al. 2009; Hughes et al. 2020).

Figure P-6 and Figure P-7 show the results for the more extreme rainfall events that exceed the 90th percentile of 3-day observed MAPs for Dec–Mar 1989–2017. The threshold value was 2 inches/3 days for the Feather and 2.5 inches/3 days for the Yuba. There were 367 observed events for the Feather and 365 for the Yuba. Given these relatively small sample sizes, the 95% confidence intervals for SEDI and HSS are large and thus the results show little statistical difference between the three models. There is a tendency for the WWRF and GEFSv12 to perform better than GEFSv10 in the Yuba watersheds through days 3-5 for the SEDI score. This tendency is not seen in the Feather. There is a tendency for the GEFSv12 to outperform GEFSv10 beginning on days 6-8 for the Feather and for all periods for the Yuba using the HSS, but the HSS differences are not statistically significant except on days 11-13. Although the differences in these scores are not generally statistically significant, they do suggest the higher resolution models (i.e., WWRF and GEFSv12) outperform the GEFSv10 in the Yuba for the more extreme events. This is not as clear in the Feather.

It is important to note that the long accumulation time and smoothing (aerial averaging) of the precipitation within the watershed broaden the target for precipitation skill. Additional analysis, including shorter aggregation times, may better demonstrate differences across the models.

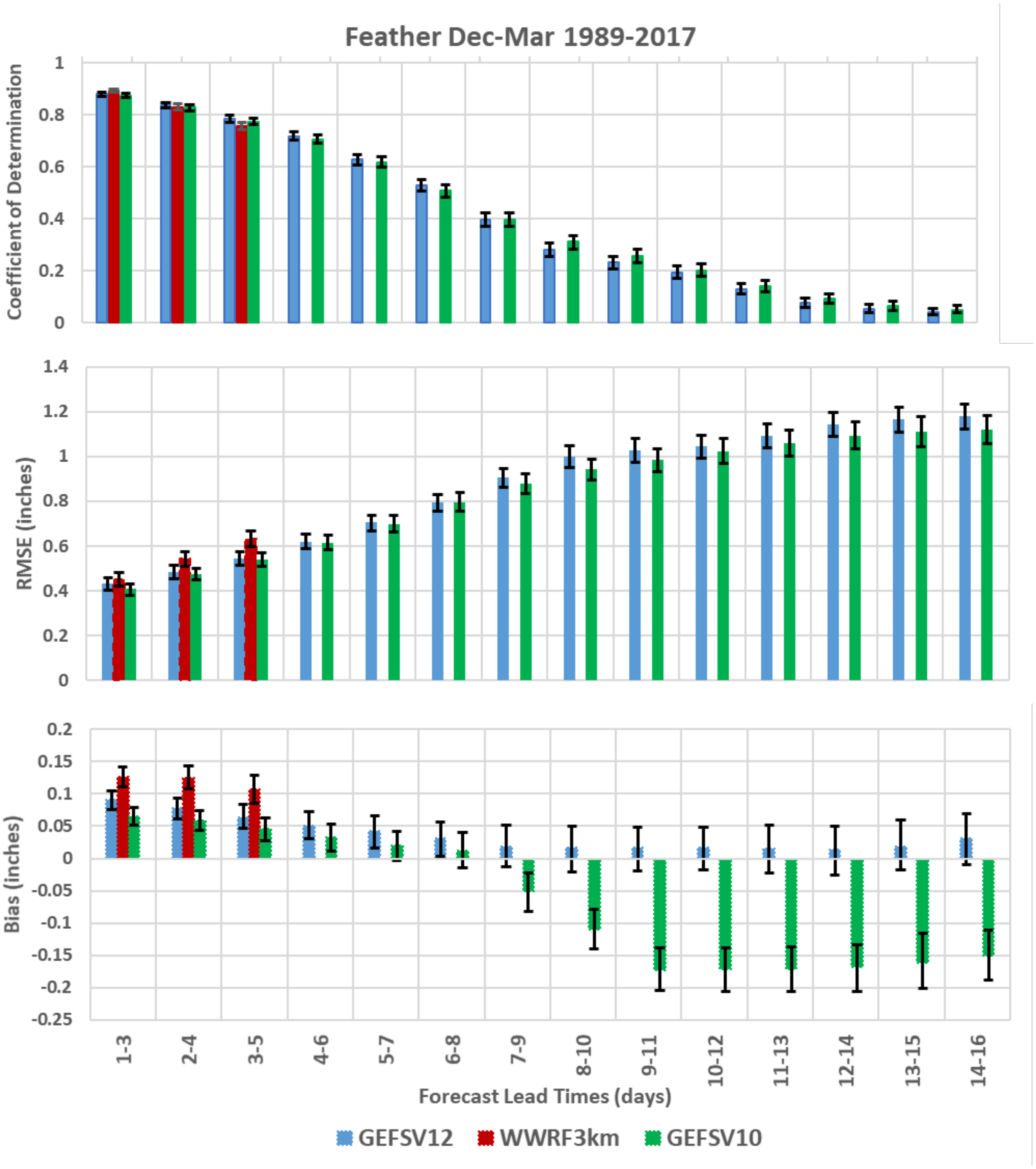


Figure P-4. *Coefficient of determination, RMSE (in), and bias (in) for 72-hr MAP for the GEFSv12 ensemble mean, WWRF 3-km, and GEFSv10 ensemble mean for the Feather watershed for the period December through March 1989-2017. Error bars denote 95% confidence intervals.*

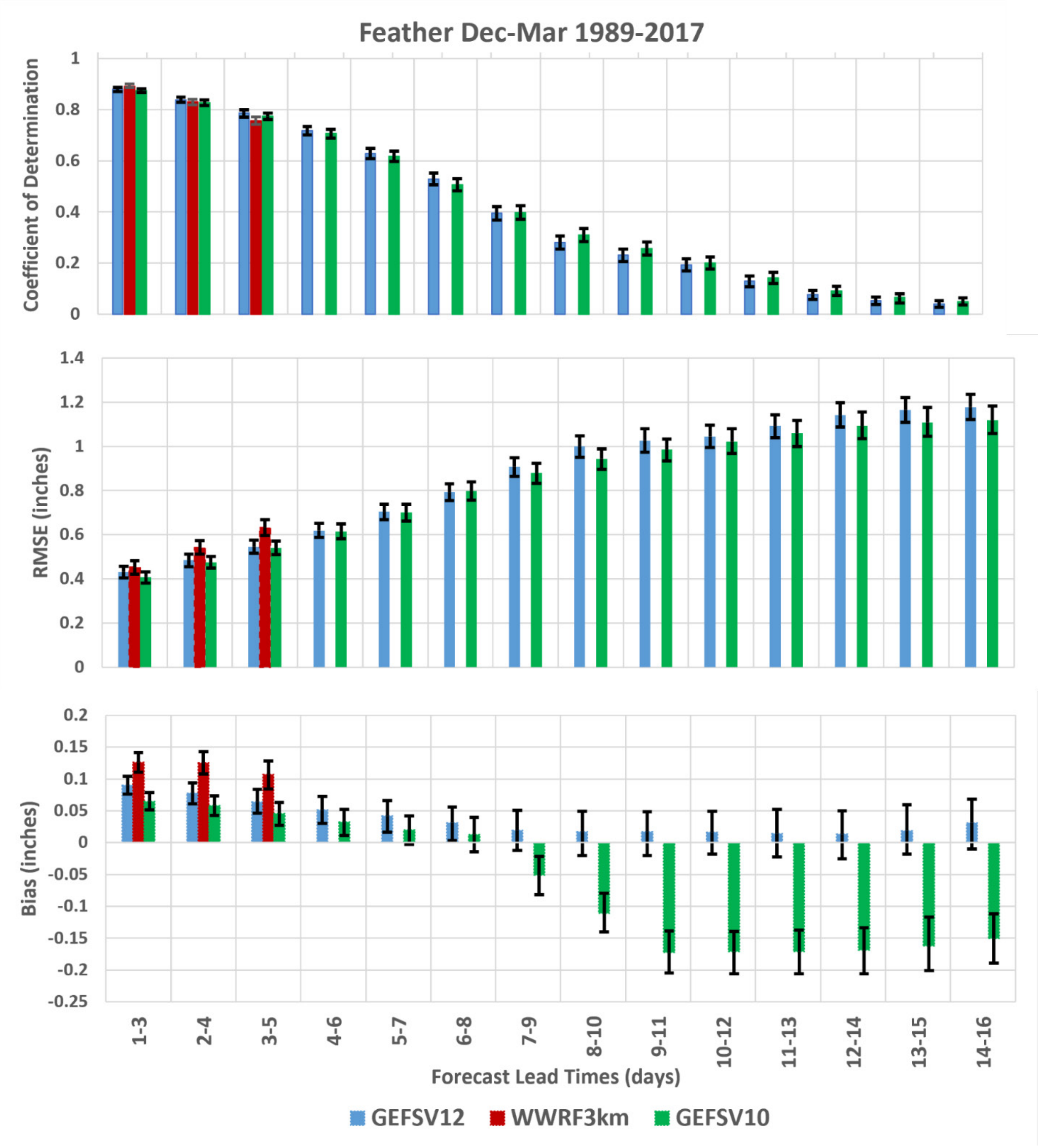


Figure P-5. *Same as Figure P-4, but for the Yuba watershed.*

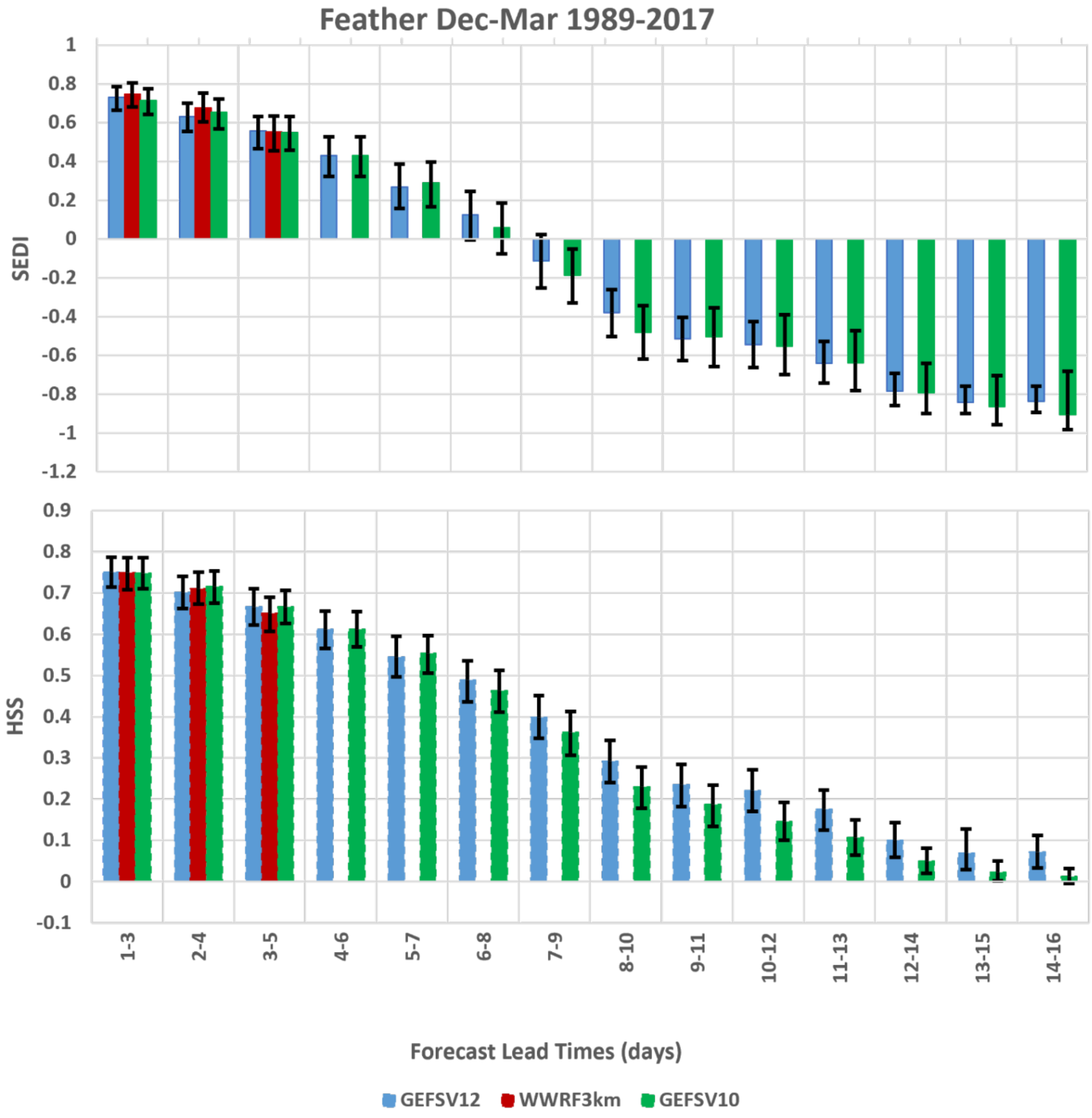


Figure P-6. *Symmetric extremal dependency index (SEDI) as colored columns and Heidke skill score (HSS) plotted as markers for the 90th percentile 3-day observed MAP for the Feather basin with error bars denoting 95% confidence intervals.*

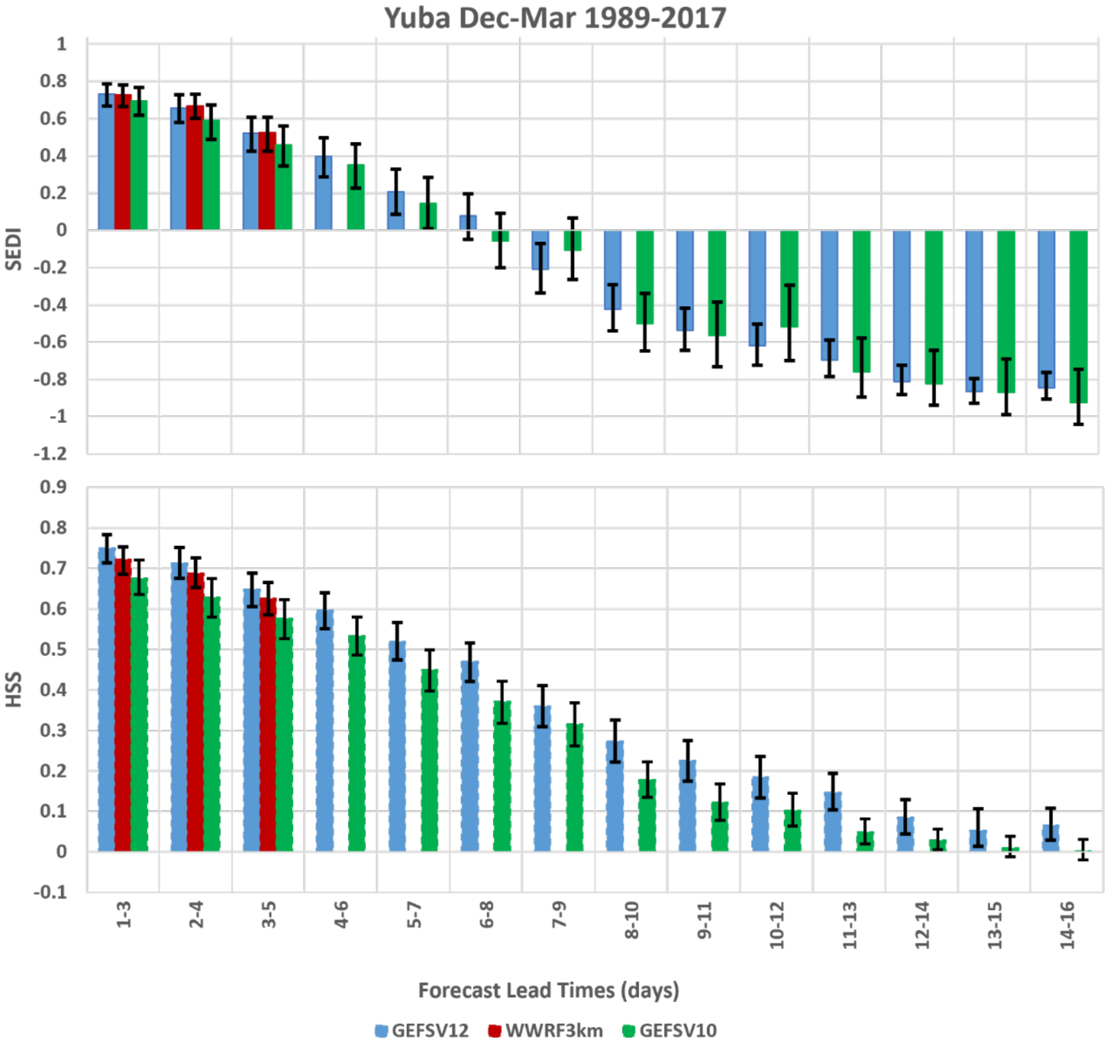


Figure P-7. *Same as Figure P-6, but for the Yuba watershed.*

Table P-1 shows the bias and percent error of GEFSv12 and WWRF QPF at a lead time of 3-5 days for the ten largest observed non-overlapping 72-h precipitation periods in the Yuba watershed during the analysis period. Overall, both the GEFSv12 ensemble mean and WWRF deterministic forecasts performed reasonably well for these upper-right tail events. The average 72-h QPF bias was -1.2 inches for the GEFSv12 ensemble mean and 0.9 inches for WWRF, suggesting that GEFSv12 (WWRF) has a tendency to underestimate (overestimate) the most extreme events in the Yuba watershed. The average forecast error for these ten events was 23% for the GEFSv12 ensemble mean and 20% for WWRF. Most GEFSv12 and WWRF forecasts were within 30% of the observed values, and only one WWRF forecast exceeded a percent error of 50%. Smaller forecast errors were found in the Feather watershed, especially for the WWRF forecasts (Table P-2). These results suggest that, on the watershed scale, both GEFSv12 and WWRF are capable of producing realistic forecasts of the most extreme 72-h precipitation events in the Yuba and Feather watersheds at lead times of 3-5 days.

Table P-1. *Table showing the largest non-overlapping observed 3-day MAP in the Yuba watershed during the entire analysis period and the corresponding GEFSv12 and WWRF QPF bias and percent error at a lead time of 3-5 days.*

Valid Date	QPE	GEFSv12 Bias	GEFSv12 Percent Error	WWRF Bias	WWRF Percent Error
3 Jan 1997	11.75	-1.49	12.68%	0.28	2.38%
11 Jan 2017	10.19	-3.71	36.41%	0.49	4.81%
12 Mar 1995	9.22	1.98	21.48%	0.33	3.58%
10 Feb 2017	8.73	-1.26	14.43%	2.99	34.25%
11 Jan 1995	8.62	1.58	18.33%	2.08	24.13%
5 Mar 1991	8.17	-2.14	26.19%	-0.16	1.96%
14 Dec 1995	7.82	-0.18	2.30%	-1.43	18.29%
11 Feb 2014	7.76	-2.51	32.35%	1.97	25.39%
17 Mar 2012	7.54	-2.29	30.37%	4.59	60.88%
17 Dec 2002	7.37	-2.28	30.94%	-2.05	27.82%
Mean		-1.23	22.55%	0.91	20.35%

Table P-2. *Same as Table P-1, but for the Feather watershed.*

Valid Date	QPE	GEFSv12 Bias	GEFSv12 Percent Error	WWRF Bias	WWRF Percent Error
3 Jan 1997	8.46	-0.25	2.96%	0.28	3.31%
11 Jan 1995	8.17	1.86	22.77%	1.69	20.69%
12 Mar 1995	8.06	1.79	22.21%	-0.38	4.71%
11 Jan 2017	7.97	-2.41	30.24%	0.10	1.25%
17 Dec 2002	6.88	-2.08	30.23%	-1.88	27.33%
10 Feb 2017	6.76	-1.50	22.19%	0.92	13.61%
5 Mar 1991	6.30	-1.15	18.25%	-0.24	3.81%

Valid Date	QPE	GEFSv12 Bias	GEFSv12 Percent Error	WWRF Bias	WWRF Percent Error
14 Dec 1995	6.22	0.84	13.50%	-0.35	5.63%
2 Jan 2006	6.16	-0.99	16.07%	0.64	10.39%
2 Mar 2006	5.70	-0.69	12.11%	0.09	1.58%
Mean		-0.46	19.05%	0.09	9.23%

P.3 Freezing level error

The Sierra Nevada Mountains lie within an elevation range that commonly fluctuates between above and below freezing temperatures during winter storms. Freezing level height (Z_{FL}) forecast error can influence the distribution and phase of precipitation over the watersheds and influence the resulting hydrologic impacts. Using an average ±350 m Z_{FL} forecast error at one to three-day lead times for the Sierra (Henn et al., 2020), Sumargo et al. (2020) developed a simplified approach that found inflow volume uncertainties of <10 percent to >50 percent of the flood pool storages at the Lake Oroville and New Bullards Bar reservoirs, depending on the Z_{FL}, antecedent moisture condition, and precipitation event magnitude. This result emphasizes the significant impact small Z_{FL} forecast errors may have and the critical need for Z_{FL} forecast accuracy for reservoir and flood control operations in the Yuba and Feather watersheds. This subtask aims to evaluate Z_{FL} forecasts within the Yuba/Feather region to identify skillful lead times, potential limitations, and areas for future model improvements.

Baseline Z_{FL} forecast skill metrics are evaluated at Oroville (OVL, 114 m elevation), and Colfax (CFF, 644 m elevation) using archived real-time forecasts from the California-Nevada River Forecast Center (CNRFC) and existing field campaign observations. The CNRFC Z_{FL} forecast data were evaluated over eight cool seasons (November through April) between water years (WY) 2013 through 2021. Freezing level forecasts from the CNRFC are available from their data archive website (https://cnrfc.noaa.gov/archive/) and are initialized daily at 12Z. Existing field campaign observations include Frequency-Modulated Continuous Wave (FMWC) snow level radars (Johnston et al., 2017) at CFF and OVL. Field observations from the FMCW at CFF and OVL were downloaded from https://psl.noaa.gov/data/obs/datadisplay/. The FMCW data are collected at ten-minute intervals. We resampled the observations by finding the mean FMCW value of a fifty-minute window, centered on each valid time. This gave us 161 total window pairs at CFF, and 160 at OVL. The Z_{FL} forecast data was evaluated with matched observations and forecasts valid at 12Z at four 24-hr interval lead times. For each period of record, the coefficient of determination (R^2), Root-Mean Square Error (RMSE) and bias were calculated.

Figure P-8 shows the baseline skill metrics for the CNRFC Z_{FL} forecasts at CFF and OVL. The coefficient of determination ranges between 0.5 to 0.75 (i.e., captures 50% to 75% of the variance of observations) within a 24-hr lead time at CFF and OLV, respectively, and decreases to 0.4 at 96-hr lead time. Root mean square errors are twice as large or greater than the average bias, which might indicate that the CNRFC forecasts suffer from large random errors. Overall, OVL has less skill than CFF. The two sites are separated by ~70 km and differ in elevation by ~530 m. This result might suggest that local thermodynamic effects, observation quality, and/or timing of AR conditions on scales of >100 km have some impact on forecast accuracy.

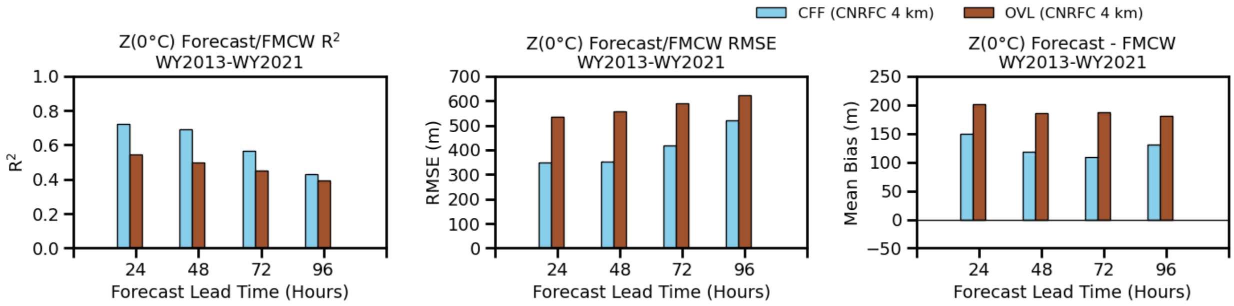


***Figure P-8**. CNRFC freezing level forecast coefficient of determination (left), root mean square error (RMSE) (middle), and mean bias (right) at Colfax (CFF, blue) and Oroville (OVL, brown) as a function of forecast lead time. Forecasts were evaluated between the cool seasons of WY2013 through WY2021.*

There are several challenges in association with adequately observing freezing level. The brightband height, or the altitude of the maximum radar reflectivity from the FMCW, represents the layer in which the hydrometeors change phase (White et al. 2002). The 0°C isotherm is assumed to be above this layer to compensate for the time/depth of melt to occur and subsequent hydrometeor breakup. Henn et al. (2020) previously found the depth of the hydrometeor melt level to be on the order of 138-236 m. The depth of the hydrometeor melt layer can also play a role in accurately forecasting the FL, where the cooling effects from evaporating/melting hydrometeors within the melt layer can, in certain environments, lead to an expansion of the isothermal melt layer, helping to lower Z_{FL} (Kain et al., 2000). The depth of these isothermal layers may not be detected by forecast models since it is highly dependent upon the precipitation rate. Isothermal layers are a source of uncertainty as assumptions are needed to possibly account for thaw and refreeze processes. All of these factors are affected by the precision of the FMCW radar return, which limits the degree in which forecast errors can be minimized (in this case, the FMCW resolution at OVL and CLF is 40 m). Finally, the profiler network throughout California is spatially limited and may not be situated correctly to capture locally generated differences in Z_{FL} due to processes such as downward bending of the melt level near the foothills of the Sierra (Minder & Kingsmill, 2013).

Similar challenges exist when calculating freezing levels from high resolution forecasts. In addition to differences between the brightband height and 0°C isotherm, comparisons of forecasts to observations can be impacted by e.g., the vertical resolution of the model. Figure P-9 shows a comparison of vertical spacing of model levels between four different configurations of the West-WRF NRT model. The simulations differ in the total number of levels and the distribution of levels within the lowest 5 km. The profiles marked *orig* represent configurations in which the default WRF model stacking structure is used, whereas the profiles marked *new* represent stacking structure that mimics (interpolated from) the ECMWF model in the lowest 5 km. The total model levels span between 60 and 120 vertical levels.

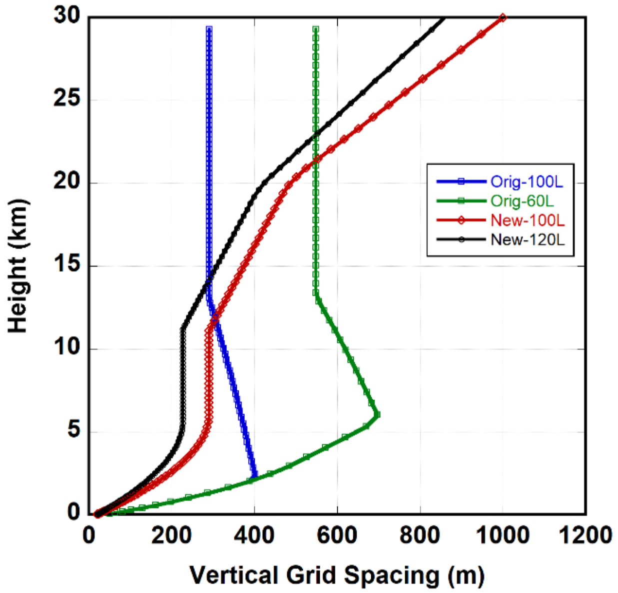


Figure P-9. *Vertical grid spacing in four West-WRF configurations.*

Figure P-10 shows the comparison of the freezing level from an event beginning 14 Jan 2017 and the evolution of the observed brightband height. The dots in Figure P-10A represent the calculated Z_{FL} from each West-WRF configuration and show a clear trend in the Z_{FL} over time. At most times Z_{FL} differences are 250m or less. However, there are timesteps where the difference is >1 km (i.e., 19 Jan 2017 at 00Z, just after the onset of possible AR conditions, Figure P-10C). At this timestep, we also notice a large difference, 5-6°C, in potential temperature (θ) between the original 60 level configuration and the new 100 level configuration. Figure P-10B shows that all four West-WRF configurations disagree on θ between 1,200m and 2,600m in height with the new West-WRF configurations showing large temperature inversions. It should also be noted that all configurations in the previous timestep forecast the Z_{FL} to be greater than the observed Z_{FL} by 1km. After calculating the mean Z_{FL} bias over all start dates, stations, and West-WRF domains, the new 100 level configuration was shown to have the most skill. However, the sample size from this study is quite small (222 pairs), and more robust analyses must be performed.

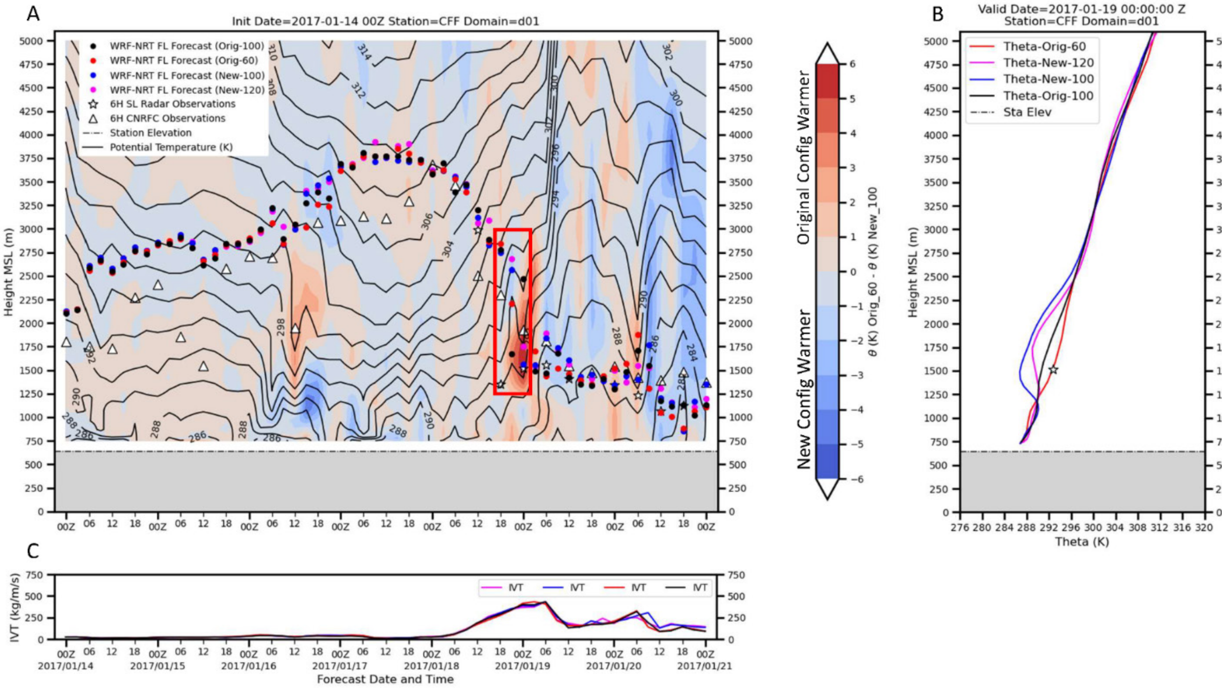


__Figure P-10.__ (A) Vertical profile time series plot at CFF, beginning 14 Jan 2017 using the 9km domain, of θ from the default 60 level West-WRF configuration (black contours), difference in θ between the original 60 and new 100 West-WRF configurations (shading), calculated Z_{FL} from each West-WRF configuration (Dots; colors represent each West-WRF configuration), FMCW observations (stars), and CNRFC observations (triangles). (B) Vertical profile of θ from each West-WRF configuration on 19 Jan 2017 at 00Z. The star is the FMCW observation from (A) at the same time. (C) Time series of IVT beginning 14 Jan 2017.

P.3.1 72-hour inflow error

The aim of this subtask is the evaluation of 72-hour inflow forecasts to New Bullards Bar (NBB) and Lake Oroville (ORO) reservoirs, with potential science goals of 1) providing baseline meteorological/hydrological forecast skill in order to assess future model improvements, 2) understanding the priority forecast skills for Forecast-Informed Reservoir Operations (FIRO) needs, and 3) determining relationships between event characteristics and model skill. To accomplish this objective, California-Nevada River Forecast Center's (CNRFC's) deterministic forecasts and probabilistic/ensemble hindcasts are chosen, given their utilities in operational forecasting efforts.

Deterministic forecasts are available for the New Year 1997 atmospheric river (AR) event at ORO and for the period of 2005 onward at both NBB and ORO, while the ensemble hindcasts are available for the period of 1985-2010. However, the ensemble hindcasts assume full natural flow, so no upstream regulations are accounted for in their simulations. In contrast, deterministic forecasts account for upstream regulations, such that they are directly comparable to the inflow. Deterministic forecast archive is also available for 2015 onward on the CNRFC website (https://www.cnrfc.noaa.gov/csv/). The evaluation focuses on two periods of analysis: 1) the impactful New Year 1997 and February 2017 AR events, and 2) the period of record as a benchmark evaluation. Additionally, AR periods are identified using Rutz's AR catalog (ftp://sioftp.ucsd.edu/CW3E_DataShare/Rutz_AR_Catalog), available from 1980 onward for the

Yuba-Feather location. Observations are mostly available at a daily resolution from California Data Exchange Center (CDEC: https://cdec.water.ca.gov/). When not available, CNRFC also maintains the daily observation archives. For this reason, many of the evaluations focus on a daily time step.

The deterministic forecasts are driven by locally developed quantitative precipitation forecast (QPF) and temperature forecast products derived from a variety of Numerical Weather Prediction (NWP) models and operational sources. Furthermore, the forecasts are generated daily with lead times of ≤5 days. The ensemble hindcasts were generated using the National Weather Service's Hydrologic Ensemble Forecast System (HEFS) in 2015. By design, HEFS translates an ensemble of meteorological inputs through hydrologic models, which in this case is a coupled snow (SNOW-17)-soil (SAC-SMA) model, to produce an ensemble of streamflow outputs. The ensemble meteorological inputs are produced as meteorological forecast uncertainties using a statistical model called the Meteorological Ensemble Forecast Processor (MEFP). MEFP is based on the Global Ensemble Forecast System version 10 (GEFSv10) precipitation and temperature reforecast datasets that are available from 1985 to 2010 .

The initial inspection of the deterministic daily inflow forecast indicates that the forecasts perform well throughout the 5 days of lead time (see Appendix: Figure A1). Moreover, the correlations between the forecasts and observation amount to >0.75 in most cases, even when evaluated at different seasons, except in autumn at ORO. (Note that summer cannot be evaluated due to the lack of forecast data availability.) Similar results occur in the root-mean-squared error (RMSE), where the RMSE grows with the lead time (mostly by <25% from 1-day to 5-day lead time), except in winter at NBB where the RMSE decreases with the lead time (by ~15% from 1-day to 5-day lead time). On the other hand, the mean biases show a more significant variation with the lead time, where the biases become more negative with lead time in both NBB and ORO cases. This variation is largest in the winter, where the biases are positive at 1–2-day lead times and negative at longer lead times, and smallest in the autumn.

For each of the evaluated initialization dates, the 72-hour (or 3-day) inflows for NBB and ORO are subsequently computed by summing up the inflow forecasts/hindcasts (hereby simply forecasts) with rolling lead-time aggregates 1-3 days, 4-6 days, and 7-9 days from the initialization dates/times. Different lead-time aggregates are evaluated in order to assess the forecast skill at shorter-to-longer lead times, especially if the skill degrades significantly with lead time. The same procedure is applied to the observations for comparison, where the difference between the forecast and the observation indicates the forecast bias. Over the long term (1985-2010), the rank histogram (Talagrand et al., 1997; Hamill, 2001) and the reliability diagram (Hartmann, 2002) methods are also used to assess the ensemble forecast reliability against the observation (see Appendix).

Figure P-11 shows the resulting 72-hour inflow aggregates for the deterministic forecasts initialized on 3-9 February 2017, leading towards the Oroville Dam crisis. During this period, the forecast biases do not seem to exhibit a strong overestimation/underestimation tendency up to 7 February 2017 initialization (averaging 2% underestimation at NBB and 3% overestimation at ORO), but underestimate the 3-day inflow volumes afterwards in both NBB and ORO cases (averaging by 31% at NBB and by 17% at ORO). The ORO result is similar to the New Year 1997 AR event (see Appendix: Figure A2). However, this outcome is not necessarily representative of the majority of other times, including other AR-related high flow events. Over the period of record from 2005 onward, the forecast biases become 11% (17%) overestimation at NBB and 8% (15%) overestimation at ORO, when evaluated during the top 5% forecast inflows (AR-event inflows) only (see Appendix: Figure A3).

Figure P-12 shows the example for the ensemble forecasts initialized on 27-31 December 1997, leading towards the New Year 1997 AR event. The forecasts exhibit underestimations in most ensemble members in both NBB and ORO cases, as indicated by the ensemble means and, in some cases, ensemble 95th percentile values amounting to lower than the observed inflows. The error distribution as shown by boxplots more explicitly illustrates this underestimation (see Appendix: Figure A4). Although the error distribution ranges from -80% to 150% of the observation, underestimations occur across most ensemble members. These underestimations are most apparent in the initialization date/lead-time aggregate combinations that correspond to the peak flow period on 1 January 1997. When evaluated for the top 5% forecast AR-event inflows on record at ORO, the forecast error ranges from -23% to +16%, averaging -12%, at 1–3-day lead-time aggregate (see Appendix: Figure A5). These numbers become -50% to +15% (-60% to +12%), averaging -31% (-42%) at 4-6 (7-9) day lead-time aggregate. The result is slightly different in the NBB case, with relatively more ensemble members showing overestimations. The forecast error ranges from -20% to +30%, averaging -5%, at 1–3-day lead-time aggregate. These numbers become -36 to +28% (-59% to +17%), averaging -19% (-37%) at 4-6 (7-9) day lead-time aggregate. Overall, this result is consistent with the mostly negative biases in the rank histograms, except for the 1-3 lead-time aggregate at NBB where the rank histogram is rather equally distributed (see Appendix: Figure A6). This outcome is similarly reflected in the corresponding reliability diagrams, where the forecasts are shown to be most reliable, i.e., when the forecast vs. observed frequencies are close to a 1:1 relationship, for the 1–3-day lead-time aggregate at NBB (see Appendix: Figure A7).

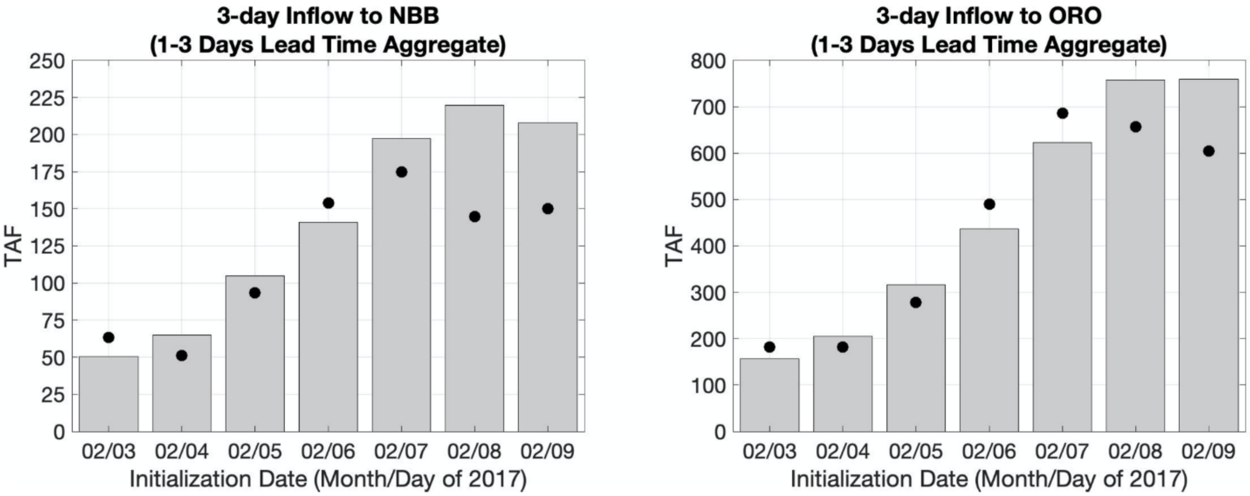


Figure P-11. *72-hour (3-day) deterministic inflow forecasts (dots) and observations (bars) at NBB (left) and ORO (right) reservoirs in thousand acre-feet (TAF), aggregated for lead times 1-3 days, shown for initialization dates 3-7 February 2017. Note the difference in y-axis scales between NBB and ORO.*

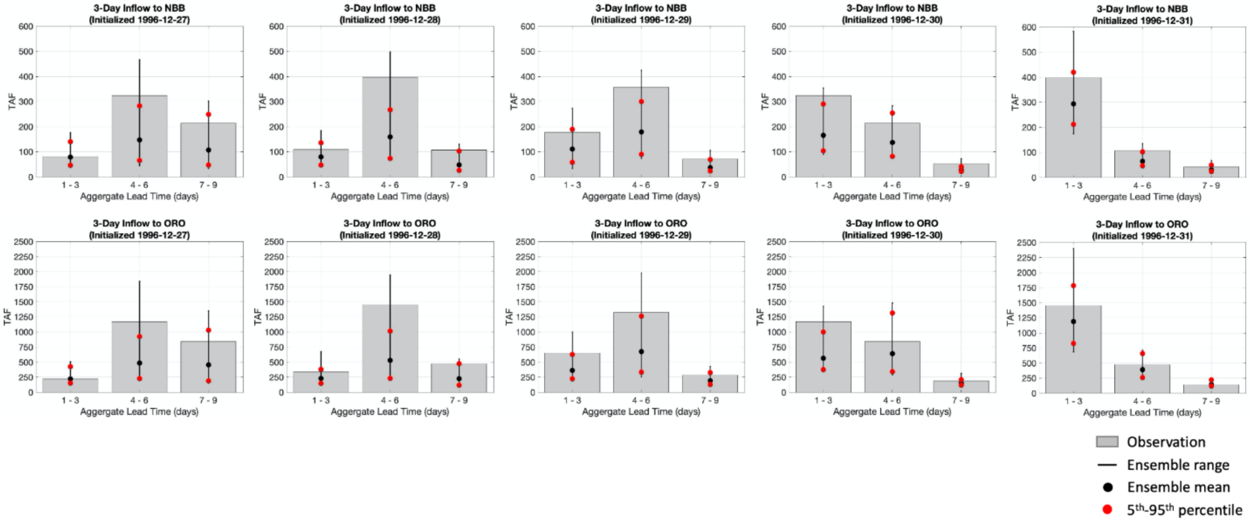


Figure P-12. *72-hour (3-day) ensemble full-natural inflow forecasts (lines and dots) and observations (bars) at NBB (top) and ORO (bottom) reservoirs in thousand acre-feet (TAF), aggregated for lead times 1-3, 4-6, and 7-9 lead days, shown for initialization dates 27-31 December 1997 (left-right). Note the difference in y-axis scales between NBB and ORO.*

Attachment P-1: Inflow deterministic and probabilistic assessments appendix

The correlations, mean biases, and RMSEs of the 24-hr deterministic inflow forecasts at NBB and ORO are computed against the daily observations. The computations are repeated for different forecast lead times from 1 day to 5 days and for different periods: all time, winter (December-February: DJF), spring (March-May: MAM), summer (June-August: JJA), and autumn (September-November: SON) from 2005 onwards, corresponding to the period of availability. The results indicate that the correlations and RMSEs are relatively stable throughout the 5 days lead times, and that the biases decrease with increasing lead time (Figure P1-1). Although this pattern occurs in all seasons, including the all-time period, it is most evident in DJF, reflecting the seasonal precipitation and runoff activities. The skills are absent in JJA, reflecting the lack of forecast data availability during the summer.

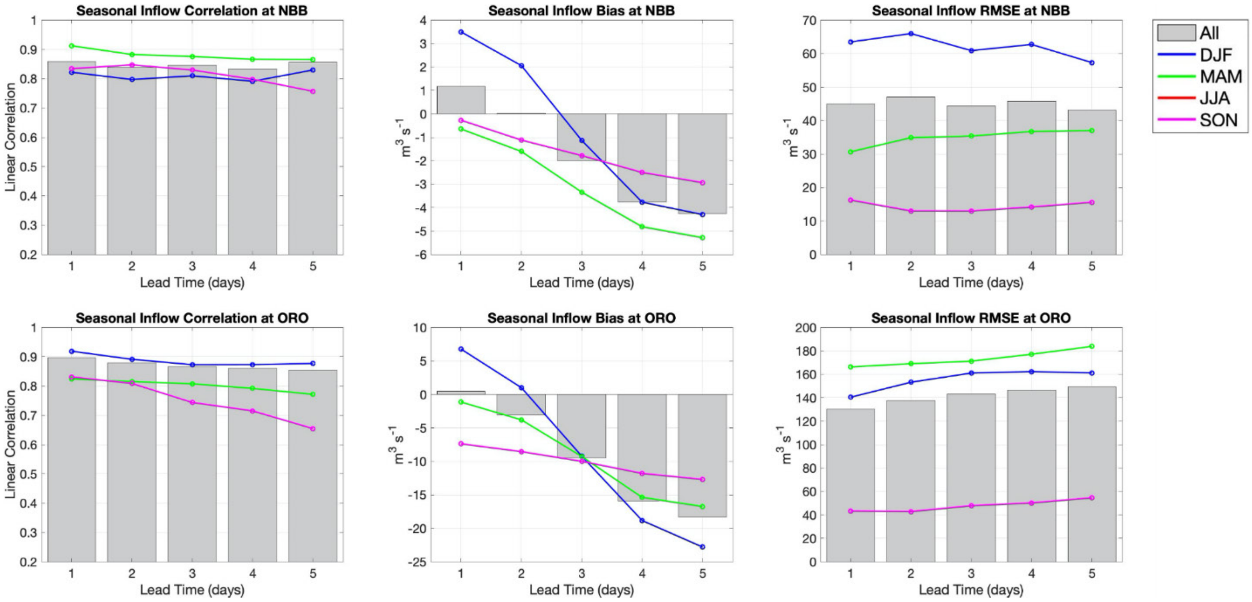


Figure P1-1. The seasonal correlations (left), mean biases (middle), and RMSE (right) of daily deterministic inflow forecasts to NBB (top) and ORO (bottom) against observations. The bars indicate all seasons, while the colored lines indicate the individual seasons: winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

The deterministic forecast 3-day aggregated inflow volumes at ORO are computed for rolling lead times 1-3 days and initialization dates 27-31 December 1996, corresponding to the New Year 1997 AR event (Figure P1-2). The forecasts show underestimations throughout the lead times and initialization dates, but most prominently for the initialization date closer to the peak flow period centered around 1 January 1997.

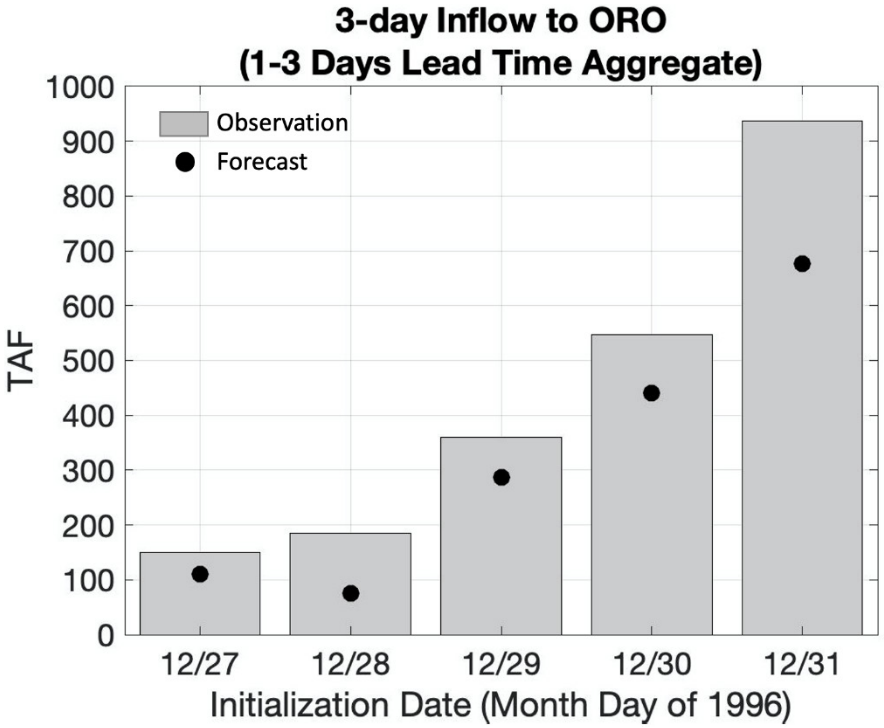


Figure P1-2. 3-day deterministic inflow forecasts (dots) and observations (bars) at ORO (bottom) reservoir, aggregated for lead times 1-3 days and shown for initialization dates 27-31 December 1996.

The deterministic forecast mean biases and RMSEs of the 3-day inflow volumes at NBB and ORO are computed for rolling lead time aggregates 1-3 days. Three different scenarios are considered: 1) all time, 2) top 5% forecast inflow events, and 3) top 5% forecast AR-inflow events (i.e., only those coinciding with the AR periods as indicated in the Rutz AR Catalog).

The mean biases are smallest in the all-time scenario and largest in the top 5% AR-inflow scenario (Figure P1-3). In all scenarios, the mean biases are all positive. On the other hand, the biases tend to be relatively moderate in the top 5% inflow scenario. This result reflects the inclusion of low flow periods in the former and the effect of AR-related extreme events in the latter. It also reflects the lack of and the effect of either meteorological/precipitation input or inflow model processes on the inflow forecasts (or both), respectively. The pattern in the magnitude differences between the three scenarios is similarly reflected in the RMSEs.

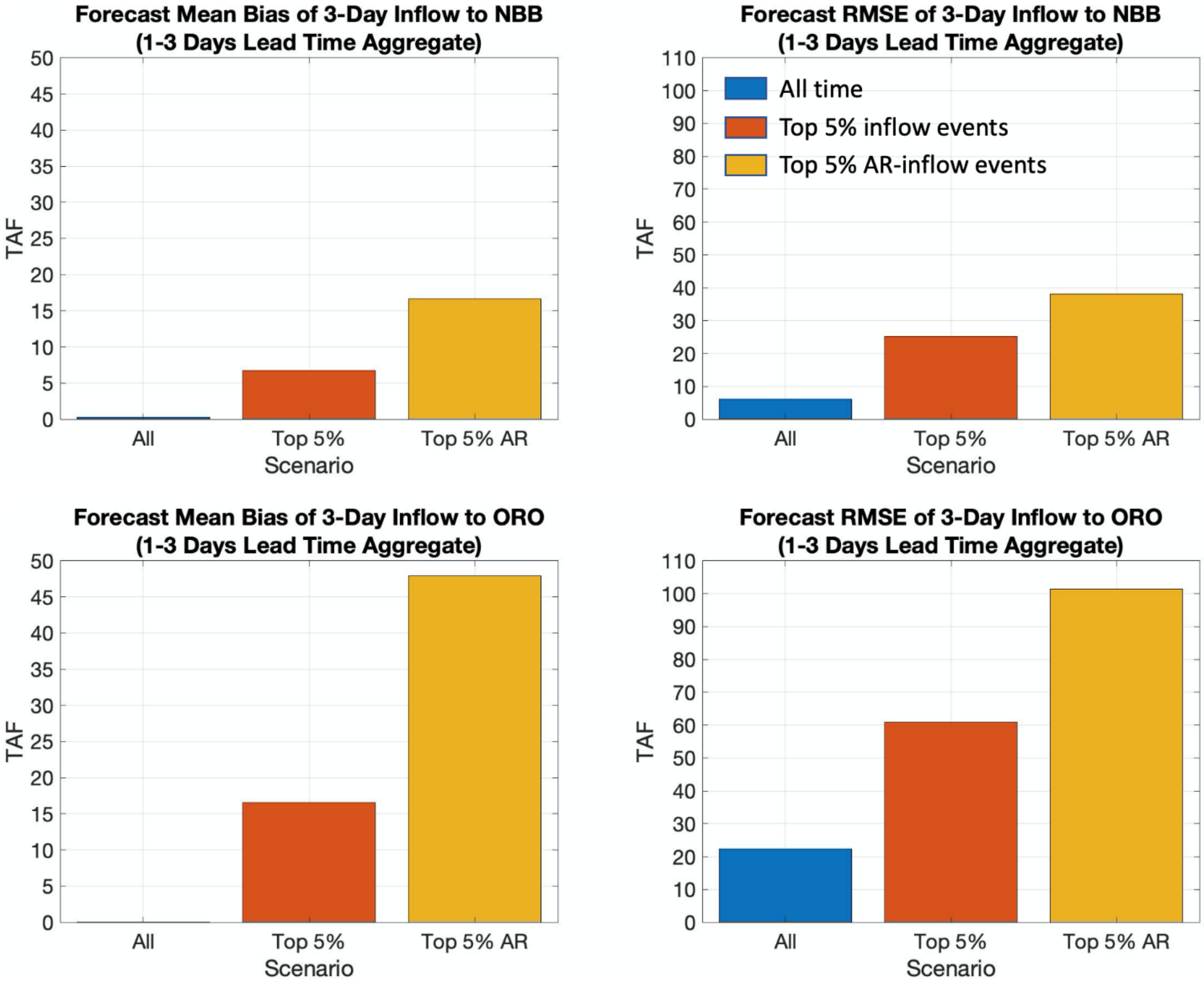


Figure P1-3. Deterministic forecasts mean biases (left) and RMSE (right) of 3-day inflows to NBB (top) and ORO (bottom) against observations. The colors denote different scenarios: all time (blue), top 5% inflow periods (red), and top 5% inflow periods corresponding to AR events only (yellow).

The ensemble forecast error (bias) is further computed and visualized using the boxplot method for the New Year 1997 AR event, specifically for the initialization dates 27-31 December 1996 (Figure P1-4). While the forecast error range tends to be larger with more high outliers at longer lead times, the magnitude of the error fluctuates with initialization dates, depending on how close it is to the peak flow period. For example, the forecast error range tends to be larger and more negative at lead time aggregate 4-6 days in the 27-28 December 1996 initializations, and at lead time aggregate 1-3 days subsequently, corresponding to the valid times closer to the peak flow period around 1 January 1997. The bias tends to be smaller at lead time aggregate 7-9 days due to the fact that the associated valid times are in the post-peak flow period.

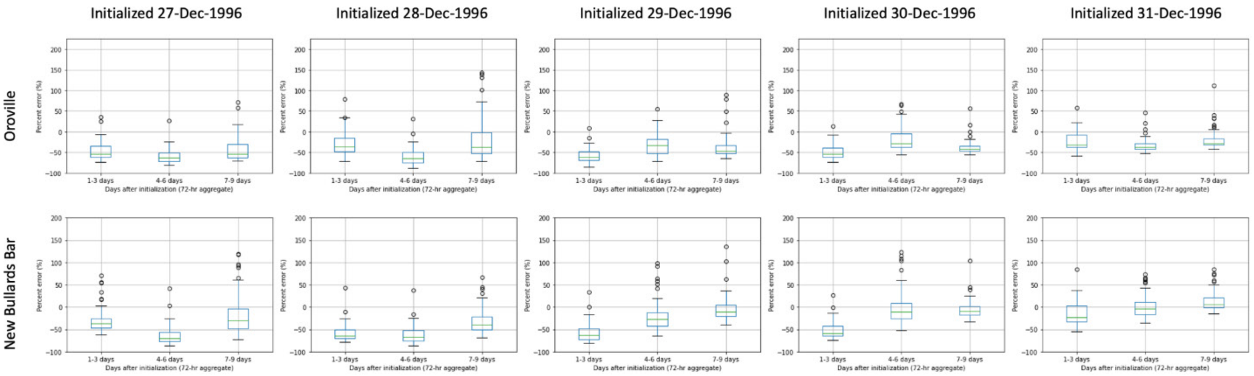


Figure P1-4. Boxplots of ensemble forecast errors for the 3-day inflows to ORO (top) and NBB (bottom) reservoirs against observations in percents, initialized on 27-31 December 1996 (left-right) for rolling-lead times 1-3 days, 4-6 days, and 7-9 days.

The process above is repeated for the ensemble forecasts, whose period of availability spans from 1985 to 2010. The overall pattern in the bias and RMSE magnitudes are similar, where the top 5% AR-inflow scenario tends to have a larger and more negative bias and RMSE, especially at longer lead times, except the all-time cases show near zero to slightly positive biases (Figure P1-5). Furthermore, the variation among the ensemble members is also significant, particularly in the top 5% AR-inflow scenario and at longer lead times. Both top 5% inflow scenarios, however, exhibit both positive and negative biases across the ensemble members, with mostly negative biases in the ensemble means and interquartile ranges.

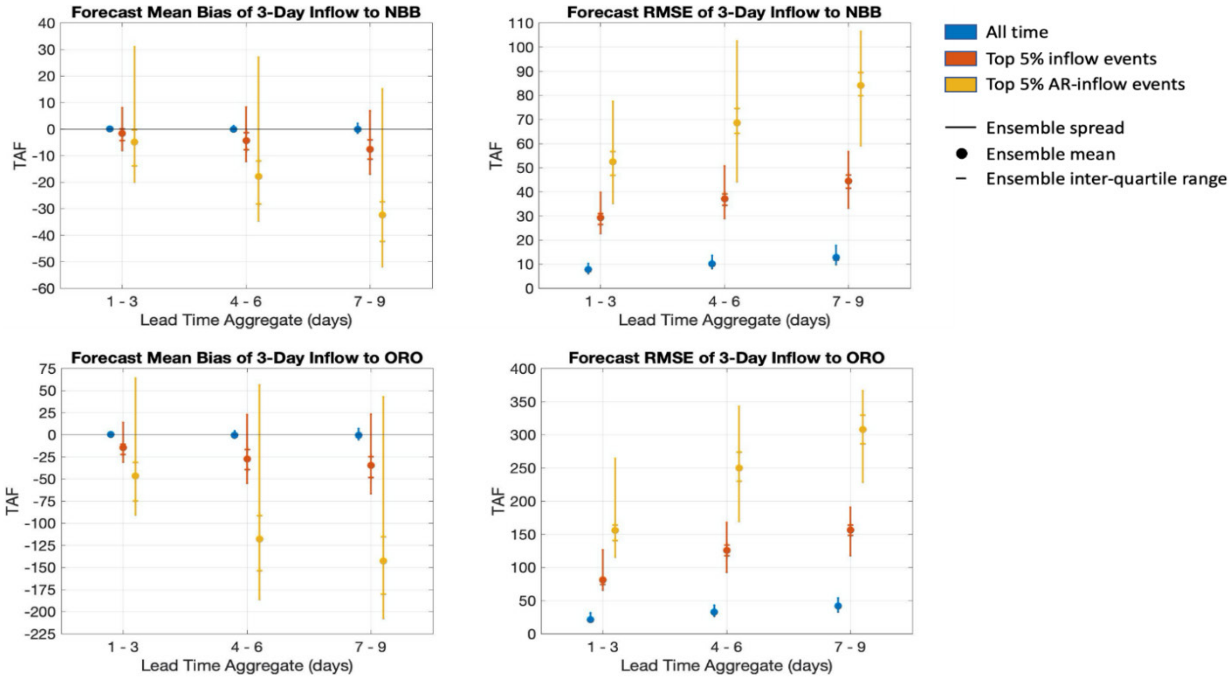


Figure P1-5. Similar to Figure A3, except for the ensemble forecasts. The lines denote the ensemble spreads, while the circles denote the ensemble means and the stripes denote the interquartile ranges.

The cumulative rank histogram method is used to evaluate the ensemble forecast skill and tendency. Although several scenarios are considered, including all time and the top 5% AR-inflow events, only the latter is visualized in this assessment. For note, the all-time scenario consistently indicates a strong positive bias in both NBB and ORO cases, and at all aggregate lead times.

The histograms show noticeable differences in the outcomes between the NBB and the ORO cases (Figure P1-6). In the NBB case, the histograms indicate relatively consistent spread at lead time aggregate 1-3 days. This spread is largely retained, but indicates a slightly negative bias tendency in the lead time aggregate 4-6 days. The negative bias tendency is more apparent at lead time aggregate 7-9 days. In the ORO case, the negative bias tendency occurs in all lead time aggregates. Overall, this result indicates that the ensemble forecast tends to underestimate the magnitude of inflow volume, consistent with the results shown in the other baseline assessment figures.

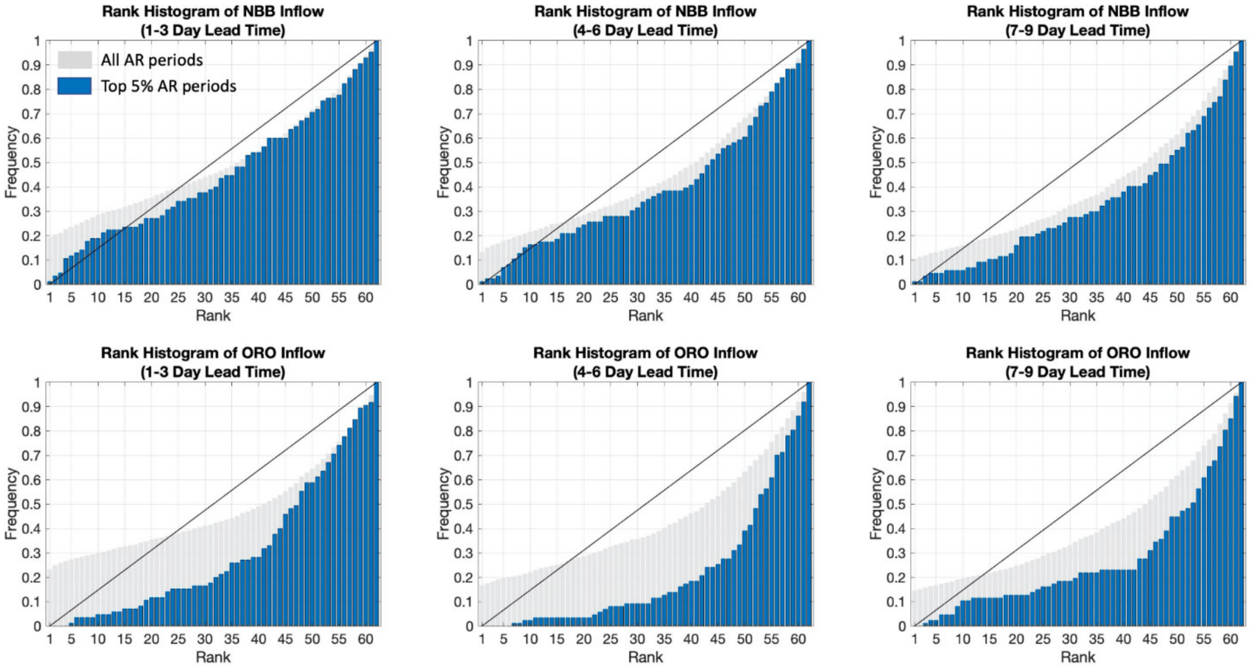
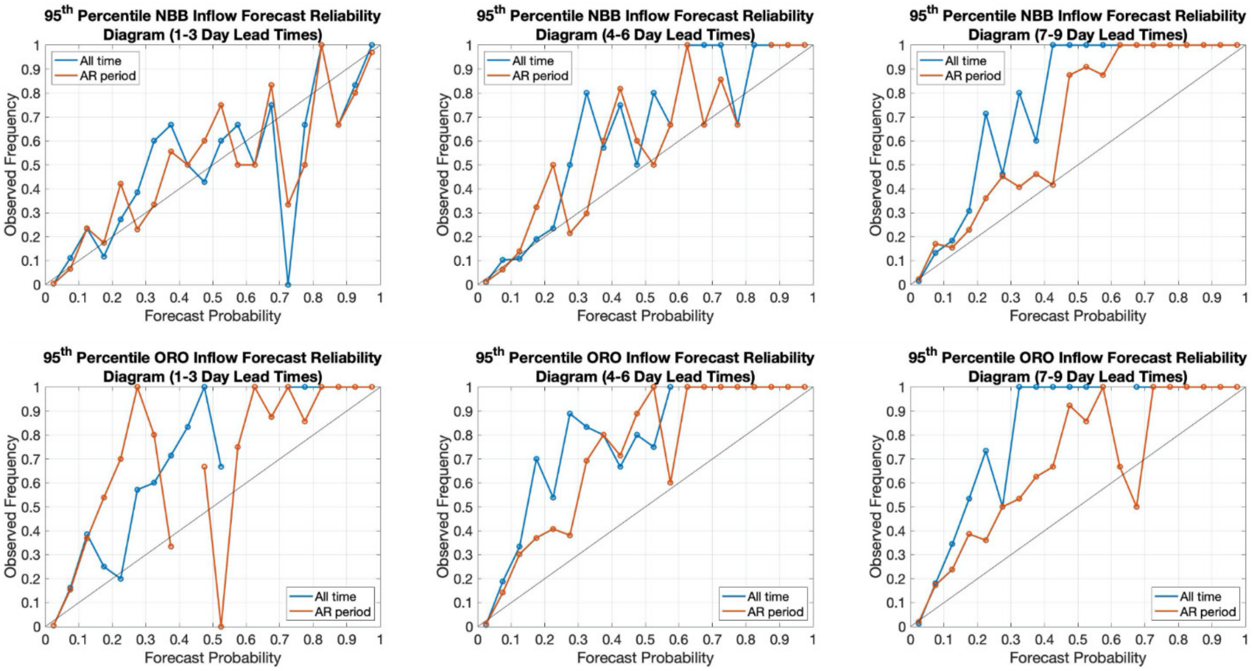


Figure P1-6. Cumulative rank histograms of 3-day inflows to NBB (top) and ORO (bottom) reservoirs at lead times 1-3 days (left), 4-6 days (middle), and 7-9 days (right) for the top 5% AR-inflow periods (blue). For comparison, those for all AR periods are also shown (gray). The diagonal line denotes the 1:1 relationship.

The ensemble 3-day inflow volume forecasts are further evaluated using the reliability diagram method. Figure P1-7 shows the reliability diagrams for both NBB and ORO cases and at the same lead time aggregates in the rank histogram. The diagrams exhibit relatively close to a 1:1 relationship between the forecast probability and observed frequency in the NBB case at the lead time aggregate 1-3 days, indicating the relatively high 3-day inflow volume forecast reliability. This relationship becomes farther away from the 1:1 relationship at longer lead times. This departure is even more apparent in the ORO case.


95th Percentile NBB Inflow Forecast Reliability Diagram (1-3 Day Lead Times)

95th Percentile NBB Inflow Forecast Reliability Diagram (4-6 Day Lead Times)

95th Percentile NBB Inflow Forecast Reliability Diagram (7-9 Day Lead Times)

95th Percentile ORO Inflow Forecast Reliability Diagram (1-3 Day Lead Times)

95th Percentile ORO Inflow Forecast Reliability Diagram (4-6 Day Lead Times)

95th Percentile ORO Inflow Forecast Reliability Diagram (7-9 Day Lead Times)

Figure P1-7. Reliability diagrams of 3-day inflows to NBB (top) and ORO (bottom) reservoirs at lead times 1-3 days (left), 4-6 days (middle), and 7-9 days (right) for the top 5% inflow, both for all time (blue) and AR-only (red) periods. The diagonal line denotes the 1:1 relationship.

Table P1-1. Brier skill scores (BSS) of CNRFC ensemble inflow hindcasts for the period of 1985-2010 at NBB and ORO. The BSS are computed with a 95th flow percentile threshold, for lead time aggregates 1-3, 4-6, and 7-9 days and for all time and AR only scenarios.

Lead Time Aggregate	BSS (All Time)		BSS (AR Only)	
	NBB	ORO	NBB	ORO
1-3 days	0.5	0.51	0.39	0.39
4-6 days	0.49	0.48	0.36	0.36
7-9 days	0.49	0.47	0.35	0.35

Attachment P-2: Yuba-Feather 72-h QPF Verification Appendix

This section includes the results of several additional analyses related to precipitation verification in the Yuba and Feather watersheds.

The first analysis identified the ten largest positive and negative GEFSv12 and WWRF 72-h precipitation forecast errors at lead times of 3-5 days in the Yuba and Feather watersheds. Such an analysis could be leveraged to investigate the sources of meteorological uncertainty that lead to poor predictability and large forecast errors. Tables P2-1 and P2-2 show the ten largest positive (left side) and negative (right side) GEFSv12 and WWRF forecast errors, along with the corresponding valid dates and observed 72-h MAP, in the Feather and Yuba watersheds. In the Feather (Table P2-1), the largest negative GEFSv12 and WWRF forecast errors ranged from -2.5 to -3.7 inches. In the Yuba (Table P2-2), where observed precipitation extremes are higher, the largest negative forecast errors ranged from -2.8 to -5.0 inches. For nearly all of these events, GEFSv12 and WWRF forecasted less than 50% of the total 72-h MAP, indicative of forecast misses of large events. Whereas the ranges of the ten largest negative forecast errors were similar between GEFSv12 and WWRF, the ranges of ten largest positive forecast errors differ substantially. In the Feather, only two GEFSv12 forecast errors exceeded +3 inches, but eight WWRF forecast errors exceeded +3 inches. In the Yuba, only two GEFSv12 forecast errors exceeded +4 inches, but nine WWRF forecast errors exceeded +4 inches. Many of these over-forecasts were associated with light-to-moderate precipitation events (< 2 inches), indicative of large forecast busts.

The second analysis investigated the sensitivity of the GEFSv12 72-h QPF verification metrics to the initial conditions used to generate the reforecasts. GEFSv12 uses the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) for the 1989-1999 period and the GEFSv12 reanalysis (Hamill et al. 2021) for the 2000-2019 period. Figures P2-1 and P2-2 show the GEFSv12 coefficient of determination (columns), RMSE (filled markers), and bias (open markers) for the 1989-1999 (blue) and 2000-2017 periods (red) in the Feather and Yuba watersheds. Confidence intervals for each metric are denoted by the error bars. Note that the confidence intervals for the 1989-1999 period are generally much larger than the confidence intervals for the 2000-2017 period due to the smaller sample size. In the Feather (Figure P2-1), the coefficient of determination during the 2000-2017 period is statistically higher than during the 1989-1999 period at lead times of 2-4, 3-5, 4-6, and 5-7 days. The RMSE during the second period is consistently lower than during the first period, with a statistically significant difference at lead times up to 5-7 days. In the Yuba (Figure P2-2), the coefficient of determination during the second period is statistically higher than during the first period at lead times up to 5-7 days. Similar to the Feather, the RMSE is consistently lower in the Yuba during the second period, but the only statistically significant difference in RMSE appears at a lead time of 4-6 days. In both watersheds, there is generally little difference in the bias between the first and second periods.

The sensitivity to initial conditions was also applied to the forecast verification of 90th percentile events in both watersheds. Figures P2-3 and P2-4 show the GEFSv12 SEDI (columns) and HSS (filled markers) for the 1989-1999 (blue) and 2000-2017 (red) periods in the Feather and Yuba watersheds. Due to the small numbers of extreme events during each period, the confidence intervals for SEDI and HSS are quite large. In both watersheds, the SEDI is higher during the second period at lead times up to 6-8 days, but the differences are not statistically significant. The HSS is higher during the second period at lead times up to 8-10 days, but the only statistically significant differences appear in the Yuba watershed (Figure P2-4) at lead times of 4-6 and 5-7 days. Overall, this analysis suggests that the use of GEFSv12 reanalysis to define the initial conditions for the GEFSv12 reforecasts led to an improvement in 72-h precipitation forecasts in the Feather and Yuba watersheds at lead times most relevant for FIRO operations.

Table P2-1. Table showing the largest negative (left side) and positive (right side) GEFSv12 and WWRF 72-h precipitation forecast errors in the Feather watershed at a lead time of 3-5 days. Errors highlighted in red (blue) indicate events in common between GEFSv12 and WWRF that were underestimated (overestimated).

GEFSv12			WWRF			GEFSv12			WWRF		
Valid Date	QPE	Bias	Valid Date	QPE	Bias	Valid Date	QPE	Bias	Valid Date	QPE	Bias
22 Jan 1993	4.34	-3.65	12 Dec 1992	4.53	-3.20	2 Feb 1996	0.45	3.52	21 Jan 2012	1.08	6.04
15 Dec 2002	5.26	-3.32	11 Dec 1992	4.60	-3.09	8 Jan 2017	1.12	3.37	15 Dec 2016	0.72	4.05
24 Dec 2005	4.38	-3.22	22 Jan 1993	4.34	-2.92	11 Jan 2005	1.28	2.93	15 Jan 2000	0.15	4.03
2 Jan 1997	8.43	-3.07	12 Feb 2007	5.62	-2.90	31 Dec 2002	2.54	2.92	20 Jan 2012	0.13	3.92
11 Dec 1992	4.60	-3.04	20 Dec 2005	3.22	-2.87	5 Jan 1997	1.44	2.82	9 Feb 1999	3.58	3.77
4 Mar 2009	4.72	-2.90	12 Dec 2016	3.38	-2.79	15 Jan 2000	0.15	2.74	15 Jan 1995	4.62	3.57
23 Dec 2005	4.24	-2.81	23 Jan 1997	3.42	-2.61	20 Feb 2004	3.55	2.62	21 Feb 1993	2.98	3.37
12 Dec 1992	4.53	-2.80	10 Dec 1992	4.21	-2.57	13 Jan 1995	5.18	2.61	4 Jan 1997	6.22	3.10
11 Dec 2016	4.02	-2.71	24 Jan 1997	3.54	-2.41	31 Jan 1996	0.44	2.58	22 Jan 2000	0.77	2.98
23 Jan 1997	3.42	-2.65	21 Dec 2005	3.30	-2.36	29 Jan 2008	1.82	2.54	4 Mar 1991	4.62	2.96
Mean		-3.02			-2.77	**Mean**		2.86			3.78

Table P2-2. Same as Table P2-1, but for the Yuba watershed.

GEFSv12			WWRF			GEFSv12			WWRF		
Valid Date	QPE	Bias	Valid Date	QPE	Bias	Valid Date	QPE	Bias	Valid Date	QPE	Bias
22 Jan 1993	5.68	-4.97	22 Jan 1993	5.68	-4.30	8 Jan 2017	1.62	4.17	21 Jan 2012	1.26	8.89
2 Jan 1997	11.25	-4.76	24 Jan 1997	5.12	-3.91	2 Feb 1996	0.53	4.05	15 Dec 2016	0.45	5.37

GEFSv12			**WWRF**			**GEFSv12**			**WWRF**		
Valid Date	QPE	Bias	Valid Date	QPE	Bias	Valid Date	QPE	Bias	Valid Date	QPE	Bias
24 Dec 2005	5.73	-4.26	20 Dec 2005	3.95	-3.57	20 Feb 2004	2.68	3.56	16 Mar 2012	5.52	4.97
23 Jan 1997	4.87	-3.86	12 Dec 2006	5.33	-3.52	15 Dec 1995	5.26	3.22	17 Mar 2012	7.54	4.59
11 Jan 2017	10.19	-3.71	23 Jan 1997	4.87	-3.51	29 Jan 2008	1.91	3.20	15 Jan 1995	6.57	4.38
28 Dec 1996	4.30	-3.59	6 Mar 1997	7.16	-3.20	23 Dec 2010	1.37	3.18	20 Jan 2012	0.03	4.35
23 Dec 2005	5.41	-3.56	5 Jan 2017	4.83	-3.20	5 Jan 1997	2.83	3.09	9 Feb 1999	5.67	4.19
15 Dec 2002	5.26	-3.54	13 Dec 1995	7.53	-3.04	16 Dec 2016	2.59	3.03	29 Jan 2008	1.91	4.19
11 Dec 2016	5.84	-3.39	26 Jan 1997	4.39	-2.88	7 Mar 1995	0.73	2.87	27 Feb 2000	1.25	4.11
26 Jan 1997	4.39	-3.06	5 Feb 1996	3.63	-2.80	28 Jan 1998	0.45	2.87	31 Jan 1996	0.59	3.99

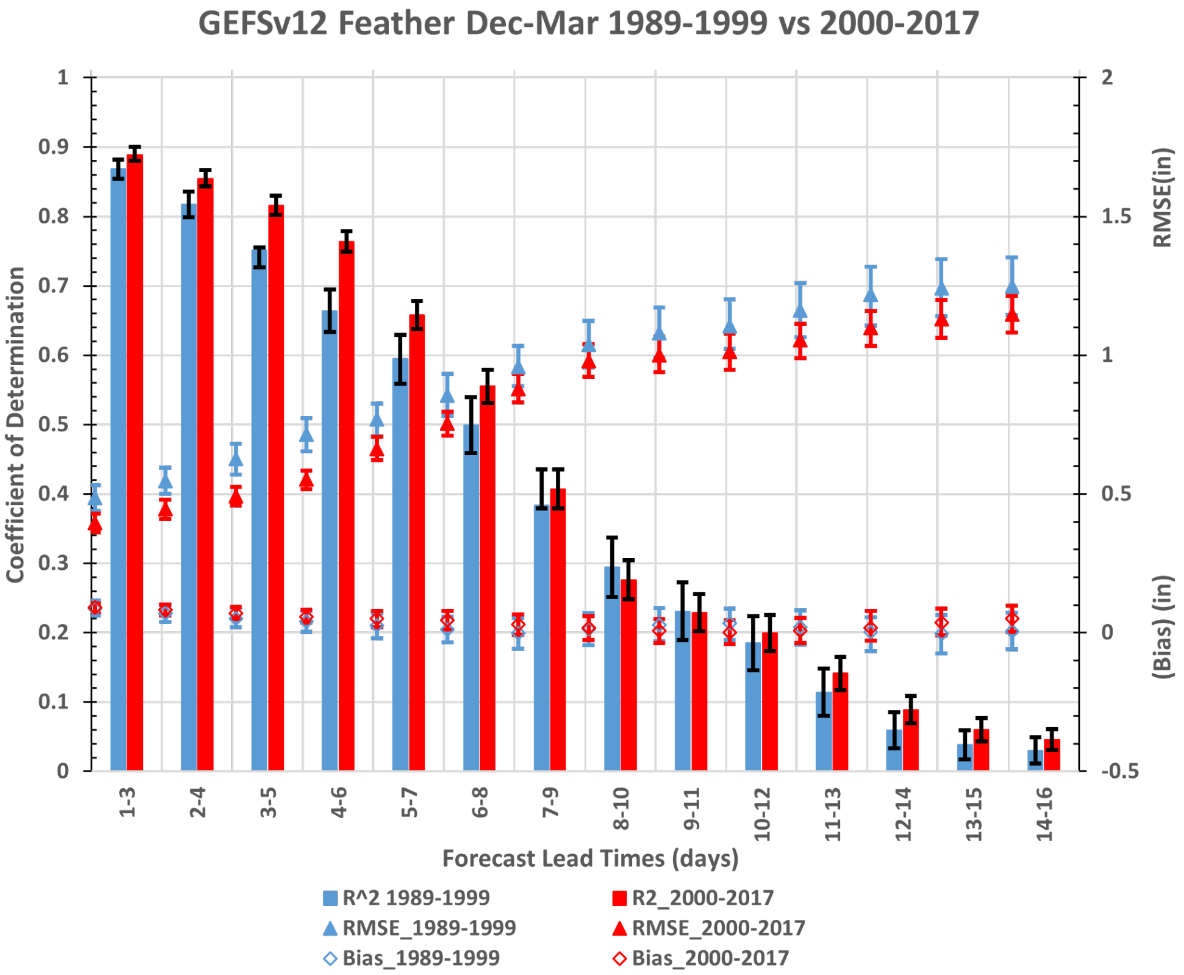


Figure P2-1. GEFSv12 ensemble mean coefficient of determination (bars), RMSE (filled markers), and bias (open markers) for 72-hr mean areal precipitation in the Feather watershed during 1989-1999 (blue) and 2000-2017 (red). Errors bars denote 95% confidence intervals.

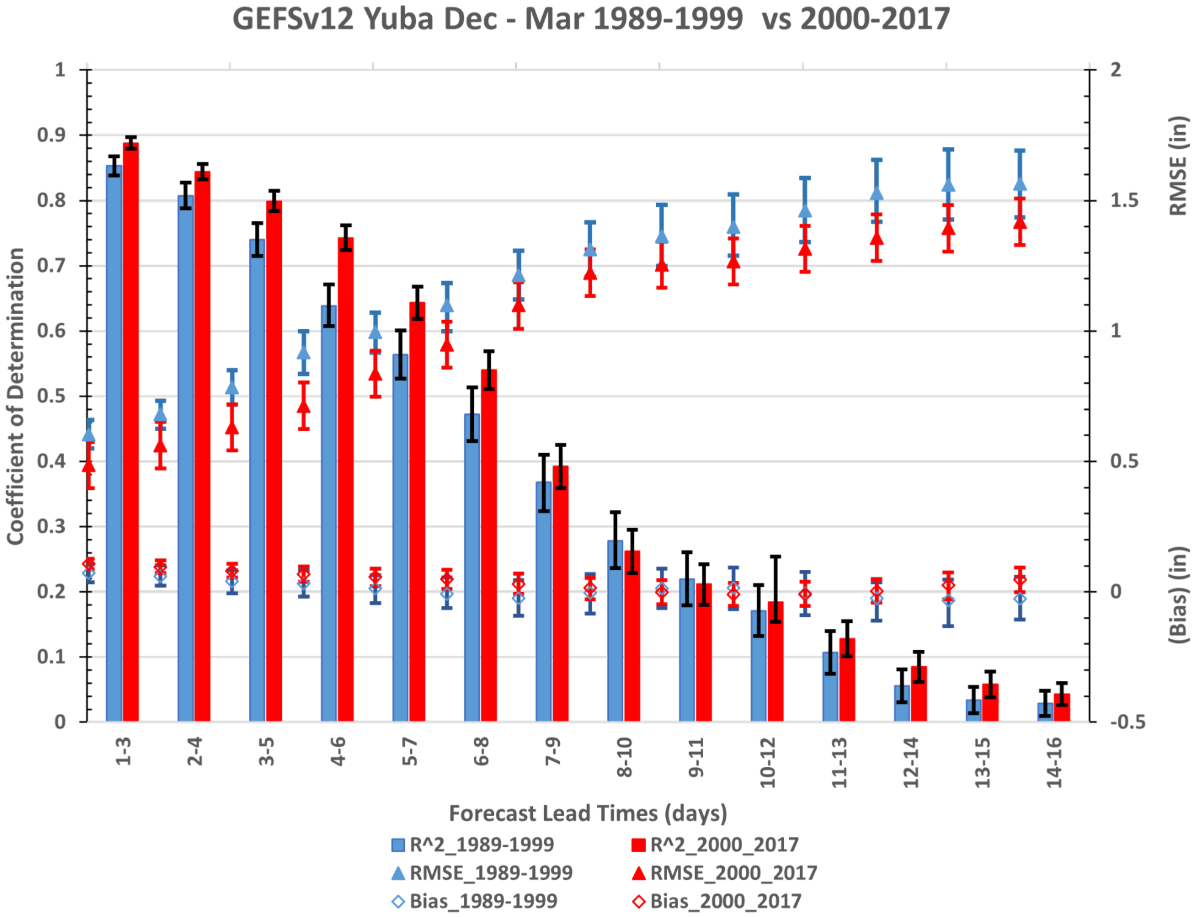


Figure P2-2. Same as Figure P2-1, but for the Yuba watershed.

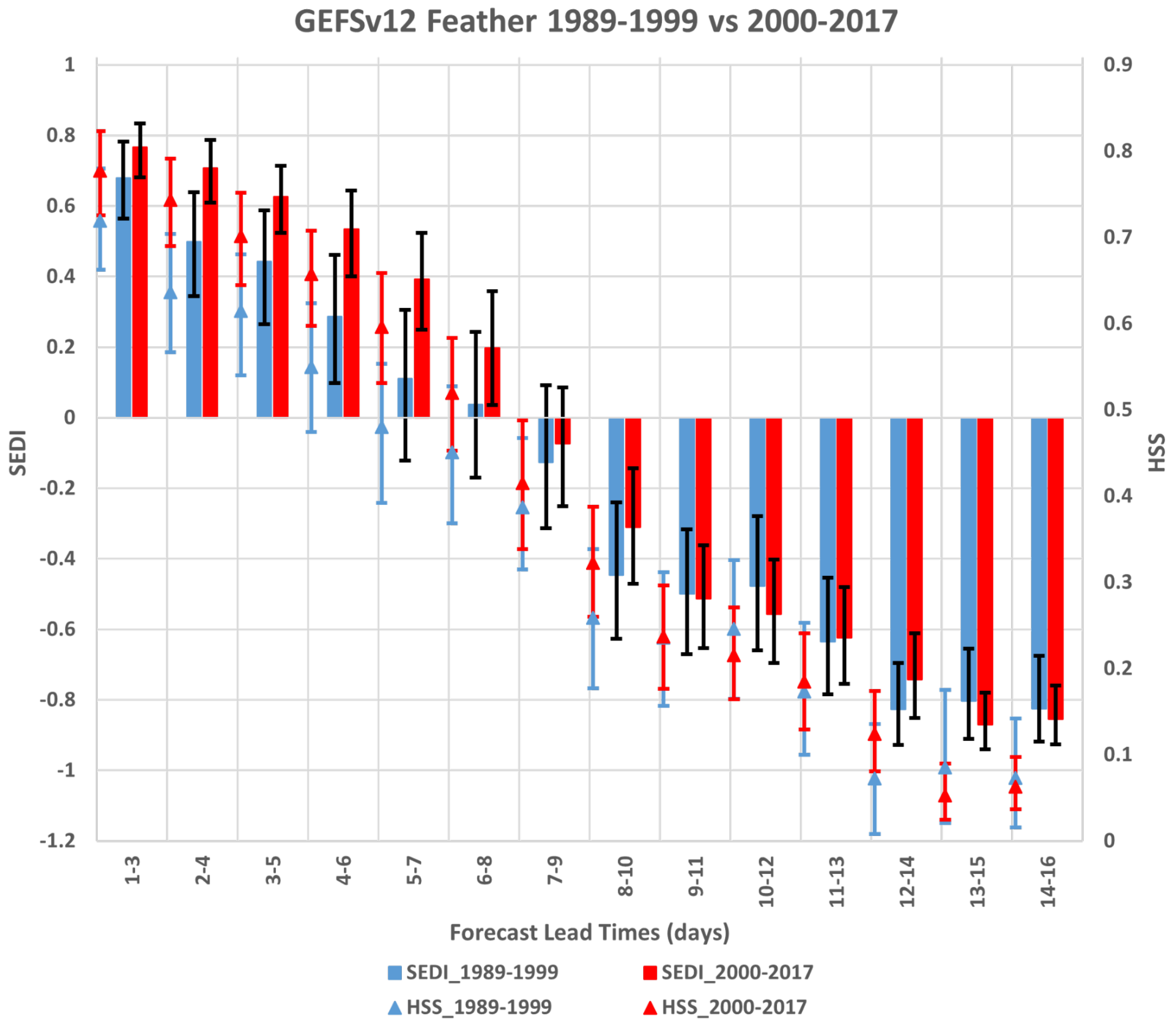


Figure P2-3. GEFSv12 ensemble mean SEDI (bars) and HSS (filled markers) for 72-hr mean areal precipitation in the Feather watershed during 1989-1999 (blue) and 2000-2017 (red). Errors bars denote 95% confidence intervals.

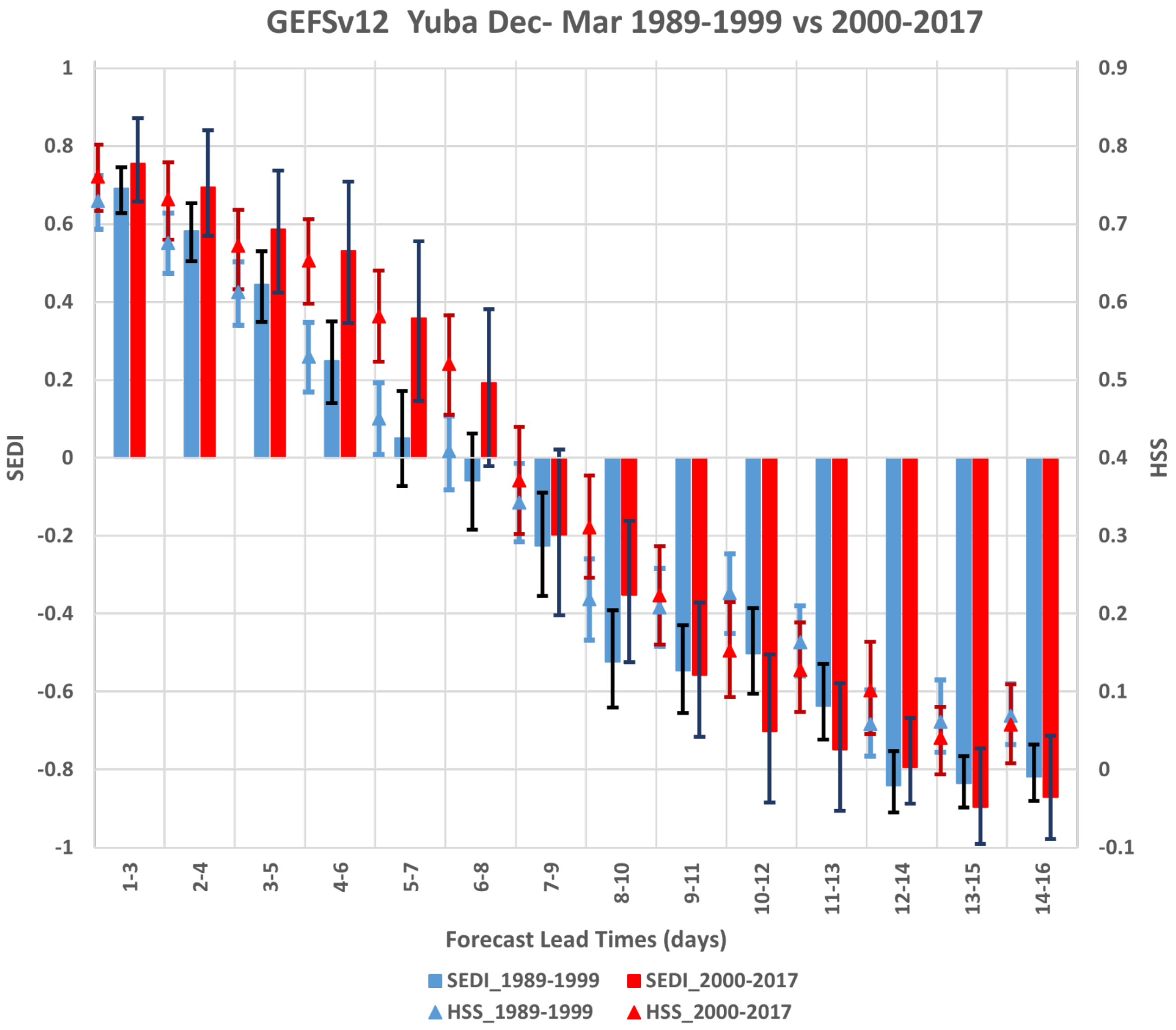


Figure P2-4. Same as Figure P2-3, but for the Yuba watershed.

Appendix Q—Decision Support Tools (Section 7)

Q.1 Introduction and Overview

Q.1.1 Introduction

Definition

Decision Support Tool

For Y-F FIRO and WCM Update efforts, DSTs refers to tools used to support New Bullards Bar and Lake Oroville reservoir operations during the flood season where decisions are governed by USACE Water Control Plans for the respective reservoirs. These tools can include the Y-F F-CO DSS, the USACE CWMS, forecasting tools, and other situational awareness tools.

Forecast-Informed Reservoir Operations (FIRO) is a reservoir operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operational policies and rules with enhanced monitoring and improved weather and water forecasts.

Water managers at Yuba Water and Department of Water Resources (DWR)'s Operations Control Office make decisions about the operation of New Bullards Bar Reservoir and Lake Oroville. Both operators receive forecasts of inflows and downstream unregulated flows and river conditions from the California-Nevada River Forecast Center (CNRFC) and Flood Operations Center and use this information along with information from other sources to make decisions about reservoir releases. The operating agencies consider their mission, the needs of their customers, downstream constraints, and the current state of their reservoirs when making release decisions. Those decisions include current operations (how much to release immediately) and future operations (how much to release in the future if the forecasts are correct or incorrect).

The Forecast-Coordinated Operations (F-CO) Program has developed a Decision Support System (DSS) as a centralized data and common modeling framework for F-CO during normal conditions and storm events. The F-CO DSS has two general features: entering forecasted reservoir releases and performing reservoir operation simulations using the Hydrologic Engineering Center's Reservoir System Simulation (HEC-ResSim). The DSS is located in the DWR California Data Exchange Center (CDEC), which directly receives updated runoff forecasts from CNRFC and DWR, the current release schedule and the reservoir's top of conservation level from DWR, and supporting data (i.e., precipitation, reservoir elevation) from Center for Western Weather and Water Extremes (CW3E).

FIRO will build on the existing relationships and tools among the F-CO project partners including State-Federal FOC, Operations Control Office (OCO) of the State Water Project (SWP), United States Army Corps of Engineers (USACE) Sacramento District, CNRFC, and Yuba Water Agency. F-CO and FIRO share the same goal of reducing flood risk for communities along with the Yuba-Feather Rivers system. The F-CO Program provides a pre-existing, coordinated operations framework and decision support system, which is initiated prior to and during major floods events. A key to successful FIRO implementation is improving understanding of the landing, magnitude, and duration of atmospheric rivers (ARs), which results in more accurate precipitation forecasting, runoff forecasting, and forecasting lead time for major storm events. As part of the FIRO implementation strategy, F-CO operations will integrate FIRO's improved precipitation and runoff forecasts to determine the pre-release of water in advance of major storms. These early releases will create additional storage in the reservoir to capture peak inflow to the reservoir, thereby reducing peak flood releases downstream. FIRO will also explore when reservoir operations can possibly produce secondary benefits of increased water supply reliability using different operating strategies, such as guide curves that allow for earlier refill or encroachment into the flood space without impacting flood operations.

Existing and emerging decision support tools (DSTs) were evaluated specific to the Yuba-Feather FIRO project to determine the benefits and limitations of individual tools. Review of DST performance for management of large storm events is critical to determine the adequacy of available tools and enhancements required. This effort will include assessing the performance of new forecast products over an extended historical record to determine their predictive skill for a large number of observed extremes, as well as their false alarm rate.

Interaction between the forecast information source (CW3E, NWS) and the end-user (DWR, USACE, Yuba Water Agency) will be essential as the FIRO Yuba-Feather PVA ventures to develop enhanced decision support tools that end users can readily understand and easily employ. Previous discussions in a similar context have highlighted that this information is not translated among atmospheric scientists, hydrologists, reservoir operators, and stakeholders with perfect fidelity and that assuming perfect fidelity can have consequences. An iterative approach to developing forecast diagnostics and DSTs that simply and effectively meet end-user needs via constant interaction (e.g., technical workshops) is essential to the success of FIRO.

Q.2 Goals and Objectives

The goals and objectives of the DST evaluation effort were identified during the development of the Y-F FIRO workplan, and further refined by the DST Workgroup during the development of the DST Workgroup Charter.

Q.2.1 Goal

Identification and evaluation of the DSTs (for the development and coordination of YF FIRO and WCM) need efforts including evaluation of FIRO alternatives to support interim operations and integration into WCMs and support for future FIRO research and planning efforts. It is not the intent of the DST evaluation effort to change the decision-making and responsibilities associated with the coordinated flood operations of the Yuba-Feather system.

Q.2.2 Objectives

The objectives of the research are:

1. Facilitate understanding of the available Y-F decision support tools.
2. Provide input on how DSTs will support Y-F FIRO development and WCM updates.
3. Provide input on what enhancements are needed to existing DSTs and what tools are needed to support Y-F FIRO and WCM updates.
4. Establish protocols for evaluation of DSTs during the development phase to ensure analysis results meet relevant professional standards and that input data and assumptions used by DSTs are consistent.

5. Create a transparent and collaborative work environment where the DST team can effectively support the tasks from the YF FIRO work plan and serve as a DST information resource for other subgroups.
6. Meet FIRO and WCM update project timelines.

Q.3 Technical Task

The technical tasks for the assessment of DSTs needed to support Y-F FIRO are listed below. The work carried out for each of these tasks is described in the next sections.

Q.3.1 Identification of Existing and Emerging DSTs

DST Existing Tools and Uses: Facilitate the team's understanding of the existing Y-F DSTs (Y-F F-CO DSS and USACE CWMS) and associated DSTs components. Gather and produce documentation to memorialize this.

Q.3.2 Identification of Decision Makers

Who are the decision-makers that should be considered in the evaluation of DSTs?

Q.3.3 Assessment of DST Information Gaps

DST Gap Analysis: Identify needs for any additional enhancements to DSTs (including component data feeds, processing tools, models, reporting, and collaboration tools) and any new DST components required. Describe findings and recommendations in a technical memorandum.

Q.3.4 DST Requirements for FIRO Alternatives Analysis

Use of DSTs for FIRO Alternatives Analysis: Review how forecasts are currently represented in Y-F DSTs and how future forecast enhancements developed under Y-F FIRO can be integrated. Gather and produce documentation to memorialize this.

Q.3.5 Discuss Potential DSTs Enhancement Needed

Support WRE efforts with the exploration of opportunities to integrate FIRO alternatives into existing DSTs (e.g., enhanced use of forecast ensembles and refinement of system operation) and identify primary constraints. Coordinate regularly with the WRE team for the exchange of information. Maintain documentation of meeting discussions and decisions.

Q.3.6 Coordinate with PVA Workgroups

Coordinate regularly with the WRE workgroup and other technical workgroups for the exchange of information (section 6 describe in detail the coordination between different workgroups).

Q.3.7 Develop Protocols for Evaluation of DSTs

Establish protocols for the evaluation of DSTs and describe methods in a technical memorandum.

Q.3.8 Updating Water Control Manuals and the use of DSTs

Provide input on how updated WCM updates should describe F-CO Program in the context of FIRO and the use of DSTs.

Q.4 DST Workgroup Efforts – Timeline

DST workgroup activities are shown in Figure Q-1. During the year 2021, activities related to the formation of the DST workgroup, information gathering, DST symposium was completed. Currently, the DST workgroup is focused on DST gap analysis.

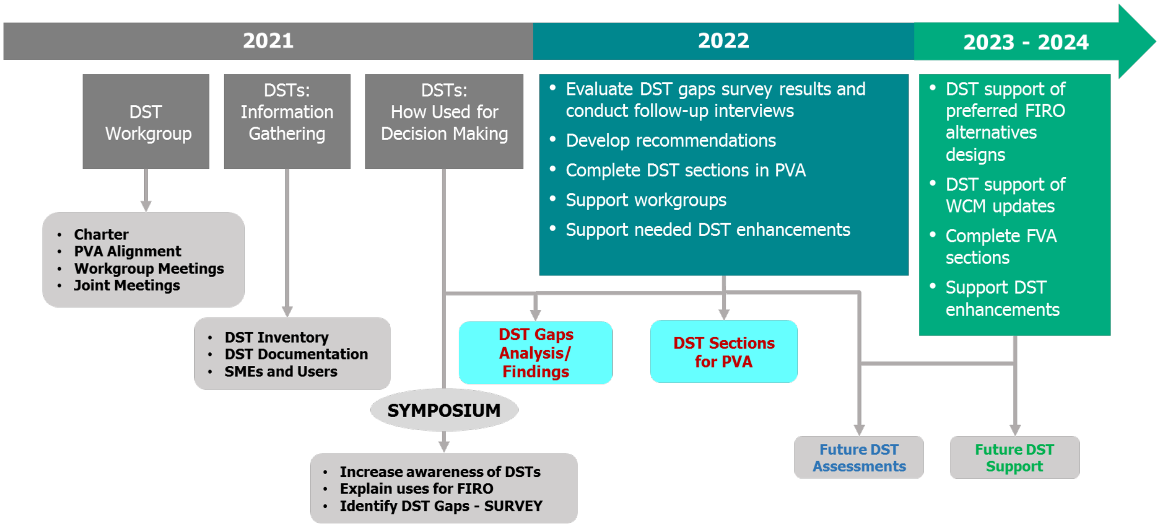


Figure Q-1. *Timeline for DST workgroup activities.*

Q.5 Identification of Existing and Emerging DSTs

DSTs refers to tools used to support New Bullards Bar and Lake Oroville reservoir operations during the flood season where decisions are governed by United States Army Corps of Engineers (USACE) Water Control Plans for the respective reservoirs. These tools include the Y-F F-CO DSS, the USACE CWMS, forecasting tools, and other situational awareness tools. The identification of the DSTs was conducted using the steps below:

1. An inventory of DSTs was initiated and shared with the DST workgroup.
2. Identified SMEs associated with each DST.
3. Identified key references/documentation for each DST.
4. DST co-leads worked with the DST workgroup members to review.

An inventory of existing and emerging DSTs relative to the Yuba-Feather FIRO effort identified over 30 DSTs. Table Q-1, Table Q-2, and Table Q-3 show the identified DSTs, supporting organization, subject matter experts (SMEs), brief description, and forecast cycle to support New Bullards Bar and Lake Oroville reservoir operations. These DSTs include real-time reservoir operations, agency-specific reservoir operations, and forecasting tools.

Table Q-1. *Real-time Flood Reservoir Operations Tools.*

No.	Name	Type	Operations Support	Use	Organization	SME	Description	Forecast Cycle	Status	Reference/ URL
1	Yuba-Feather Forecast Coordinated Operations.	Reservoir Operations.	Flood	Operations	Department of Water Resources (DWR)	Cale Nasca	Coordinate operations between Lk. Oroville and NBB	Variable	Operational	Cale (2021); CDEC (2021a)
2	Ensemble Forecast Operations	Reservoir Operations.	Flood	Operations	Sonoma Water (SW)	Chris Delaney	Risk based reservoir operations	Variable	Viable for Lake Mendocino and Prado Dam	Delaney et al. (2020)
3	Corps Water Management System (CWMS)	Reservoir Operations.	Flood	Operations	United States Army Corps of Engineers (USACE)	Jenny Fromm	Coordinate operations between Lake Oroville and NBB	Variable	A Sacramento Corps Water Management System (CWMS) watershed exists	USACE (2022)
4	Alternatives Tools and Approaches Under Consideration	Reservoir Operations.	Flood	Operations	DWR/SWP/YWA Department of Water Resources (DWR)/ State Water Project (SWP)	WRE/Rob et al				
5	SPK Hourly Spreadsheets	Reservoir Operations.	Flood	Operations	United States Army Corps of Engineers (USACE)	Jenny Fromm / Marchia Bond	Hourly spreadsheet models for flood control. One for ORO and one for NBB		Operational, but ESRD operations still need to be added.	

Table Q-2. *Agency-Specific Reservoir Operations Tools.*

No.	Name	Type	Operations Support	Use	Organization	SME	Description	Forecast Cycle	Status	Reference/ URL
1	State Water Project (SWP) Operations	Reservoir Operations	Flood/ Supply	Operations	Department of Water Resources (DWR)	Tracy Pettit	Water Management of the SWP	Daily/Weekly/ Monthly	Operational	DWRe (2022)
2	Operator Crystal Ball (OCB)	Reservoir Operations	Hydro/Supply/ Flood	Operations	Yuba Water Agency (YWA)	John James	Hydroelectric optimization and Lake Englebright water management over a daily and weekly time period, and short-term flood ops (F-CO hourly NBB releases)	Daily/Weekly	Operational	
3	Yuba River Development Model (YRDPM)	Reservoir Operations	Supply/Hydro/ Flood	Longer-range planning	Yuba Water Agency (YWA)	John James	Yuba Watershed including Middle and South Fork (Nevada Irrigation District (NID) and Pacific Gas and Electric Company - PG&E operations) for project uses (relicensing, Voluntary Settlement Agreements, Seasonal Storage, Environment/fisheries) and long-range operational uses (supply forecasts, power forecasts, flood planning)	Hourly	Operational	
4	SPK Hourly Spreadsheets	Reservoir Operations	Flood	Operations	United States Army Corps of Engineers (USACE)	Jenny Fromm Marchia Bond	Hourly spreadsheet models for flood control. One for ORO and one for NBB		Operational, but ESRD operations still need to be added.	

Table Q-3. *Forecasting Tools and Inputs*

No.	Name	Type	Operations Support	Use	Organization	Subject Matter Experts	Description	Forecast Cycle	Status	Reference/ URL
1	Ensemble/ Deterministic Streamflow Forecast	Hydrologic	Supply/Flood	Situational Awareness	California-Nevada River Forecast Center (CNRFC)	Alan Haynes	15-day, 39-member ensemble, 5-day forecast, Long-term seasonal forecast	6-hour	Operational	CNRFC (2000a & b)
2	B120 Water Supply Forecast Summary	Hydrologic	Supply	Situational Awareness	Department of Water Resources (DWR)	Sean de Guzman	Seasonal runoff forecast	Weekly (Feb to June)	Operational	CDEC (2021a, b, c)
3	Freezing Level Forecasts	Weather	Flood/ Supply	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	Brian Kawzenuk	Freezing elevation sub-divided by watershed	6-hour	Experimental	CW3E (2021a)
4	West Weather Research and Forecasting (West-WRF)	Weather	Flood	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	Luca Delle Monche	Regional High-resolution model	Daily	Experimental	CW3E (2021b); NOAA (2017)
5	Watershed Precipitation Forecasts	Weather	Flood/ Supply	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	Jay Cordeira	1- through 7-day precipitation forecasts for FIRO watersheds	12-hour	Experimental	CW3E (2021c)

No.	Name	Type	Operations Support	Use	Organization	Subject Matter Experts	Description	Forecast Cycle	Status	Reference/ URL
6	Integrated Vapor Transport (inclusive of many tools)	Atmospheric	Flood	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	Brian Kawzenuk	Warning for atmospheric rivers	6-hour	Operational	CW3E (2021d)
7	Atmospheric River (AR) Landfall Tool	Atmospheric	Flood	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	Jay Cordeira	Warning for atmospheric rivers	6-hour	Operational	CW3E (2021e)
8	Atmospheric River (AR) Scale	Atmospheric	Flood	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	F. Martin Ralph/Brian Kawzenuk	Atmospheric river strength	6-hour	Experimental	CW3E (2021f)
9	Subseasonal Atmospheric River (AR) Outlook	Climatic/ Subseasonal	Flood/ Supply	Situational Awareness	Center for Western Weather and Water Extremes (CW3E)	Michael DeFlorio	Subseasonal (6-weeks) atmospheric river activity	Daily	Experimental	CW3E (2021g)

No.	Name	Type	Operations Support	Use	Organization	Subject Matter Experts	Description	Forecast Cycle	Status	Reference/ URL
10	National Oceanic and Atmospheric Administration (NOAA) Climate Outlook/ North American Multi-Model Ensemble (NMME)	Climatic/ Subseasonal	Flood/ Supply	Situational Awareness	National Centers for Environmental Prediction (NCEP)	Alan Haynes	Multiple horizon outlooks of precipitation and temperature	Daily	Operational	NOAA (2001); NOAA (2021); Kirtman et al. (2014)
11	California Nevada River Forecast Center (CNRFC) Weather-Related Products	Climatic/ Subseasonal	Flood/ Supply	Situational Awareness	National Centers for Environmental Prediction (NCEP)	Dan Kozlowski	Focus on the real-time decision-making aspects			

Q.6 Identification of Decision Makers

The decision-makers (stakeholders) are the manager and key/lead reservoir operator from each partner organization involved in the Y-F FIRO. These decision-makers are responsible and accountable for real-time decision making related to Y-F coordinated flood operations during large floods events. The information of the decision-makers is summarized in Table Q-4 and Table Q-5.

Table Q-4. *DST Decision Maker and Principal User List.*

No.	Partner Organization	Name	Position	Responsibility		Connection to Yuba-Feather Decision Support Tools				E-Mail
				Operations	Forecast Provider	Flood-related Decisions	Other Decisions	Principal User	Consulted for Input	
1	Yuba Water Agency (YWA)	John James	Project Manager, Water Operations	Flood/Water Supply		x				jjames@yubawater.org

No.	Partner Organization	Name	Position	Responsibility		Connection to Yuba-Feather Decision Support Tools				E-Mail
				Operations	Forecast Provider	Flood-related Decisions	Other Decisions	Principal User	Consulted for Input	
2		Maury Miller	Engineer, Reservoir Operations	Flood/WS				x		mmiller@yubawater.org
3	Department of Water Resources (DWR)/State Water Project (SWP)	Tracy Pettit	Project Manager, State Water Project Operations	Flood/Water Supply		x				Tracy.Pettit@water.ca.gov
4		Norman Lee	Manager, SMS	Flood/Water Supply		x				norman.lee@water.ca.gov
5	Department of Water Resources (DWR)//HFO	Jeremy Hill	Chief, Operations Support Branch, Division of Flood Management	Flood		x				Jeremy.Hill@water.ca.gov
6		Cale Nasca	Manager, Reservoir Coordination Operations	Flood	x	x		x		cale.nasca@water.ca.gov
7		Angelique Fabbiani-Leon	Engineer, Reservoir Coordination Operations	Flood	x			x		Angelique.Fabbiani-Leon@water.ca.gov
8	United States Army Corps of Engineers	Jenny Fromm	Manager, Water	Flood Release Oversight		x		x		Jennifer.R.Fromm@usace.army.mil

No.	Partner Organization	Name	Position	Responsibility		Connection to Yuba-Feather Decision Support Tools				E-Mail
				Operations	Forecast Provider	Flood-related Decisions	Other Decisions	Principal User	Consulted for Input	
	(USACE) - Sacramento District Water Operations		Management Section							
9		Marchia Bond	Engineer, Water Management Section	Flood Release Oversight		x		x		marchia.v.bond@usace.army.mil
10		Joe Forbis	Chief, Water Management Section	Flood Release Oversight		x				joseph.c.forbis@usace.army.mil
11	National Weather Service (NWS)/ California-Nevada River Forecast Center (CNRFC)	Brett Whitin	Senior Hydrologist	Forecasting	x					Brett.Whitin@noaa.gov
12		Cindy Matthews	Senior Hydrologist	Weather C&O			Public C&O			cindy.matthews@noaa.gov
13		Peter Fickenscher	Development & Operations Hydrologist	Forecasting	x					peter.fickenscher@noaa.gov
14	National Marine Fisheries Service (NMFS)	Eric Danner	Team leader, Southwest Fisheries Science Center (SWFSC)	n/a			Env		x	Eric.Danner@noaa.gov
15		Steve Lindley	Director, Southwest Fisheries Science Center (SWFSC)	n/a			Env		x	steve.lindley@noaa.gov

Table Q-5. *DST Decision Maker consulted (participate in the review of findings, not discussions).*

				Responsibility		Connection to Y-F DSTs				
No.	**Partner Organization**	**Name**	**Position**	**Operations**	**Forecast Provider**	**Flood-related Decisions**	**Other Decisions**	**Principal User**	**Consulted for Input**	**E-Mail**
1	University of California San Diego (UCSD)/Scripps Institute of Oceanography	Marty Ralph	Director, Center for Western Weather and Water Extremes (CW3E)	Forecasting Technologies	x				x	mralph@ucsd.edu
2		Julie Kalansky	Operations Manager	Forecasting Technologies	x				x	jkalansky@ucsd.edu
3	United States Army Corps of Engineers (USACE) - Research and Development	Cary Talbot	Chief, Flood and Storm Protection Division	Research & Development, Best Practices					x	cary.a.talbot@erdc.dren.mil
4		Elissa Yeates	Research Hydraulic Engineer	Research &Development, Best Practices					x	Elissa.M.Yeates@erdc.dren.mil
5	Lake Mendocino Forecast-Informed Reservoir Operations (FIRO)	Jay Jasperse, Sonoma County Water Agency (SWA)	Chief Engineer	Flood/Water Supply					x	Jay.Jasperse@scwa.ca.gov
6		Patrick Sing, United States Army Corps of Engineers (USACE)	Senior Hydraulic Engineer	Flood					x	Patrick.F.Sing@usace.army.mil

No.	Partner Organization	Name	Position	Responsibility		Connection to Y-F DSTs				E-Mail
				Operations	Forecast Provider	Flood-related Decisions	Other Decisions	Principal User	Consulted for Input	
7	Prado Dam Forecast-Informed Reservoir Operations (FIRO)	Kim Moone, United States Army Corps of Engineers (USACE)	Principal Operator	Flood/Water Supply					x	moon.h.kim@usace.army.mil

Q.7 Assessment of DST Information Gaps

The DST Gap Analysis was performed using the three approaches: (1) Symposium, (2) Surveys, and (3) Discussion with Stakeholders. The objectives of the DST Gap Analysis were:

- Build an understanding of existing DSTs, including DSS, forecasting tools, and other supporting situational awareness tools used to support real-time reservoir operation decision-making for flood and water supply management within the Yuba-Feather watershed system and similar watersheds.
- Explore how existing DSTs meet decision-maker/operator needs in the Yuba-Feather watershed.
- Explore additional needs of decision-makers/operators that have not currently been met by existing DSTs in the Yuba-Feather watershed.

Q.8 Symposium

The purpose of the Symposium was to present the existing DSTs to the Stakeholder group (decision-makers and managers). The SMEs presented the existing DSTs (identified by the DST Workgroup) at the DST Symposium held in October 2021. The symposium was attended by decision-makers and managers who have performed, authorized, or coordinated with the New Bullards Bar Dam and Reservoir operations on the North Fork of the Yuba River and Oroville Dam and Reservoir on the Feather River. Presentations were also recorded and made available to those Stakeholders not able to attend. The general guidance to help SMEs structure their DST presentations were:

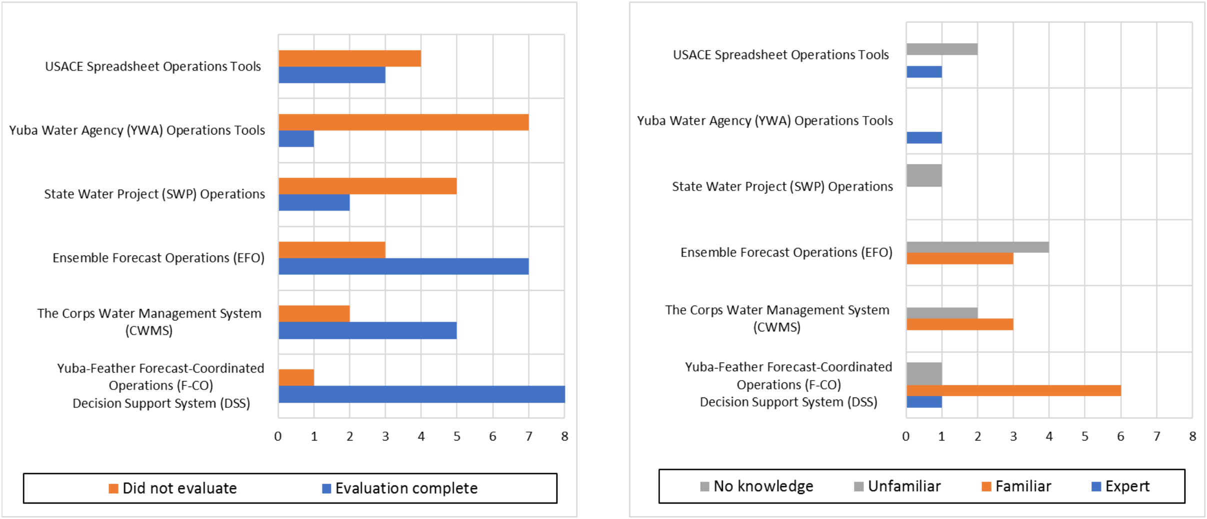
- Gear the presentations toward Stakeholders.
- Focus on DST use/application from a user perspective.
- Provide case examples.
- Record presentations for Stakeholders not able to attend the DST Symposium.

Q.9 Surveys

The DST Gap Survey was conducted to gather input on the information gaps in DSTs and identify needs and recommendations for enhancing and further evaluating DSTs. The DST Gap Survey covered 18 DSTs of which 7 were DSS tools and 11 were forecast and situational (observational) awareness tools. DST Gap Surveys were completed by 9 individuals representing operators and managers associated with YWA, DWR-SWP, and USACE. The key questions asked in the surveys were:

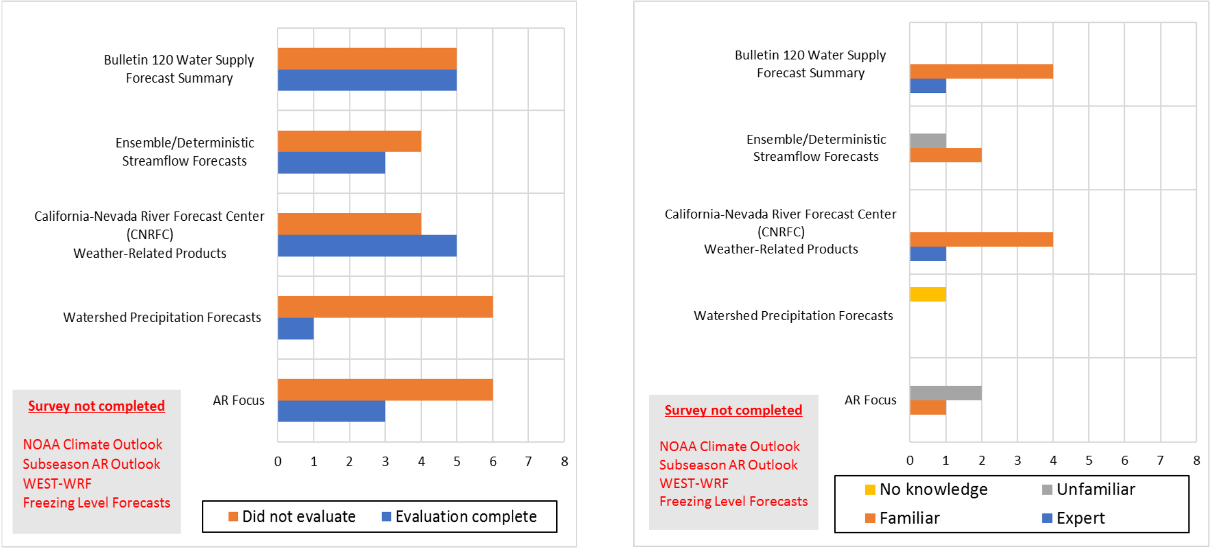
- Can the tool provide additional information that may be useful? If so, please describe this information briefly; and
- What enhancements are needed to fulfill your agency’s current operational objectives?

Surveys were completed by all agencies responsible for reservoir operations decisions (responsible agencies), including DWR and DWR-SWP; YWA; and USACE. Figure Q-2 & Figure Q-3 show the evaluation summary and familiarity of the DSS and forecast tools identified using the DST Gap Survey.



(a) (b)

Figure Q-2. *Summary of the survey of DSS tools, (a) evaluation summary of the DSS tools, and (b) familiarity with the DSS tools.*



(a) (b)

Figure Q-3. *Summary of the survey, (a) evaluation summary of the Forecast tools, and (b) familiarity with the forecast tools.*

Q.10 Discussions

The purpose of the Stakeholders' Discussions was to gather information about the needs/gaps about making real-time flood operations decisions, and the relationship of those decisions to other uses, such as water supply, environmental compliance, and hydropower. Stakeholders were identified from each Y-F FIRO partner organization. Following the symposium, discussions were held with agencies responsible for these operations, including the California Department of Water Resources, the State Water Project operations office, the Yuba Water Agency, and the USACE Sacramento District Water Management Section. The following discussions took place in March of 2022:

- USACE, March 3, 2022, Jenny Fromm (Lead Water Manager Water Management Section), Marchia Bond (Senior Engineer Water Management Section).
- YWA, March 8, 2022, John James (Manager of Resource Planning).
- DWR-SWP, March 9, 2022, Tracy Pettit-Polhemus (Manager SWP Operations), Norman Lee (Manager SMS), Dustin Jones (Supervising Engineer Division of O&M).

The discussion objectives were:

- Review and discuss the survey results and obtain agency feedback.
- Discuss questions posed by the DST Workgroup co-leads.
- Discuss agency questions and comments about the DST survey results and perspectives on DST needs with the implementation of FIRO in the Yuba-Feather watershed.

The discussion questions include:

- What are the challenges of managing the array of DSTs that produce forecasts and provide access to observations?
- What forecast and observation tools/products would you like to learn more about?
- What are the major gaps/needs for improvement in DSTs or the information they provide?
- Describe priorities, if any, of addressing uncertainty, for example: need better integration and user-friendly illustration of ensemble products in DSTs.
- Are there DST or data integration/linkage needs? What would be the potential benefits of this integration/linkage?

Q.11 Discuss Potential DSTs Enhancements Needed

Q.11.1 Gaps

This DST Gap Analysis using Survey and Discussions reveals several knowledge gaps in the forecast products and DST tools. Figure Q-4 through Figure Q-15 show the knowledge gaps and potential enhancements needed in the DST and forecast tools. The knowledge gap regarding the forecast products identified is how to use forecasts from different sources and utilize this information consistently. More specifically, the survey results indicate:

- A lack of understanding of the CW3E and NOAA forecast and observational products, and the individual tool's goal and intended use.
- The extensive amount of information provided by these forecast and observational products can be overwhelming to users, highlighting the need to improve how these products are connected to and used within the operational stream.
- A lack of understanding of the uncertainty and accuracy of the different forecast products, suggesting a need to explore accuracy of different forecast products and publish this information in a user-friendly context.

Also, there was less feedback provided on forecast and observational tools as compared to DSS tools, further supporting the finding that there is a lack of understanding of these tools and the information they provide.

The survey also identified gaps in the operational tools, including:

- Integration of tools, for example, integration of ensemble information into spreadsheet tools.
- Available portals and platforms for information exchange between operational models and tools.
- Functionality for balancing and managing stored water to better maximize benefits and minimize risks.

Also, through the WRE workgroup evaluation of the FIRO water control plan alternatives, reservoir operations modeling gaps associated with HEC-ResSim were identified and are described in Section 7.2 of the PVA. These DST gaps will need to be resolved in the FVA to facilitate implementation of FIRO in the Yuba-Feather watershed system.

Q.11.2 Needs

The need for a DST needs to support FIRO in the Yuba-Feather reservoir system were assessed by exploring the following: the role of a DSS, why a DSS is important to the system, what DSTs are currently available, what the future need for operating under FIRO will be, and what potential enhancements will be required to existing and emerging DSTs might be needed to meet the needs of decision makers. The assessment involved identifying the available and emerging DSTs and reviewing with decision makers the DSTs that may be utilized and refined to help implement FIRO. The assessment of DST gaps is designed as a proactive approach to understanding the needs of the DSTs. This initial assessment completed for the PVA is the beginning of the process to identify gaps in DSTs and makes recommendations for how best to proceed with future phases of DST evaluations that will occur during the FVA effort, WCM updates the updates to the WCMs, and eventually the implementation phase of FIRO.

Interaction between the forecast information source (CW3E, NWS) and the end-user (DWR, Yuba Water, and USACE) will be essential as the FIRO Yuba-Feather PVA ventures to develop enhanced decision support tools that end users can readily understand and easily employ. Previous discussions in a similar context have highlighted that this information is not translated among atmospheric scientists, hydrologists, reservoir operators, and stakeholders with perfect fidelity and that assuming perfect fidelity can have consequences. An iterative approach to developing forecast diagnostics and DSTs that simply and effectively meet end-user needs via constant interaction (e.g., technical workshops) is essential to the success of FIRO.

The following needs are based on results of the DST assessment efforts:

- Training to improve the understanding and use of the forecasting and observational products.
- Further exploration into the integration of forecast and observational products for situational awareness into the operational tools.
- Identify needed coordination/integration/exchange between operational tools, such as between CWMS and FCO DSS tools: (1) How can information be exchanged between operational tools, and (2) How can tools be better integrated (or coordinated) so that they can quickly and effectively share information.
- How to equip tools to balance stored water and releases to meet FIRO objectives.

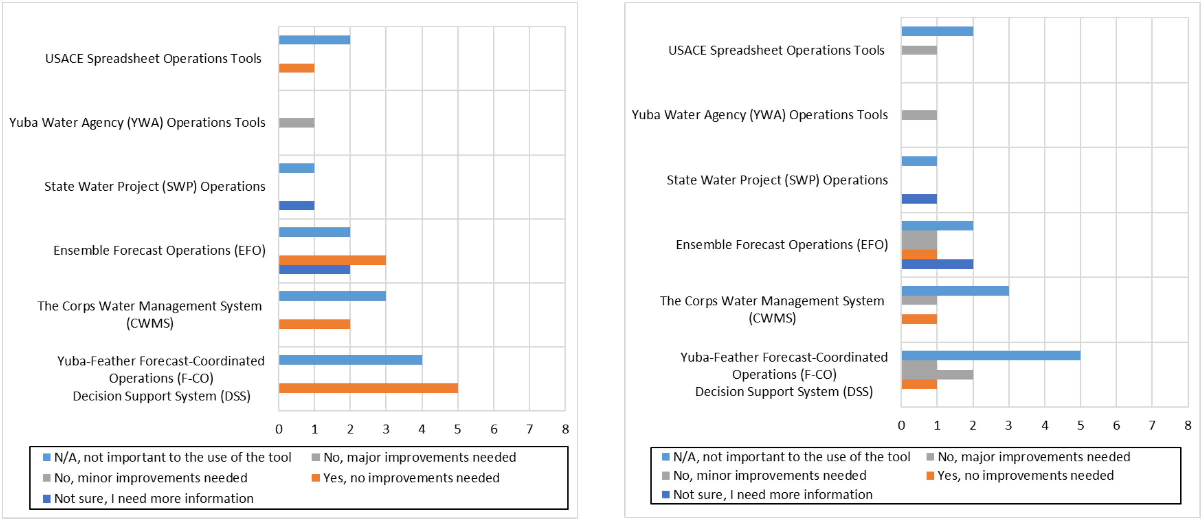
The following needs and recommendations are based on needs identified through the DST workgroup process:

- Need a DSS that supports implementation of a FIRO WCP.
- A reservoir operations tool to implement FIRO WCPs.

Q.12 Recommended Action

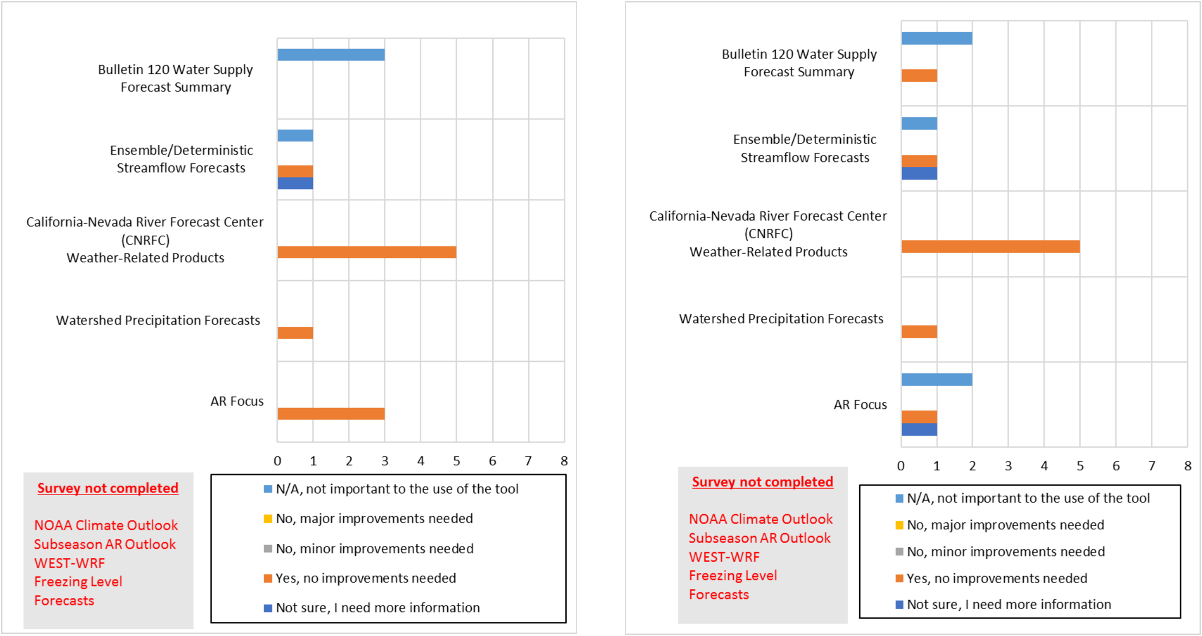
The following recommendations are based on the results of the DST assessment efforts:

- Investigate how to improve the consistency of which forecast and observational products are used, and how they are used.
- Complete a Tabletop Exercise or Information Discovery Exercise to get the researchers and operators together to use the forecasting and situational awareness tools for a historical event, like the 1997 or 2017 events, to understand the operational needs and how forecast tools can be helpful. And for researchers to gain an understanding of operator needs those researchers can further investigate for making future enhancements to tools.
- Use the F-CO DSS for the development and implementation of a DSS to support FIRO operations.
- Identify the forecast information attributes that would be defined in a WCP and represented in a DSS.
- Revise HEC-ResSim to support FIRO water control plans.



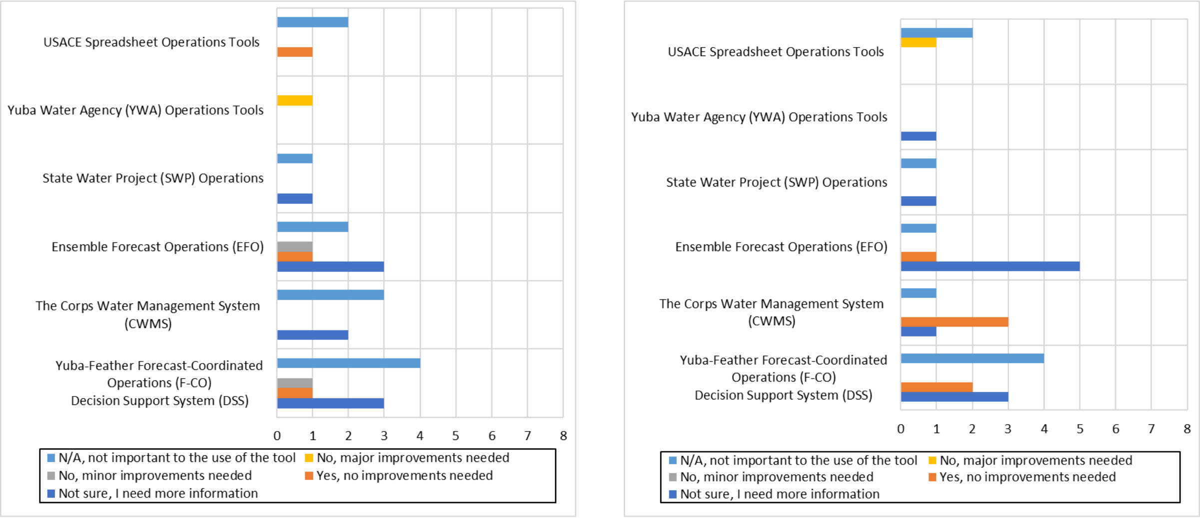
(a) (b)

Figure Q-4. *Survey results for the gap analysis of DSS tools, (a) short-term forecast of precipitation, and (b) long-term forecast of precipitation.*



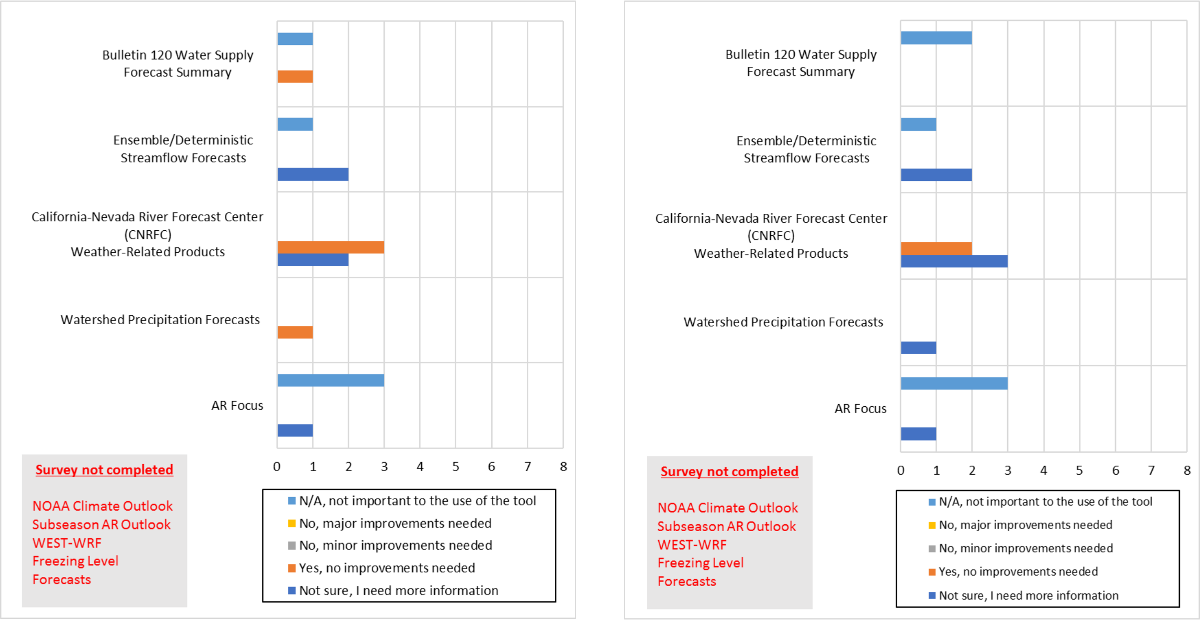
(a) (b)

Figure Q-5. *Survey results for the gap analysis of forecast tools, (a) short-term forecast of precipitation, and (b) long-term forecast of precipitation.*



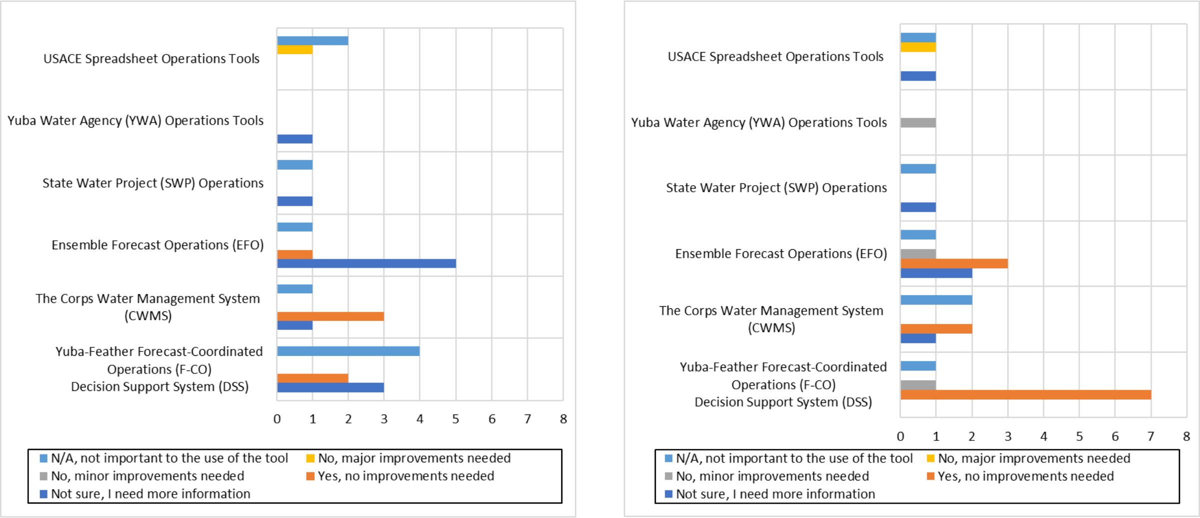
(a) (b)

Figure Q-6. *Survey results for the gap analysis of DSS tools, (a) rain/snow separation elevation, and (b) losses in the computation of direct runoff.*



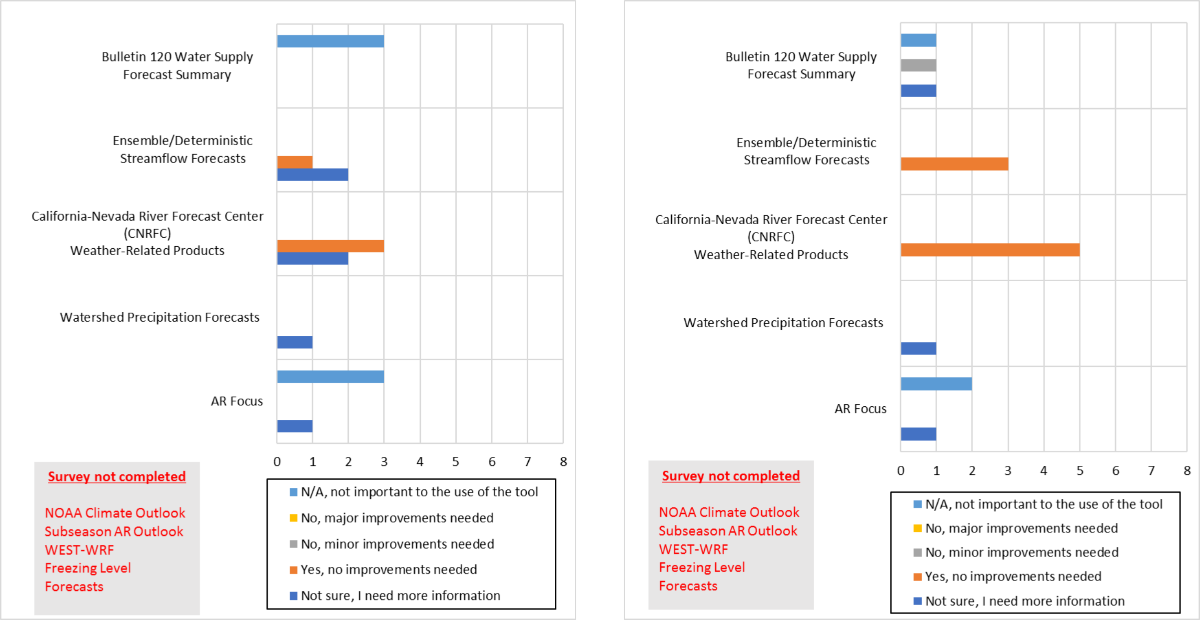
(a) (b)

Figure Q-7. *Survey results for the gap analysis of forecast tools, (a) rain/snow separation elevation, and (b) losses in the computation of direct runoff.*



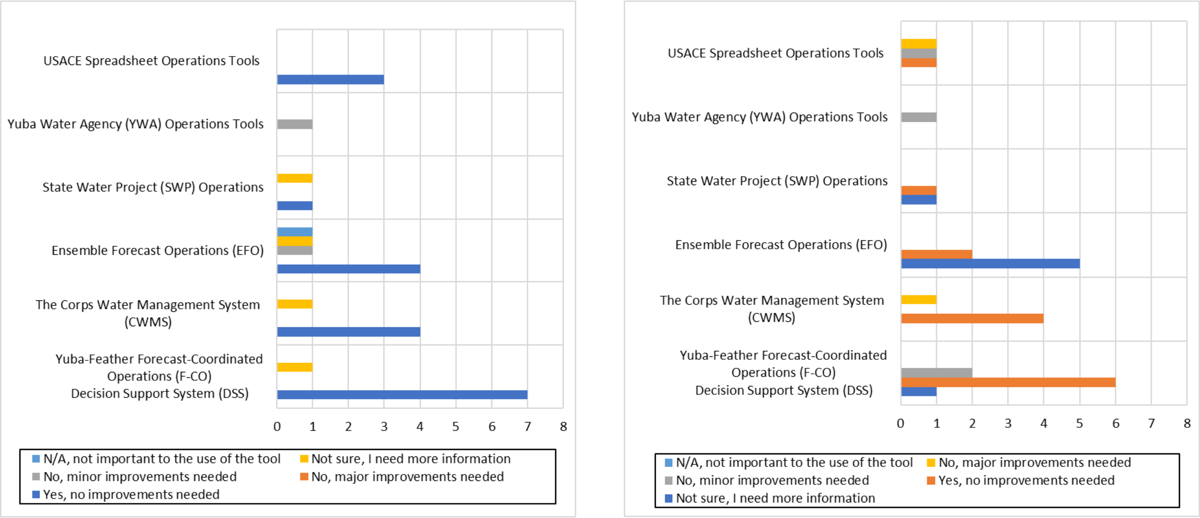
(a) (b)

Figure Q-8. *Survey results for the gap analysis of DSS tools, (a) rainfall-runoff transform, and (b) inflow forecasting.*



(a) (b)

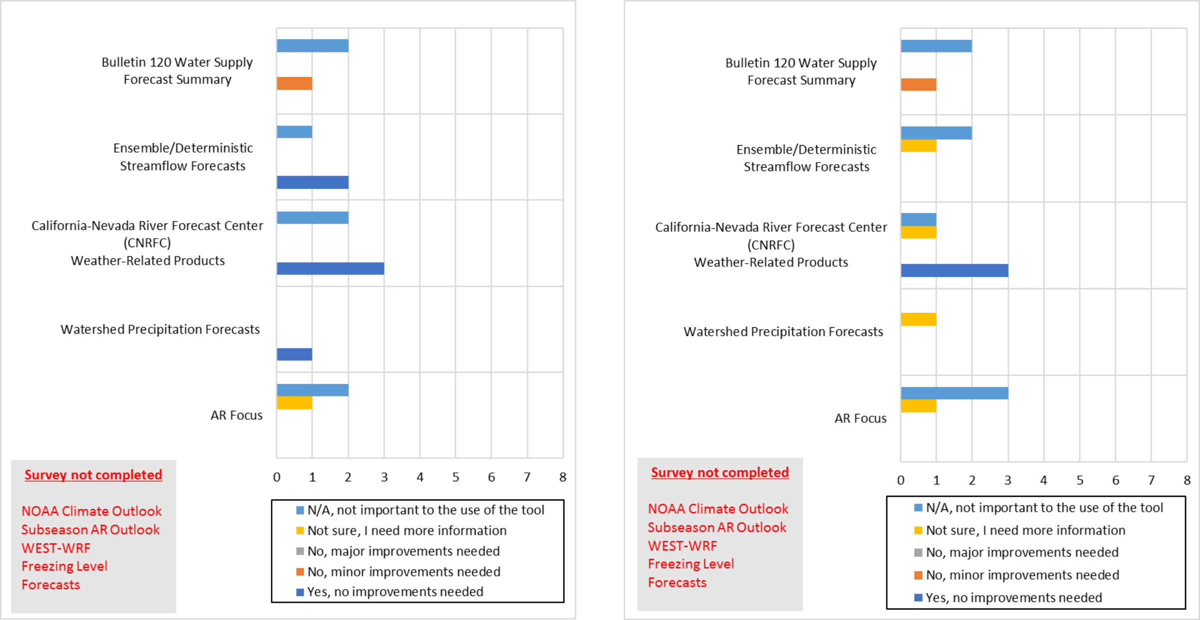
Figure Q-9. *Survey results for the gap analysis of forecast tools, (a) rainfall-runoff transform, and (b) inflow forecasting.*



(a)

(b)

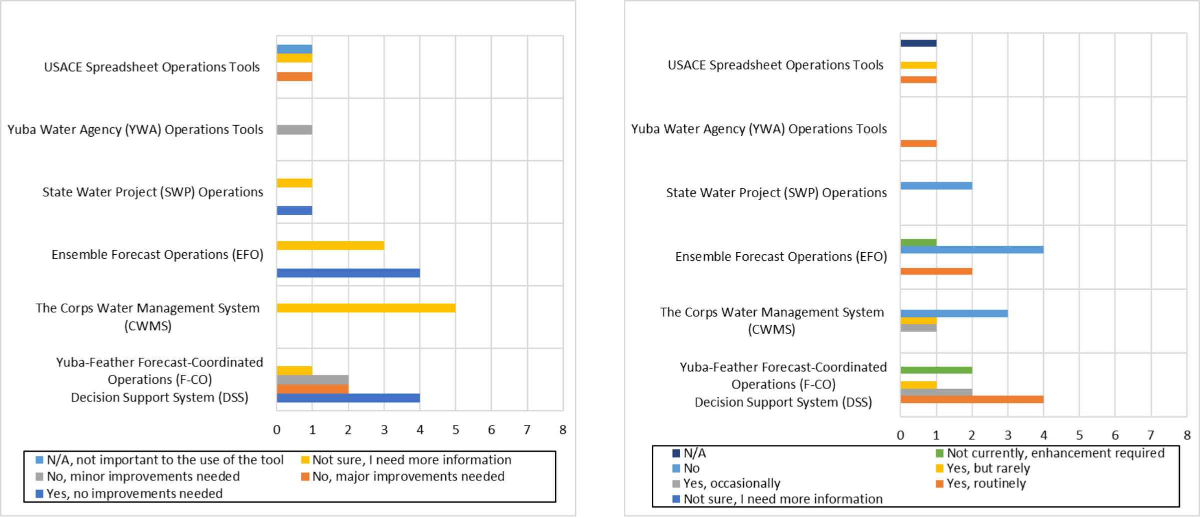
Figure Q-10. *Survey results for the gap analysis of DSS tools, (a) release decision support, and (b) system performance.*



(a)

(b)

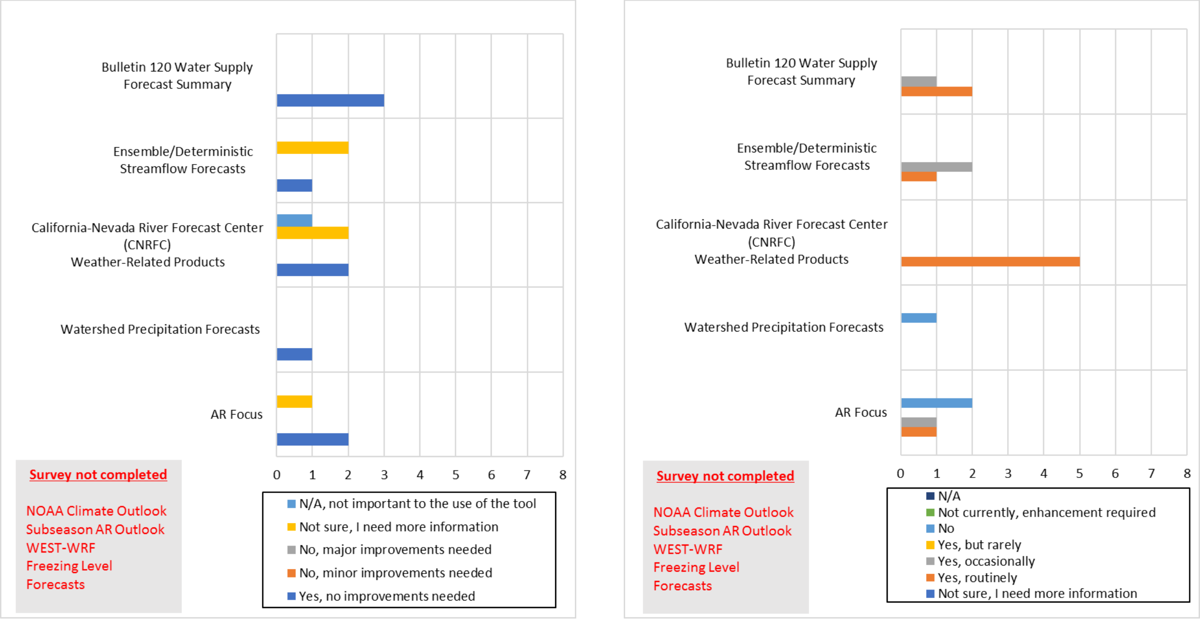
Figure Q-11*. Survey results for the gap analysis of forecast tools, (a) release decision support, and (b) system performance.*



(a)

(b)

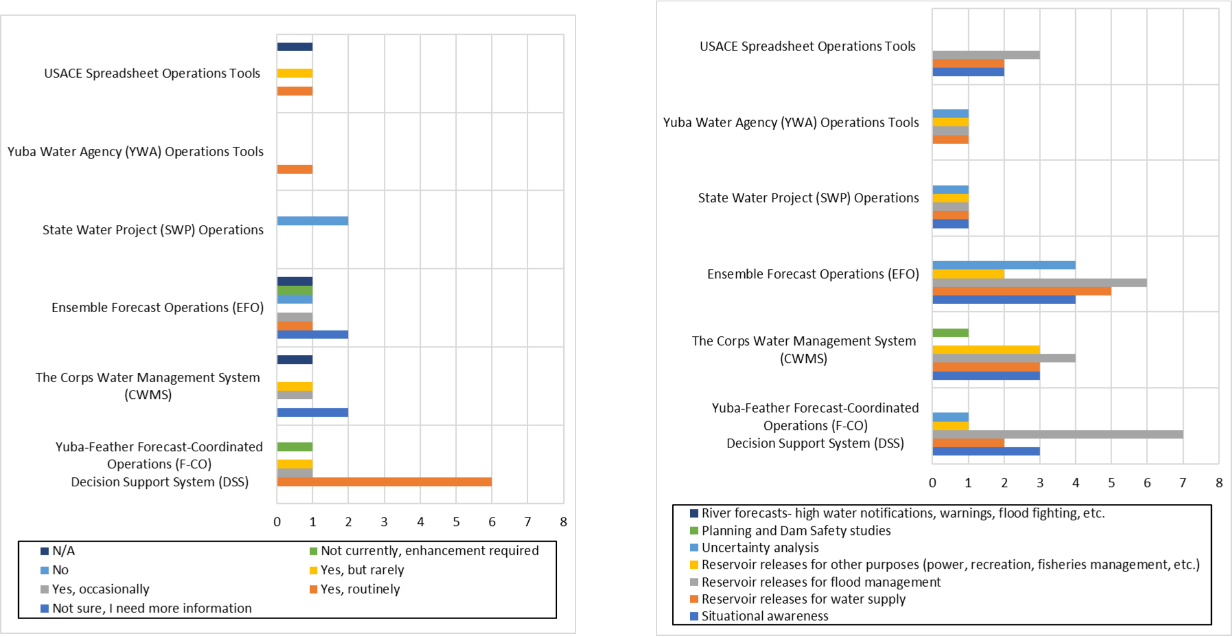
Figure Q-12. *Survey results for the gap analysis of DSS tools, (a) uncertainty analysis, and (b) is the tool currently used by your agency to make decisions?.*



(a)

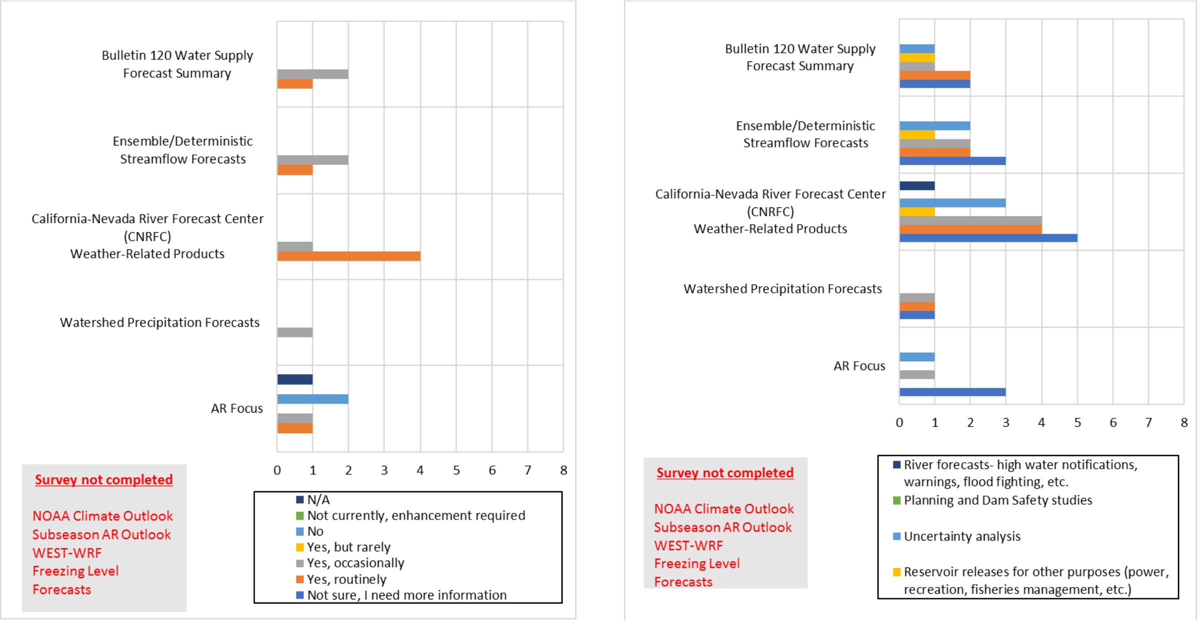
(b)

***Figure Q-13**. Survey results for the gap analysis of forecast tools, (a) uncertainty analysis, and (b) is the tool currently used by your agency to make decisions?.*



(a) (b)

Figure Q-14. *Survey results for the gap analysis of DSS tools, (a) Does the tool have the required functionality or provide the necessary information for your agency to make decisions in accordance with your mission/objective?, and (b) Based on your understanding of this tool, what types of decisions would this tool be useful for? (Select all that apply.)*



(a) (b)

Figure Q-15. *Survey results for the gap analysis of forecast tools, (a) Does the tool have the required functionality or provide the necessary information for your agency to make decisions in accordance with your mission/objective?, and (b) Based on your understanding of this tool, what types of decisions would this tool be useful for? (Select all that apply).*

Q.13 Coordination with Other Workgroups

Identification and evaluation of the DSTs needed to support the development and coordination of YF FIRO and WCM update interrelated efforts, including evaluation of FIRO alternatives to support interim operations and integration into WCMs, and support for future FIRO research and planning efforts. These planning efforts include coordination with other technical workgroups (see Table Q-6 for the DST technical team (Team Charter)). The DST technical team meet regularly each month and completed 10 meetings by date: (1) May 12, 2021, (2) June 16, 2021, (3) July 21, 2021, (4) August 18, 2021, (5) September 15, 2021, (6) October 20, 2021, (7) November 17, 2021, (8) December 17, 2021, (9) January 19, 2022, and (10) February 11, 2022.

***Table Q-6**. DST technical team (Team Charter) and organizations.*

Organization	Team Members
Yuba Water Agency	John James
Department of Water Resources (DWR)/ State Water Project (SWP)	Dustin Jones, Tracy Pettit
Department of Water Resources (DWR)/HFO	Angelique Fabbiani-Leon
Department of Water Resources (DWR)/DES	Stephanie Chun
SPK	Jenny Fromm, Marchia Bond
California Nevada River Forecast Center (CNRFC)	Brett Whitin
Robert K Hartman Consulting Services (RKHCS)	Rob Hartman
MBK Engineers	Ben Tustison, Carly Narlesky
HDR, Inc	Donna Lee, Nathan Pingel, Mike Konieczki
Center for Western Weather and Water Extremes (CW3E)	Forest Cannon, Julie Kalansky, Mike DeFlorio, Duncan Axisa, Ming Pan, Chad Hecht, Anna Wilson, Ava Cooper
United States Army Corps of Engineers (USACE)/ Engineer Research and Development Center (ERDC)	Elissa Yeates, Karlie Wells

The objectives of the different workgroup’s coordination are:

- Facilitate understanding of the available Y-F decision support tools.
- Provide input on how decisions support tools will support Y-F FIRO development and WCM updates.
- Provide input on what enhancements are needed to existing decision support tools and what tools are needed to support Y-F FIRO and WCM updates.
- Establish protocols for evaluation of DSTs during the development phase to ensure analysis results meet relevant professional standards and that input data and assumptions used by DSTs are consistent.
- Create a transparent and collaborative work environment where the DST team can effectively support the tasks from the YF FIRO work plan and serve as a DST information resource for other subgroups.
- Meet FIRO and WCM update project timelines.

The FIRO/WCM alignment focus are to consider:

- How Y-F FIRO alternatives can be implemented in Y-F F-CO DSS and USACE CWMS in terms of forecast ingestion and processing, and reservoir operation modeling, including system operation.
- Integration with precipitation-runoff modeling, hydraulic routing, and consequence modeling, if needed.
- How forecasts are currently represented in DSTs and how future forecast enhancements developed under Y-F FIRO can be integrated into DSTs.
- How testing of operational rules is currently supported in DSTs and how Y-F FIRO alternatives can be supported by DSTs. And how this would inform WCM updates and associated modeling and analysis.
- WCM updates that allow flexibility for future enhancements and evolution of DSTs.

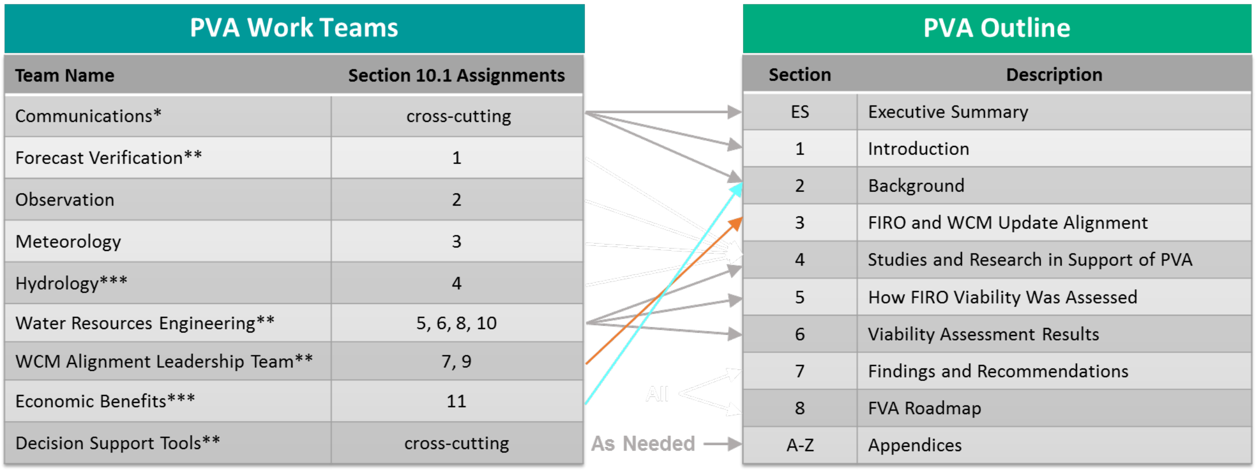
Table Q-7 shows the DST team members and their role (RACI chart) in other technical workgroups. Whereas the Other Workgroup column shows the connection of DST workgroup members to other PVA workgroups. The DST workgroup membership has good distribution as members of the other six technical workgroups. At least one member of the DST workgroup (and multiple members in most cases) is a member of each of the other workgroups. The abbreviations in **bold red** indicate if a DST member is a lead for another workgroup. This DST member will help with coordination/communication between groups. Workgroups not represented by a lead are Observation, Outreach & Communications, and Economics. DST members with membership in these groups will help with coordination/communication between groups. The PVA workgroup and coordination are summarized in Figure Q-16.

Table Q-7*. Team Members and Roles (RACI chart).*

Name	Organization	Position	Responsible	Accountable	Consulted	Informed	Other Workgroup
Cale Nasca	Department of Water Resources (DWR)	Reservoir Operations	X				Water resources Engineering, Obs, Hydrology, Ldr
Chris Delaney	Sonoma Water Agency	Project Manager support	X				Water resources Engineering, Ver
Roger Putty	GEI Consultants Inc (Department of Water Resources /Yuba Water Agency)	Tech and Project Manager	X				Water resources Engineering, Obs, Meteorology, O&C, Economy
John James	Yuba Water Agency	Water Operations Project Manager			X		Water resources Engineering, Obs, Meteorology, O&C
Dustin Jones	Department of Water Resources (DWR)/State Water Project (SWP)	Project Managers Support			X		Water resources Engineering, Ver, Obs, O&C, Economy
Tracy Pettit	Department of Water	Water Operations			X		Ver, Obs

Name	Organization	Position	Responsible	Accountable	Consulted	Informed	Other Workgroup
	Resources (DWR) /State Water Project (SWP)						
Stephanie Chun	Department of Water Resources (DWR) /DES	Tech Support			X		
Angelique Fabbiani-Leon	Department of Water Resources (DWR) /HFO	Water Resources Engineer		X			Ver
Jenny Fromm	United States Army Corps of Engineers - SPK	Lead Water Manager			X		Water resources Engineering, Meteorology, O&C
Marchia Bond	United States Army Corps of Engineers - SPK	Water Operations		X			Ver
Brett Whitin	California Nevada River Forecast Center (CNRFC)	Service Coordinator Hydrology		X			**Hydrology**, Obs
Rob Hartman	Robert K Hartman Consulting Services (RKHCS)	Tech Support		X			**Water Resources Engineering**, Ver, Obs
Ben Tustison	MBK (Yuba Water Agency)	Engineer Support			X		Water resources Engineering, Hydrology
Carly Narlesky	MBK Engineers (YWA)	Engineer Support		X			Water resources Engineering, Hydrology
Donna Lee	HDR, Inc	Tech support			X		Water resources Engineering, Obs, Hydrology, O&C
Nathan Pingel	HDR, Inc	Tech support			X		Water resources Engineering, Hydrology, O&C, Economy
Mike Konieczki	HDR, Inc	Tech support		X			
Forest Cannon	Center for Western Weather and Water Extremes	Atmospheric River Lead		X			**Met**, Ver, Obs
Julie Kalansky	Center for Western Weather and Water Extremes	Dep Director			X		O&C
Mike DeFlorio	Center for Western Weather and Water Extremes	S2S Lead				X	
Duncan Axisa	Center for Western Weather and Water Extremes	FIRO Lead		X			Water Resources Engineering, **Ver**, Obs, Meteorology, Hydrology, O&M, Economy
Ming Pan	Center for Western	Hydrology Lead			X		Water Resources Engineering,

Name	Organization	Position	Responsible	Accountable	Consulted	Informed	Other Workgroup
	Weather and Water Extremes						Hydrology, Ver, Obs
Chad Hecht	Center for Western Weather and Water Extremes	Staff Meteorologist and Forecaster			X		



PVA Work Teams

Team Name	Section 10.1 Assignments
Communications*	cross-cutting
Forecast Verification**	1
Observation	2
Meteorology	3
Hydrology***	4
Water Resources Engineering**	5, 6, 8, 10
WCM Alignment Leadership Team**	7, 9
Economic Benefits***	11
Decision Support Tools**	cross-cutting

PVA Outline

Section	Description
ES	Executive Summary
1	Introduction
2	Background
3	FIRO and WCM Update Alignment
4	Studies and Research in Support of PVA
5	How FIRO Viability Was Assessed
6	Viability Assessment Results
7	Findings and Recommendations
8	FVA Roadmap
A-Z	Appendices

***Figure Q-16**. PVA workgroup coordination and assignments.*

Q.14 Develop Protocols for Evaluation of DSTs

The technical tasks for achieving the goals and objectives of the DST evaluation effort were identified during the development of the Y-F FIRO workplan, and further refined by the DST Workgroup during the development of the DST Workgroup Charter. The workgroup identified as a technical task, the need to establish protocols for the evaluation of DSTs and to describe those methods in a technical memorandum. However, during the PVA effort the DST Workgroup determined that the focus of the DST evaluation effort should be on identifying information gaps. A detailed evaluation of DSTs will be completed during the FVA when the preferred FIRO alternative will be developed. At that time the requirements of DSTs to support those alternatives will be identified.

With this in mind, the DST Workgroup was not able to take on this technical task of developing protocols for evaluating DSTs since these protocols will be informed in part by the DST requirements dictated by the preferred FIRO alternative. For this reason, the DST Workgroup will complete this technical task during the development of the FVA.

Q.15 Updating Water Control Manuals and Use of DSTs

As noted above, the technical tasks for achieving the goals and objectives of the DST evaluation effort were identified during the development of the Y-F FIRO workplan, and further refined by the DST Workgroup during the development of the DST Workgroup Charter. The DST Workgroup identified as a technical task, the need to provide input on how updated WCM should describe the F-CO Program in the context of incorporating FIRO into the WCM update, and the related use of DSTs. However, during the PVA effort the DST Workgroup determined that the focus of the DST evaluation effort should be on identifying information gaps, and not on recommending DSTs for supporting FIRO in the WCM update. For this reason, the DST Workgroup will complete this technical task during the development of the FVA.

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Appendix R—Yuba-Feather FIRO Economic Benefits (Section 9)

R.1 Yuba-Feather FIRO Economic Benefits

Multipurpose reservoirs provide quantifiable economic benefits that include water supply reliability during dry periods, flood damage risk reduction during wet periods, recreation, navigation, hydropower, ecological benefits, and climate resilience (Klemeš 1977, Datta and Burges 1984, Graham and Georgakakos 2010).

Flood damage risk reduction benefits can be described in terms of reductions in expected annual damage (EAD) and expected annual loss of life (EALL). Changes to EAD and EALL associated with flooding in the Yuba-Feather system can be estimated for the FIRO preferred alternative relative to existing operations. To quantify the potential economic benefits, downstream stage-frequency curves associated with the FIRO preferred alternative can be used as inputs to the US Army Corps HEC-FDA (Flood Damage Reduction Assessment) model, which has previously been configured for use in the Yuba-Feather watersheds (YCWA, 2018; DWR, 2017).

The Yuba Water (2018) assessment evaluated three flood risk management improvement actions, including the preferred alternative of Forecast-Informed Operations (F-IO) at Lake Oroville and New Bullards Bar combined with the construction of a second spillway at New Bullards Bar. The preferred alternative was predicted to reduce expected annual damage (EAD) from $35.8 million to $22.3 million, a net with-project inundation reduction benefit of $13.6 million (dollar values in 2016 dollars). EAD under without-project and with-project conditions was estimated using HEC-FDA over 11 impact areas consistent with the 2017 CVFPP Update. Expected damage reduction benefits were determined for: direct damages to structures/content, crops, highways and streets, and vehicles; other costs comprising business losses, emergency response costs, and displacement and temporary housing; and statistical lives lost. A similar approach can be used to evaluate the economic value of flood damage risk reduction for the FIRO FVA.

The valuation of water supply reliability involves distinctions between private and social, long-run and short-run, at-site and at-source, per-period and capitalized, and use and nonuse values (Young and Loomis, 2014). One simple metric of the private, short-run, at-site, per period, use value of water in the Yuba-Feather watersheds is the cost of water delivery, or unit water charge, for the Feather River Area which is estimated at $538 per acre foot in 2022 dollars ($493 in 2019 dollars, DWR Bulletin 132-18, p. 297). The combined capacity of Lake Oroville and New Bullards Bar is over 4.5 million acre-feet. Improvements to dry season water supply reliability could generate appreciable value. Period-of-record simulations of FIRO alternatives over winter periods can be used to generate estimates of the value of additional water available in the spring by applying unit water charges for the Feather River area (DWR, 2018).

Hydropower benefits, including increased energy generation and decreased greenhouse gas emissions, can be described quantitatively or qualitatively by simulating expected pool elevations and hydropower generation decisions and outcomes over the course of a water year. Pool elevation simulations combined with recreation use values can be used to quantify the economic benefits of boating and other recreational activities on the reservoirs (Rosenberger, 2016). FIRO may provide ecological benefits to fisheries and endangered salmonid populations

(Jasperse et al., 2020). Ecological impacts are not easily monetized but qualitative assessments of benefits may be feasible (Yuba Water, 2018). The valuation of ecological benefits associated with FIRO may be informed by the NEPA process to be carried out during the water control manual updates for Lake Oroville and New Bullards Bar. Finally, FIRO may provide improved climate resilience as inflows are expected to become more volatile in a changing climate. Climate resilience benefits can be assessed by evaluating the full set of FIRO benefits under a set of future climate scenarios.

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