Forecast-Informed Reservoir Operations (FIRO): A Roadmap of Lessons Learned for Implementation

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ABSTRACT

Population increases have led to dramatic changes in water demand. For over a decade, the U.S. Army Corps of Engineers (USACE) and the Center for Western Weather and Water Extremes (CW3E) has led the multi-agency, multi-disciplinary research and development initiative called Forecast-Informed Reservoir Operations (FIRO) that explores the potential of enhanced forecast skill, advanced hydrologic modelling, and improved observational networks to optimize water management decisions in reservoir operations. Traditional reservoir management strategies solely rely on historical hydrologic data, which can be insufficient for capturing the dynamic nature of extreme weather events and long-term climate variability. FIRO addresses this limitation by integrating real-time and forecasted hydrometeorological information to inform reservoir release decisions, balancing competing demands for water management purposes such water supply and conservation, flood risk management, and environmental benefits. Pilot implementations of FIRO at various sites in the United States have demonstrated its capacity to significantly improve water availability, particularly during drought periods, while simultaneously enhancing flood risk management by strategically releasing water prior to major storm events. Furthermore, FIRO can be leveraged to optimize flows for environmental benefits, such as maintaining suitable water temperatures and flow regimes for aquatic species. These improvements have been achieved without requiring substantial and costly infrastructure modifications. Lessons have been learned from years of research and development focused on assessing FIRO viability and its integration into water control manuals, the USACE guidance documents that prescribe the rules for reservoir operations. The research included advancements in forecasting techniques, hydrologic model calibration and validation, and the utilization of decision support tools tailored to specific reservoir characteristics and operational objectives. Diverse pathways for FIRO implementation were developed, considering factors such as regional climate, regulatory frameworks, and stakeholder engagement. The status of FIRO implementation at various pilot sites shows the successes, challenges, and ongoing research.

KEYWORDS: forecast-informed reservoir operations, flood risk management, reservoir management, atmospheric rivers

1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) prescribes flood control operations in water control manuals (WCMs). Many of these WCMs are decades old and may not fully capture changed conditions in watersheds or include the benefit of state-of-the-science weather and streamflow prediction. Historically, reservoir operations have been governed by rule curves primarily derived from climatology, prioritizing "water on the ground" observations. However, the stationary climate assumption is increasingly challenged by climate variability, characterized by vacillations between extreme drought and severe flooding.

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 (Jasperse et al, 2020). By integrating forecast information, FIRO may show it is appropriate for reservoir operators to encroach into flood control pools to store water for supply when forecasts are dry, or to release water ahead of extreme events to create additional flood storage capacity.

1.1 USACE Policy Update

The exploration of potential FIRO viability is supported by updates to USACE policy, specifically ER 1110-2-240 (Water Control Management). The 2016 update allowed for the use of forecasted conditions in planning future operations, provided that such operations do not compromise dam safety or flood risk management objectives (USACE, 2016). This change in guidance enabled the FIRO pilot projects to test and validate new FIRO strategies through temporary deviations to reservoir operations, laying the groundwork for permanent updates to WCMs.

1.2 Atmospheric Rivers and Forecast Skill

The viability of FIRO in the western U.S. is linked to the predictability of atmospheric rivers (ARs), which drive both water supply and flood risks in the region. Research by the Center for Western Weather and Water Extremes (CW3E) and partners has focused on improving the forecast skill for AR landfall, intensity, and duration. The premise is that improved forecast lead times support better water management decisions, such as knowing when it is safe to evacuate reservoir storage ahead of storm events. The integration of data from AR reconnaissance (AR Recon) campaigns into global models has been shown to improve precipitation forecast accuracy over the U.S., thereby enhancing FIRO operations (Zheng, M., et al, 2021).

2 VIABILITY ASSESSMENT METHODOLOGY

To operationalize FIRO, USACE and the partners in the FIRO program developed a structured, scalable framework known as the viability assessment (VA) process. This framework mirrors the rigor of a USACE feasibility study and uses a Hydrologic Engineering Management Plan (HEMP) to ensure systematic and defensible evaluation of reservoir operations strategies. The HEMP dictates a multi-step process for every VA, including objective definition, constraint identification, metric development, simulation, and comparison of alternatives (USACE, 1994).

2.1 FIRO Screening Process

To efficiently scale FIRO implementation beyond the initial pilots, USACE has developed a national FIRO Screening Process. This three-stage effort evaluates all dams in the USACE portfolio for potential FIRO suitability. The screening process examines factors such as forecast skill, reservoir infrastructure constraints, environmental considerations, and collaboration potential, and it categorizes dams into four recommendation categories:

- Strongly consider pursuing FIRO,

- Consider pursuing FIRO,
- Make improvements before pursuing FIRO, and
- Barriers to FIRO may be prohibitive – do not pursue until challenges are addressed (Yeates et al, 2023).

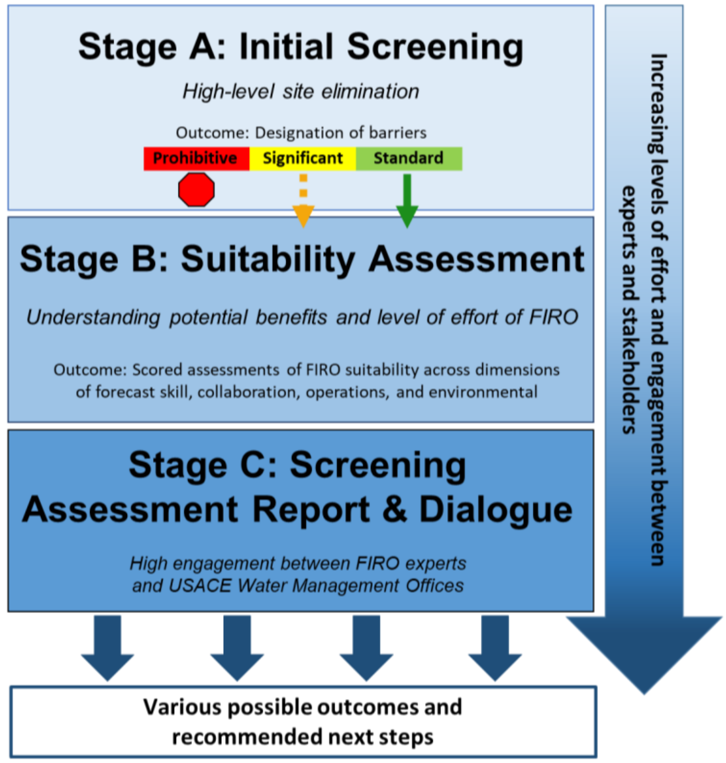

Figure 1: FIRO Screening Process Framework (Yeates et al, 2023)

2.2 Viability Assessment Pathways

For projects identified as being suitable for a VA, a set of three viability ability assessment pathways has been developed to match the level of analysis to the complexity of the site. Table 1 below summarizes key characteristics of each pathway.

Table 1 Characteristics of FIRO Viability Assessment Pathways

Pathway	Complexity	Primary Driver	Duration	Key Components
Expedited	Low	Consensus on benefits; minimal conflict	1–2 years	No PVA; uses existing models
Streamlined	Moderate	Some complexities; no major barriers	1–3 years	No PVA; minor model refinements
Full	High	Significant technical or stakeholder challenges	2–4 years	Full PVA and FVA; substantial model development

The Expedited track targets the reservoirs with the relatively lowest level of effort where minor operational changes yield benefits with low risk. The Streamlined track addresses projects with moderate complexity and allows for broader exploration of FIRO strategies without the requirement of allocate the research resources typical of a full VA. The Full track is reserved for high-complexity environments and includes a Preliminary Viability Assessment (PVA) and a Final Viability Assessment (FVA).

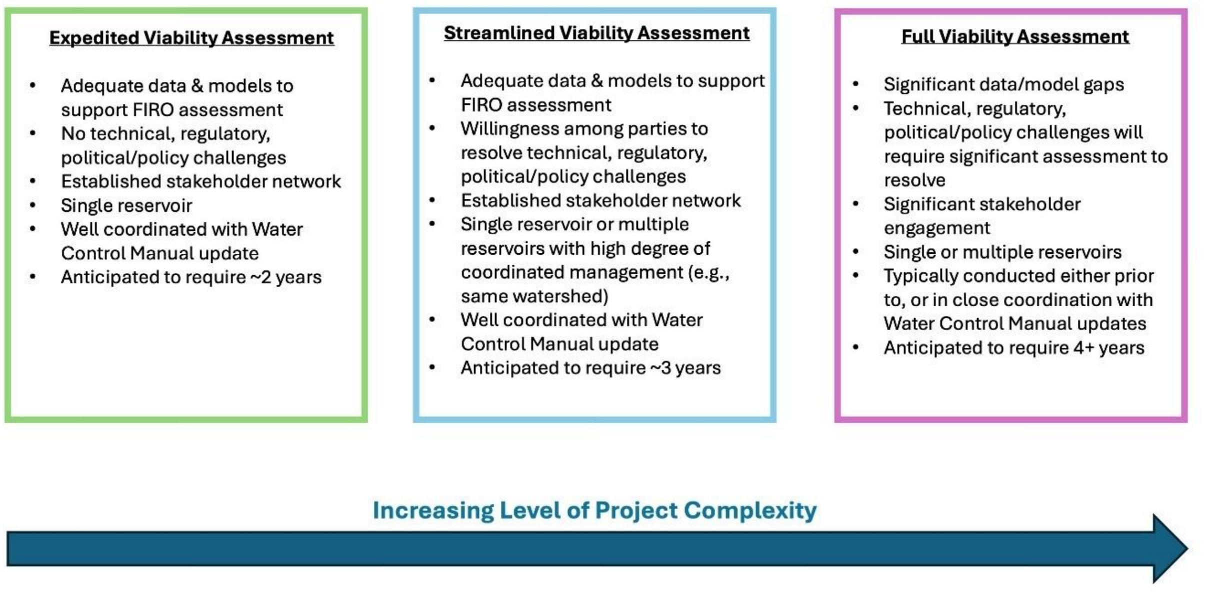

Figure 2: FIRO pathway options with increasing project complexity

3 PROGRAMMATIC LESSONS LEARNED

With the expansion of the FIRO program, several lessons can be learned regarding the processes and frameworks developed and evolved over time, going from one isolated pilot project to several pilot projects going on concurrently.

3.1 Research and Operations Partnership

A key factor in the success of FIRO has been the Research and Operations Partnership (RAOP). This approach bridges the gap between meteorologists developing numerical weather prediction models and the water managers operating the dams. By embedding researchers directly into the decision-making structure via Steering Committees, researchers gain insight into operational constraints (e.g., specific lead time requirements for safe evacuation), while operators gain a sophisticated understanding of forecast uncertainty. This bidirectional feedback loop was essential in the Lake Mendocino pilot, allowing operators to move from binary "rain/no rain" decisions to risk-based probabilistic assessments (Jasperse et al, 2020).

3.2 VA-WCM Alignment

The primary outcome of a VA is a recommendation for implementation of a FIRO strategy in a WCM update. Through the various pilot projects, there have been different alignment opportunities for VAs and WCM updates.

- Sequential Alignment (VA then WCM): In this model, the VA is completed before the WCM update begins. This allows the VA to act as a "sandbox" for innovation, unconstrained by the schedule and resourcing required of the WCM update process, but it significantly elongates the timeline for implementation.

- Concurrent Alignment (VA with WCM): In this model, the VA and WCM update proceed simultaneously. It is the fastest model by finding efficiencies in schedules. Challenges include the WCM update process requiring defined alternatives for environmental review before the VA work has fully developed them. Early coordination is identified as a critical lesson to minimize friction between these processes.

3.3 Water Control Plan (WCP) Deviations for FIRO Testing

Planned temporary deviations from the existing WCP have proven to be an essential mechanism for testing and validating FIRO strategies. A WCP is a plan of regulation for a reservoir in the interest of flood control, navigation, and other authorized purposes, and a deviation is a temporary change to a reservoir's approved WCP that can be made to respond to an unforeseen circumstance or realize opportunities to increase project benefits. These deviations allow the reservoir to implement FIRO concepts in real-time for a set period (potentially up to 5 years) while pursuing a permanent change to the WCM. This provides immediate benefits and allows operators to stress test the new rules, exposing operational challenges that models might not capture.

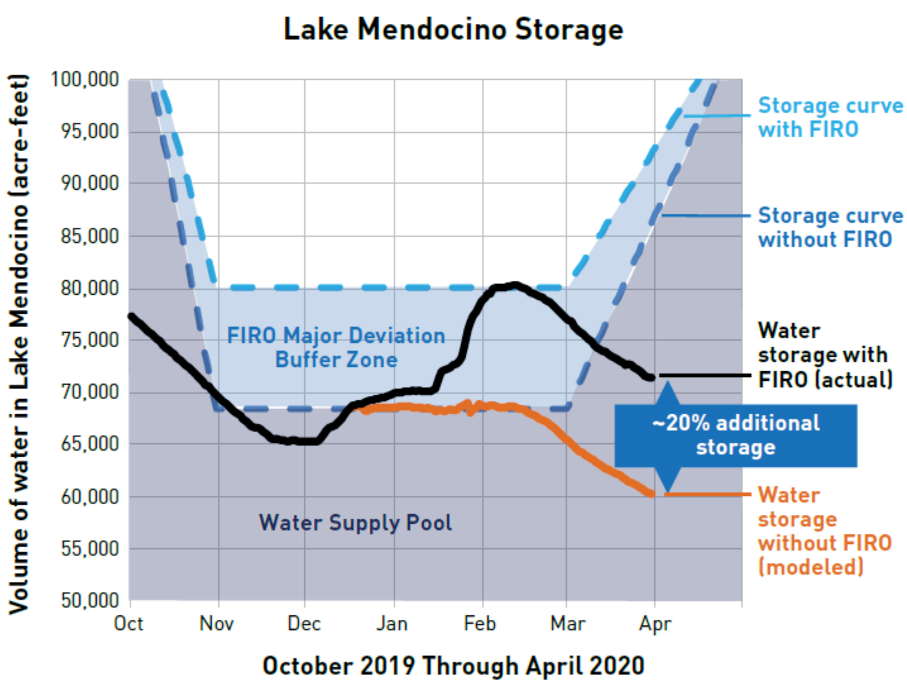

Figure 3: Water year storage graph showing 20% increase to storage due to temporary implementation of FIRO (Jasperse et al, 2020)

4 TECHNICAL FRAMEWORK AND MODELLING

The translation of FIRO from a research concept into operational reality requires a robust software infrastructure. To ensure that FIRO strategies are sustainable and safe for nationwide implementation in USACE, the USACE Hydrologic Engineering Center (HEC) has established strict standards for software compatibility, which in turn drive the development of specific modelling architectures.

4.1 Corps Water Management System (CWMS) Compatibility Standard

A formal definition of CWMS compatibility has been developed to ensure that any FIRO strategy proposed in a VA can be seamlessly transitioned into a permanent WCM update. To be considered compatible, a method must meet three criteria:

- Documentation: The operational method must be describable in Chapter 7 of the WCM in terms clear enough for future water managers to understand and execute.
- Standard Software: It must run fully within the standard CWMS modelling suite.
- Supportability: Any methods involving scripting must be developed, supported, maintained, documented, and understood by USACE district water management staff. It also must be approved by the CWMS software development team and Program Manager.

4.2 Real-Time Operations: CWMS and the Ensemble Forecast Processor

To meet the supportability and standardization requirements of the CWMS compatibility definition, HEC has adapted the Corps Water Management System (CWMS)—the USACE standard for real-time decision support—to natively handle probabilistic data.

A key technological capability in CWMS is the Ensemble Forecast Processor (EFP). This allows CWMS to natively handle probabilistic forecast information, such as the ensemble streamflow traces produced by National Weather Service's Hydrologic Ensemble Forecast System (HEFS). The EFP computes statistical metrics from the ensemble forecast and passes these metrics to the reservoir simulation model HEC-ResSim to inform logic rules, allowing water management decision-making to better account for probability, risk, and uncertainty.

4.3 Planning and Robustness: HEC-WAT and Synthetic Ensembles

While CWMS manages real-time operations, HEC-WAT (Watershed Analysis Tool) can be utilized for planning and risk analysis. Using this tool in FIRO VAs is a more recent development, and current pilot projects are developing standard operating procedures on how best to utilize HEC-WAT to support FIRO strategy development and evaluation.

A major limitation in early studies was the relatively short record of the hindcasts, the retrospective approach used to simulate and analyse past weather conditions, which often missed extreme events necessary to stress-test FIRO rules. To address this, researchers developed the Synthetic Forecast Ensemble generator (Brodeur et al., 2024). This technique creates thousands of years of plausible synthetic forecasts based on the statistical error characteristics of the actual forecast system, which allows the FIRO strategies to be tested using extreme events and quantify the risk of scenarios occurring where a forecast fails to predict a flood (CW3E, 2025).

5 RESULTS AND DISCUSSION: PILOT PROJECTS

The FIRO program has progressed from theoretical research to operational validation across several major pilot sites in the western United States.

5.1 Lake Mendocino (Russian River)

Lake Mendocino served as the proof-of-concept for the FIRO program, testing the direct use of inflow forecasts improved by AR reconnaissance work. The VA confirmed that FIRO could safely increase water supply reliability. During the 2020 water year (a drought year), operations under a planned deviation allowed the reservoir to retain approximately 13.6 Mm^3 (11,000 acre-feet) of additional storage compared to the baseline rule curve (Jasperse et al., 2020). Pertaining to flood risk, detailed modelling demonstrated that by pre-releasing water based on AR forecasts, FIRO could reduce peak reservoir stages during extreme events, thereby improving flood risk management and dam safety.

5.2 Prado Dam (Santa Ana River)

Prado Dam operates in a highly constrained urban environment and provides critical habitat for the endangered bird species Least Bell's Vireo. Water conservation was a primary focus area for the Prado Dam FIRO project, and the VA demonstrated that FIRO strategies could increase groundwater recharge by an average of 8.6 Mm^3 (7,000 acre-feet) per year. Another major achievement was the integration of ecological metrics into HEC-WAT. The model simulated inundation frequencies to ensure that higher water conservation pools did not negatively impact vireo nesting habitat. The study also identified that while precipitation gauges were adequate, stream gauge improvements were necessary to support the proposed operations (Ralph et al., 2023).

5.3 Yuba-Feather System

This system involves the coordinated operation of New Bullards Bar Reservoir and Lake Oroville to protect the downstream communities of Marysville and Yuba City. One unique characteristic of the Yuba-Feather pilot project is that it is a two-reservoir system. The VA showed that coordinated FIRO operations could significantly reduce peak flows at the confluence of the Yuba and Feather rivers. Unlike single-reservoir pilots, this project emphasized the timing of releases between two independent dams to better manage peak flows downstream. The project also highlighted the critical need to align FIRO VA timelines with concurrent WCM updates for the two reservoirs. Early coordination allowed the FIRO VA results to directly inform the ongoing comprehensive WCM update for the system (Ralph et al., 2022).

5.4 Other Ongoing FIRO Pilots

A priority at new FIRO pilot project sites is to. The FIRO program identified three sites, each in a different phase of the VA process, to better integrate HEC resourcing and tools into the project teams – Lake Sonoma (Russian River), Howard A. Hanson Dam (Green River), and the Willamette Valley in Oregon. By more comprehensively utilizing CWMS and WAT, as well as collaborating with HEC personnel as part of the work teams, best practices can be identified, and standard operating procedures can be updated and leveraged on future FIRO VAs.

6 CONCLUSION

There have been three completed FIRO pilot projects in California, each evaluating reservoirs with varying characteristics and performance objectives. Each project has shown that FIRO has the potential to be an effective reservoir operations strategy. The technical accomplishments, including utilization of the EFP and synthetic ensemble generation, have provided the necessary tools to quantify and manage forecast uncertainty.

Lessons learned from these projects are currently being used to implement FIRO across the USACE inventory. The establishment of tiered VA pathways (Expedited, Streamlined, Full) allows USACE to efficiently assess which reservoirs show the most promise. As the program expands to sites like Lake Sonoma, and Howard Hanson Dam and the Willamette Valley, the focus remains on standardizing implementation through CWMS-compatible methods, ensuring that the benefits of forecast-informed operations can be realized broadly to improve water supply reliability, flood risk management, and other authorized purposes.

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