Research to Implement Policy and Operations Change: Forecast Informed Reservoir Operations within the US Army Corps of Engineers

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ABSTRACT

A recent policy update within the US Army Corps of Engineers (USACE) allows forecasted conditions to be officially used in planning future water management operations. Since 2014, the USACE have been key partners with the Center for Western Weather and Water Extremes (CW3E) at the University of California-San Diego and with other federal, state and local agencies in a multi-agency, multi-disciplinary research and development effort called Forecast Informed Reservoir Operations (FIRO). FIRO has been exploring how improved forecast skill, hydrologic modeling and observations can better inform water management decisions in response to the USACE water management policy change.

FIRO viability is assessed at candidate sites using a research and operations partnership that brings scientists, engineers, regulators and reservoir operators together from across academia, federal, state and local agencies and their partners to assess the potential. FIRO implementation at pilot sites has demonstrated that implementation of FIRO can improve water availability, flood risk management and ecosystem benefits without costly infrastructure modifications.

This paper will summarize Phases I and II of the FIRO program, highlighting what was learned and accomplished in the first decade of the program; give a status update on progress with the goals of Phase III, the National Expansion Pathfinder, the current phase of the program; and share some thoughts on what's next for FIRO in the USACE and their partners. Legislative and agency changes to support FIRO both within USACE and beyond across its more than decade of history will also be presented.

The importance of the role of collaboration will be also emphasized. From partnering with academia to the FIRO viability assessment process, collaboration is at the heart of FIRO success – not just in determining how much flexibility in operations can be supported by the current science in meteorology, forecasting, hydrology and water operations, but also in building lasting relationships of institutional trust between stakeholders at any given reservoir.

KEYWORDS: water management, forecasts, reservoir operations, research and operations partnership, weather extremes

1 INTRODUCTION

The U.S. Army Corps of Engineers (USACE) has been engaged in a research and development effort called Forecast Informed Reservoir Operations (FIRO) since 2014. In late 2014, the U.S. Congress provided additional funding to the USACE with specific direction to conduct "research into atmospheric rivers in an effort to develop and demonstrate better prediction capabilities and apply the science to improve reservoir operations to optimize multi-purpose project objectives and to meet stakeholder water needs." Additionally, in May 2016, the USACE updated a key policy regulation governing water control management that, for the first time, explicitly allows the use of forecast information in planning future water operations. In response to these events, the USACE engaged in a multi-agency, multi-discipline research and development effort to investigate how FIRO approaches might be safely and appropriately applied at a pilot reservoir, Lake Mendocino, in the Russian River watershed in northern California. This initial FIRO investigation (FIRO Phase I), carried out over a 5-year period, concluded successfully in 2020 after demonstrating substantial benefits in a severe drought year by increasing water availability for the dry summer by almost 20 percent. The investigation results motivated a 5-year deviation from the existing water control plan at Lake Mendocino to continue FIRO operations there while an update to its water control manual (WCM) was initiated to permanently incorporate FIRO.

Prior to the conclusion of Phase I, the U.S. Congress again provided funding to begin a 5-year transferability study (FIRO Phase II) focused on exploring transferability of Lake Mendocino's results across a broader range of reservoirs and watershed conditions, all within the western coastal region of the U.S. where atmospheric rivers are the dominant storm type. Through Phases I and II, FIRO has demonstrated that significant improvements in achieving a better balance between water supply, flood risk management and ecological benefits can be achieved. The improvements come at negligible negative impact to the multi-purpose objectives at reservoirs but rather provide increased benefits to all objectives simultaneously through improved efficiency in operations, as opposed to costly and lengthy infrastructure changes. The USACE has found that similar benefits can be realized at other reservoirs through execution of atmospheric and hydrologic research and exploration of FIRO applicability nationally that the FIRO Phase III workplan is currently developing and delivering. Phase III represents a National Expansion Pathfinder, as described below.

2 PREVIOUS FIRO PHASES

Brief descriptions of the objectives, goals and deliverables of FIRO Phases I and II is provided in the following sections, giving context to the objectives, goals and deliverables of FIRO Phase III, the National Expansion Pathfinder.

2.1 FIRO Phase I: Initial Pilot

FIRO Phase I was begun in 2015 and led to the development of an effective process to determine if weather forecast skill for a reservoir is adequate to safely incorporate forecast information in reservoir operations. Successful application of FIRO was demonstrated initially for a single pilot dam, Lake Mendocino, on the East Branch of the Russian River in northern California that supports a climate-change-vulnerable region, where atmospheric river-type storms are the cause of both flooding and provider of water supply. Talbot et al. (2019) describes this effort in detail along with the Final Viability Assessment (FVA) of FIRO at Lake Mendocino published by the Lake Mendocino FIRO steering committee in 2020 (Jasperse et al., 2020).

As part of the FIRO viability assessment process, major deviations, defined as plans that deviate greater than 5% from the existing water control plan contained in the WCM, were requested and FIRO scenarios were tested in water years (WY – defined as October 1 to September 30 in California) 2019 and 2020. In WY 2019, a relatively wet year, FIRO demonstrated increased flood risk management benefits while in WY 2020, the third-driest year on record at the time, nearly 20 percent more water was made available leading into the dry summer period through flexibility in operations made available to water managers through use of FIRO (Figure 1). This amount of water is roughly equivalent to the annual water use of 22,000 households. FIRO Phase I efforts concluded in 2020 and thereafter the USACE San Francisco District began a FIRO-based update to the Lake Mendocino WCM which was approved in October 2025.

The FVA-recommended plan defines a buffer zone, which is 10% of the Lake Mendocino storage volume, as flexible space available to the water manager to use to meet multipurpose objectives, based on forecasted weather, watershed and downstream conditions.

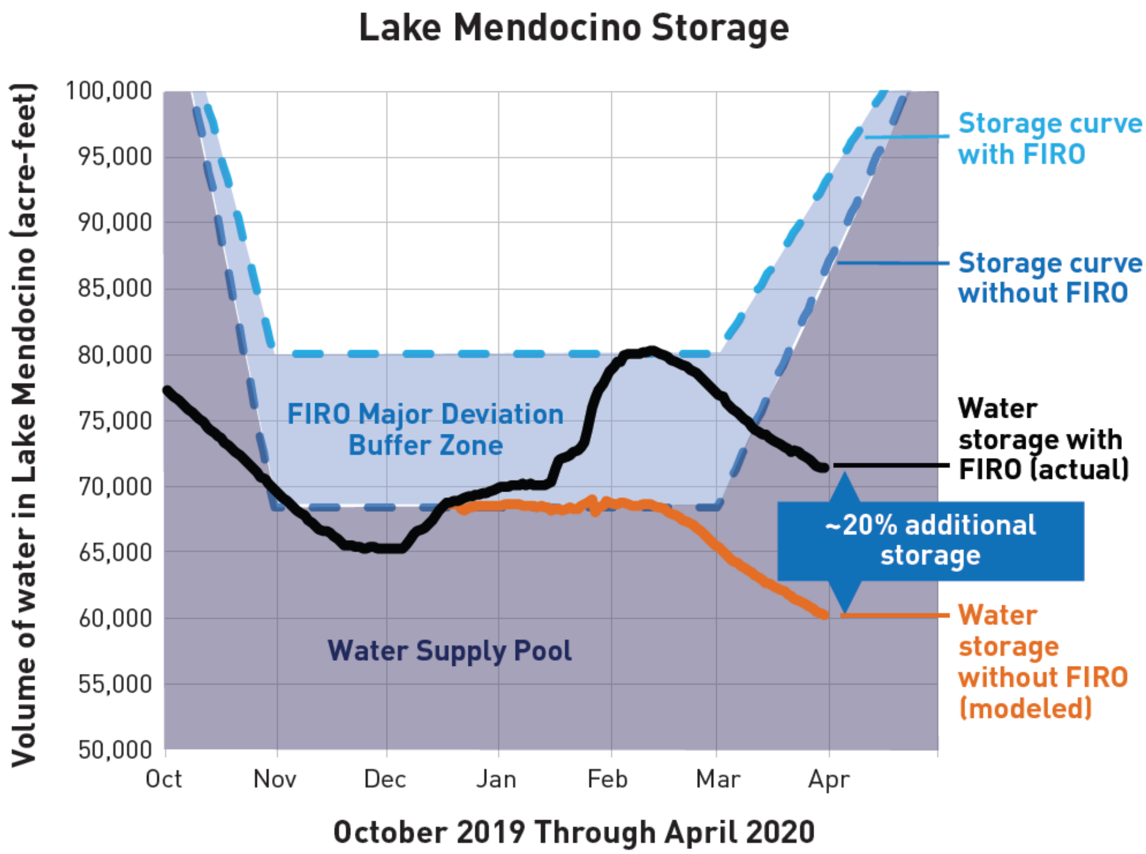

Figure 1: Lake Mendocino storage increased by ~20 percent during major deviation operations in WY 2020, compared with modeled storage without FIRO, during a year when precipitation was 38 percent of average. (figure credit: Sonoma Water)

2.2 FIRO Phase II: Transferability

Phase II, begun in 2019, explored the transferability of the findings from Phase I to other dams in the western U.S. where atmospheric rivers (ARs) are also the primary storm type, but with differing context (urban vs rural vs snow-dominated) and reservoir purposes (flood control only vs combination of supply and flood), as well as reservoir sizes and connectivity to much bigger water supply/flood control systems. These assessments are being conducted on 4 reservoirs as described in the following sections. Phase II also included development of a FIRO Screening Process – a method the USACE can use to screen the entire portfolio of USACE dams (nearly 600 with flood risk management as a purpose) to determine which dams might be suitable for further FIRO investigation and implementation. The FIRO Screening Process will also be described.

2.2.1 Prado Dam

Prado Dam, on the Santa Ana River in southern California, was built by the USACE in 1941. The Orange County Water District (OCWD) and USACE have worked together each year to maximize the capture and groundwater recharging of stormwater held behind the dam after storm events. Figure 2 shows the elevations and volumes of the current conservation pool as well as tested FIRO elevations. USACE releases water temporarily captured at Prado Dam and OCWD recharges the water into the ground 10 miles downstream. The water conservation pool has been operated at elevations up to 505 feet based on a five-year major deviation approved by USACE in March 2018. The Prado Basin Ecosystem Restoration and Water Conservation Feasibility Study was approved in 2021 to make the 505-foot conservation pool a permanent feature within the Interim WCM (Ralph et al., 2023).

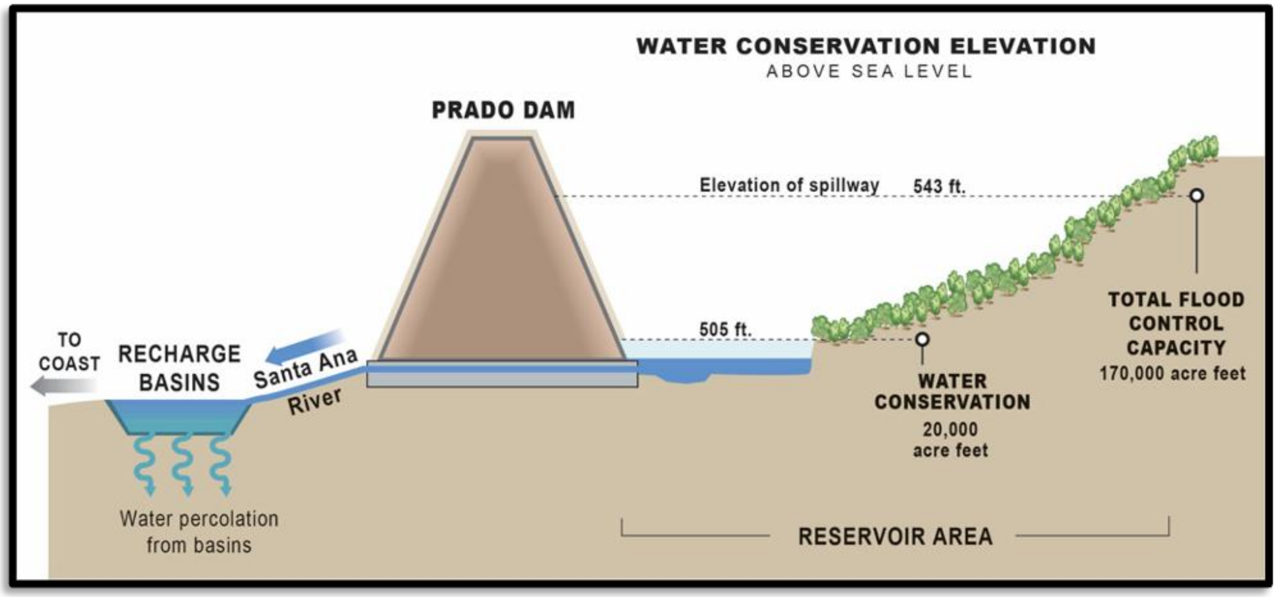

Figure 2: Schematic of Prado Dam water conservation elevation for stormwater storage and capture with tested FIRO buffer pool levels of 508 and 512 feet. (figure credit: OCWD)

Like most WCMs within the USACE, the current Prado Dam WCM does not explicitly leverage weather and water forecasts. Nonetheless, USACE water management staff consider precipitation and streamflow forecasts in their decision process while adhering to WCM guidelines and procedures. As part of the FIRO viability assessment process at this site, the Prado Dam FIRO Steering Committee conducted and published a Final Viability Assessment (PVA) in November 2023 (Ralph et al., 2023) which tested and determined the range of possible FIRO scenarios that could be supported by current operational constraints, current forecast skill and other relevant factors.

2.2.2 Yuba-Feather System

In addition to Prado Dam, a third pilot was added that consists of a two-dam system in one large watershed where snowpack is a vital water supply, and floods are strongly influenced by how much of the watershed experiences rain vs. snow in a storm. This system, the Yuba-Feather System, consists of New Bullards Bar (NBB) dam, owned and operated by the Yuba Water Agency (Yuba Water) on the Yuba River and Oroville dam (ORO), owned and operated by the California Department of Water Resources (DWR), on the Feather River (see Figure 3). By federal policy, the USACE regulates flood risk reduction operations of both reservoirs according to their respective WCMs which are written by the USACE. Releases from NBB and ORO converge in Yuba City, CA which requires that operations between these two reservoirs be coordinated. The primary objective of the Yuba-Feather FIRO project is to reduce flood risk; a secondary objective is to achieve water supply benefits where possible, while supporting environmental needs. Reducing flood risk by making reservoir releases ahead of storms creates additional temporary flood storage space for anticipated inflows but requires confidence and skill in forecasted conditions (Ralph et al., 2025).

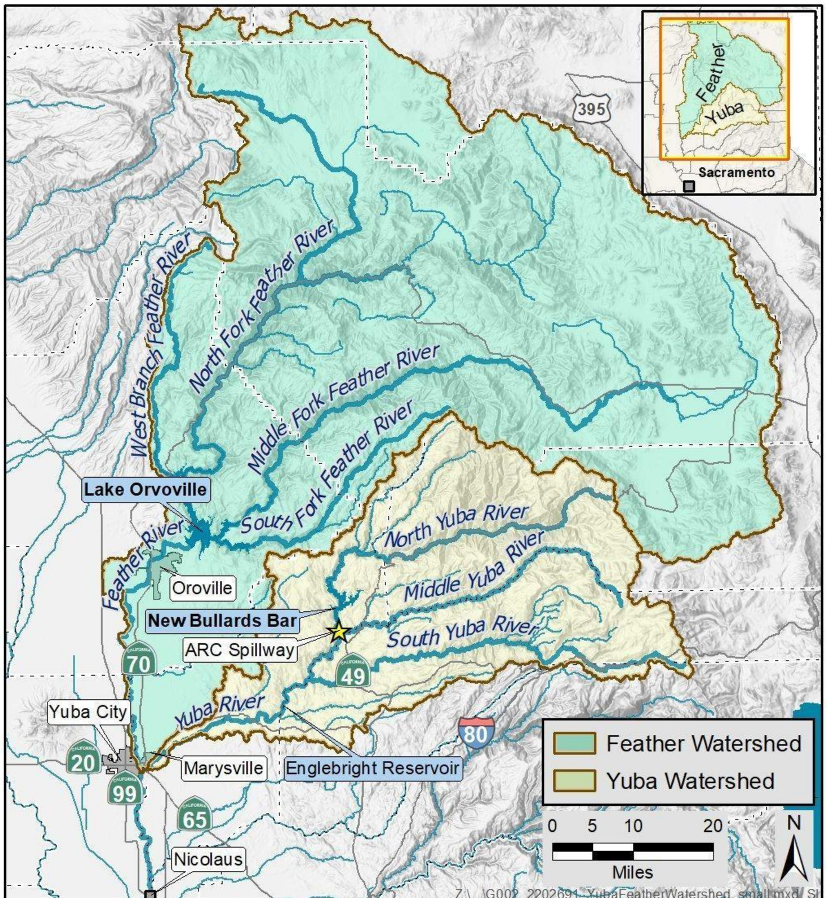

Figure 3: Map of the Yuba and Feather River watersheds.

To better leverage forecasts, Yuba Water is designing a second spillway, called the Atmospheric River Control (ARC) Spillway for NBB that allows for greater forecast-informed pre-releases at lower reservoir elevations. Using FIRO with the planned spillway will enable the management of up to an additional 117,000 acre-feet of reservoir space and the potential to reduce water levels on levees near Marysville, CA by 2 to 3 feet.

The FVA for the Yuba-Feather System, completed in February 2025, had the following key findings: 1) The FVA demonstrated that FIRO strategies combined with a planned second spillway at NBB could provide additional flood control storage capacity in the system and allow for reservoir operations flexibility to reduce downstream peak flows during major prolonged storms like 1986 and 1997 that devastated Yuba County; 2) For the scenarios tested, FIRO with the ARC spillway could provide a level of protection equivalent to the proposed (but never constructed) Marysville Reservoir, approx. 260,000 acre-feet; and 3) Post-event storages were consistently higher than pre-FIRO storages; therefore, there could be a water supply benefit, pending a full analysis in the WCM updates (Ralph et al., 2025).

2.2.3 Howard A. Hanson Dam

A fourth FIRO pilot site was selected at Howard A. Hanson Dam (HAHD) on the Green River upstream from Seattle, WA. This pilot study experienced some delays in the viability assessment process due to various factors, including the effects of the COVID-19 pandemic, but recent progress has been made that is moving this effort forward. Tacoma Water and the USACE Seattle District are collaborating with CW3E, USACE Engineer Research and Development Center, the National Weather Service (NWS), the National Marine Fisheries Service, King County River and Floodplain Management, and the Muckleshoot Indian Tribe to assess the benefits of reservoir management scenarios using forecasts at HAHD through a FIRO Viability Assessment Steering Committee. On-going construction of a downstream Fish Passage Facility plus an Additional Water Storage Project present unique opportunities to explore how FIRO at HAHD might increase the benefits of those investments through operational flexibility.

The HAHD FIRO project is investigating this key question: How can improved forecasts of landfalling ARs and associated precipitation and runoff be used to improve the reliability of spring refill to meet instream flows for fish and water supply storage objectives, improve the effectiveness of summer water management in advance of the fall flood transition period, maintain or improve operations for downstream flood risk management, and ensure forecasts and operations are flexible enough to respond to a changing climate without impacting flood risk, water storage reliability, and flows for fish? (Ralph et al., 2024)

2.2.4 FIRO Screening Process

Using lessons learned from the transferability of FIRO to additional pilot sites in Phase II, a FIRO Screening Process was developed to scale up the implementation of FIRO. The Screening Process maintains the same level of rigor and quality to the process as demonstrated at the original pilot sites but at a screening level which can be executed more rapidly than full viability assessments.

The goal of the screening process is to employ a broadly usable tool for water management agencies to determine sites where FIRO may be appropriate, including evaluating entire portfolios of reservoirs. The Screening Process is meant to be an adaptable, easy-to-use process that empowers more local ownership over FIRO implementation.

As depicted in Figure 4, the FIRO Screening Process was designed as a three-stage process with the first Stage A being an initial screening with "weed out" criteria to eliminate dams that have little or no FIRO potential due to any one of several criteria, such as not having a controlled outlet or no WCM. Stage B delves into the specifics of each candidate site, producing a spectrum of less to more suitable for FIRO scoring. This "suitability index" can be used by a water resources agency to decide where further FIRO investigation is warranted, given limited time and resources. The third Stage C involves a more thorough assessment and dialog with the USACE District responsible for those sites that are prioritized in Stage B. As depicted in Figure 4, a variety of outcomes are possible from this Stage C assessment. Possible outcomes of Stage C are that barriers to FIRO implementation may be prohibitive, or that more research and improvements in forecast skill, for example, could be needed before FIRO could be successfully implemented. Finally, Stage C could also identify sites where all indications are that FIRO suitability is high and the recommendation is to either consider or strongly consider implementing FIRO.

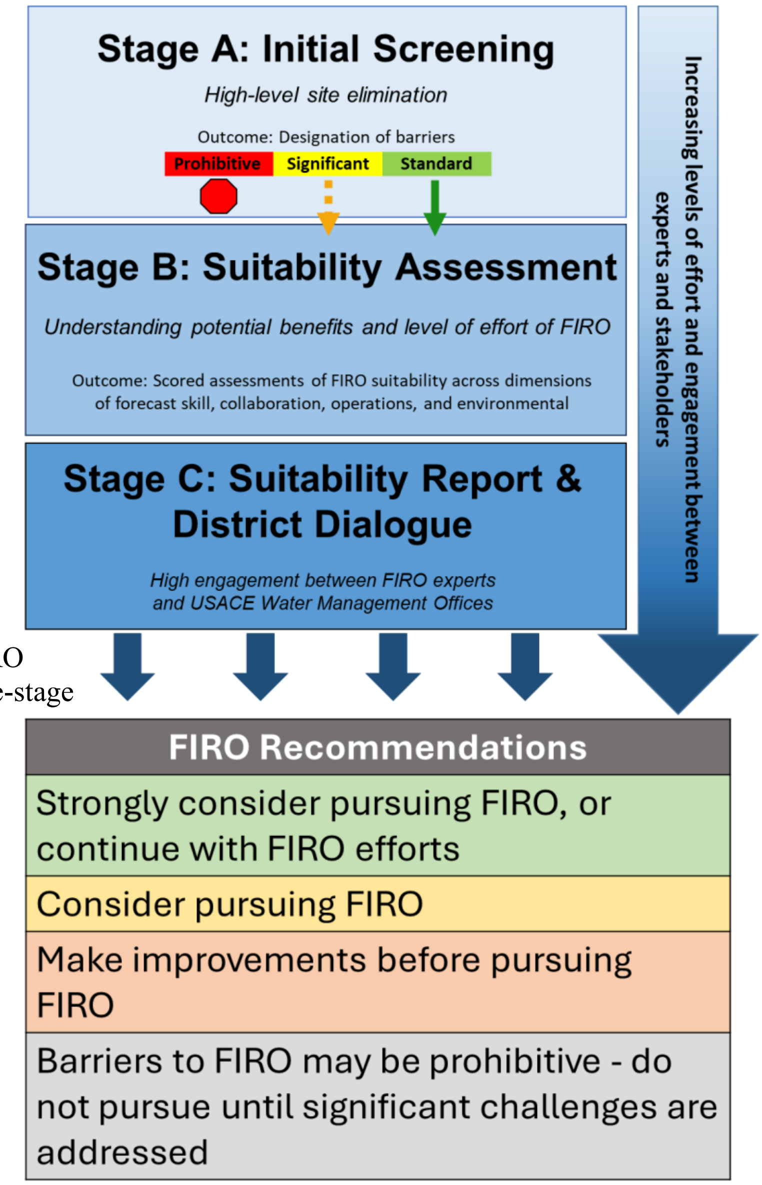

Figure 4: FIRO Screening Process stages schematic.

3 FIRO PHASE III: THE NATIONAL EXPANSION PATHFINDER

Phase III began in 2023 and accelerates FIRO assessments substantially by: expanding to systems of dams and to other regions nationally where extreme precipitation and flooding is influenced by different storm types; applying the screening process to all USACE dams; completing the FIRO viability assessments underway in Phase II; and expanding the research into improving forecast skill, particularly in areas of the U.S. that are impacted by atmospheric rivers and/or other major storm types, specifically tropical storms/hurricanes, clusters of thunderstorms, and Nor'Easters. Phase III will complete core elements of the FIRO National Expansion Pathfinder as described below.

3.1 Forecast Skill Assessment and Improvement for Multiple Types of Flooding Storms

FIRO is not viable at reservoirs where forecasts of extreme precipitation and associated floods do not have adequate skill. Although meteorology has largely struggled to improve quantitative precipitation forecasts (QPFs), FIRO Phases I and II have found that atmospheric rivers are the key storm type in the U.S. west coast flood season (fall/winter). Additionally, FIRO research has found that there is adequate skill to support FIRO operations at Lake Mendocino with additional positive results at Prado Dam, ORO and NBB. Research to improve forecasts have benefitted from focusing on the storms that predominantly produce the precipitation at these reservoirs, i.e., atmospheric rivers (ARs). FIRO viability has also been favored by the fact that watersheds along the U.S. west coast are relatively short and steep, leading to short travel times for water released from a dam to move beyond flood prone areas. AR forecast skill at lead times of even just a few days is often sufficient for FIRO to be viable at many reservoirs.

FIRO viability in other regions nationally, where different storm types dominate flooding, hinges on the forecast skill for these storms and on the watershed sizes and travel times for water released from dams. Slopes are generally much shallower and thus water travel times longer in places like much of the U.S. southeast and Great Plains. Also, convection, a frequent storm type in many parts of the country, especially in the summer, is notoriously difficult to predict accurately, while the track and intensity of landfalling tropical storms/hurricanes can also be difficult to predict, including whether they stall (e.g., hurricanes Harvey and Florence). Studies have found that forecast skill for extreme daily precipitation is best in the U.S. west (due to ARs) followed by New England and suggests the need for improvement in QPF for these storm types may be needed for FIRO to be viable.

Precipitation prediction skill is tied to the dynamical processes in the major storm types, and to the models and forecast tools that have been developed to predict them. As with atmospheric rivers in the U.S. west, a key to identifying the causes of errors in predictions of extreme precipitation in these storm types is understanding the meteorological attributes of the storms that make them capable of producing the extreme precipitation. This also leads to fruitful research pathways for improving these predictions. By analogy, the hydrologic differences in regions affected by these storms need to be considered.

3.2 Conduct Viability Assessments of Systems of Dams

Phase III will assess two major systems of dams (representing at least 8 dams in each system), for which coordination across several dams in an entire larger watershed is required. The first of these will be the Willamette Valley watershed system, with its 13 reservoirs owned and operated by the USACE, where ARs are the main drivers of floods and a leading source of water supply both for municipal, agriculture and ecological uses. The Willamette Valley FIRO Viability Assessment was initiated in 2025 with workplan development for the viability assessment across the numerous dams of the system underway. The second system of dams to be evaluated will be in a region outside of the western U.S. where non-AR storm types are a key factor and will be identified later in 2026.

3.3 Conduct FIRO Screening Process on all USACE Flood Risk Management Dams

All or parts of the western U.S. are impacted by AR events, some to greater degrees than others. The FIRO Screening Process was developed from lessons learned by applying FIRO to the initial pilot sites described in Section 2. The screening process was then tested using all 85 USACE South Pacific Division dams, covering the states of California, Nevada, Utah, Arizona, New Mexico and parts of Colorado. Additionally, the other aspects of Phase III are exploring FIRO in regions characterized by other storm types and reservoir operations strategies, constraints and methods, allowing the systematic growth of the scientific and engineering knowledge base needed to perform well-founded future assessments of FIRO applicability across a much broader range of conditions than has been explored in the first pilot reservoir, Lake Mendocino, and the transferability study basins in the West.

In 2025 Stage A of the screening process was applied to the nationwide portfolio of USACE dams and reservoirs that have flood risk management missions. Figure 5 depicts the results of the Stage A screening for all 593 dams in the USACE portfolio. Dams depicted in red (184 or 31%) are those that did not pass Stage A of the screening due to prohibitive barriers to FIRO that were identified. Dams identified with significant barriers to FIRO are shown in yellow (299 or 50%). Dams in this category are eligible to be considered for further screening in stages B and C if the responsible USACE District indicates an interest in doing so. Dams with no significant or prohibitive barriers are shown in green (110 or 19%) and are all proceeding to stages B and C of the screening process (Yeates et al., 2026).

Stages B and C have been completed for all dams passing Stage A within the South Pacific Division and are currently being conducted for all dams passing Stage A within the Northwestern and South Atlantic Divisions (see Figure 5). Stages B and C for the dams passing Stage A in the additional USACE Divisions will be conducted later in 2026 and into 2027.

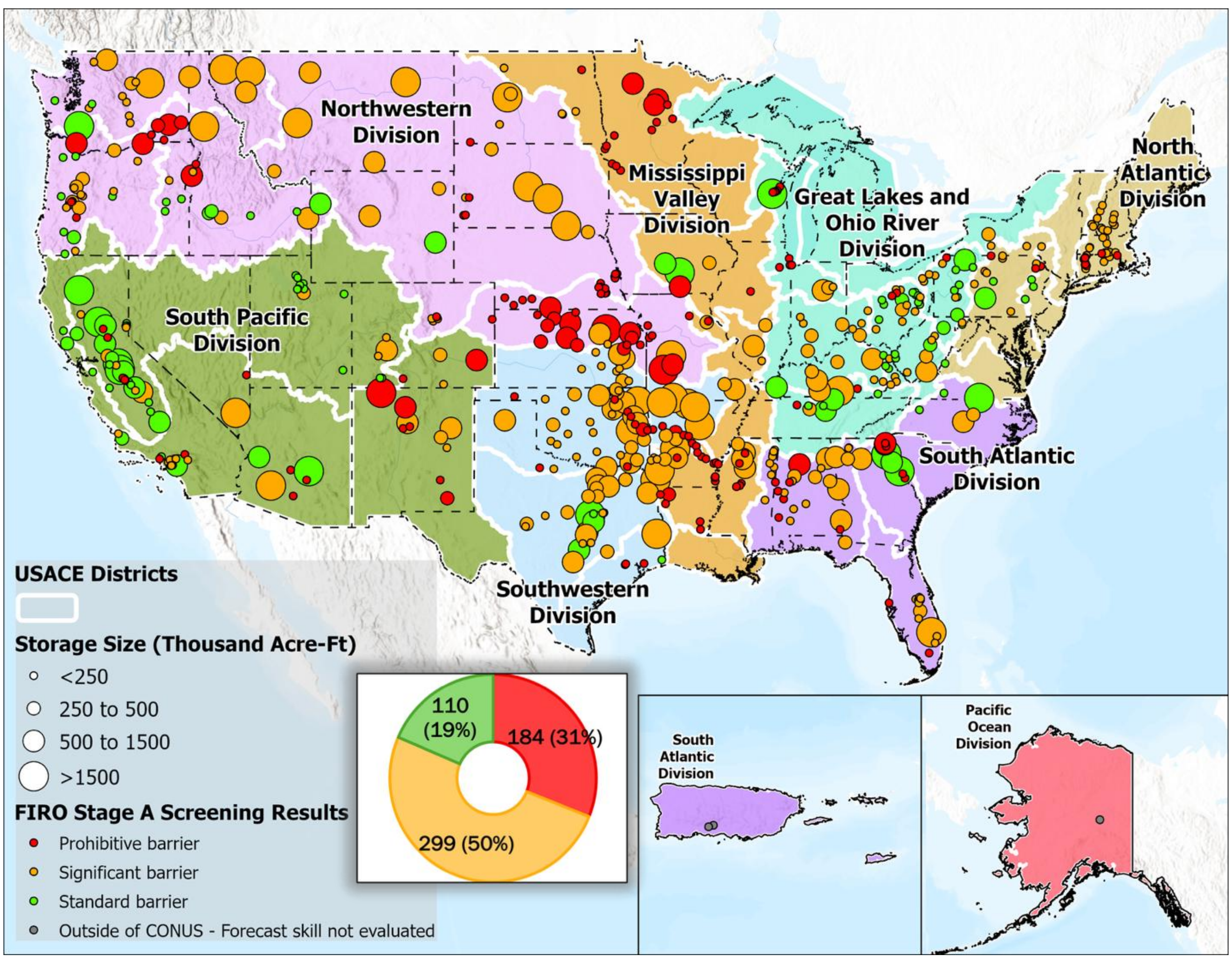

Figure 5: FIRO Screening Process Stage A results for the entire 593 dams within the USACE Flood Risk Management portfolio. An interactive version of these results can be found here: https://storymaps.arcgis.com/stories/79d51b5579ef4b0493b3c8471443bba4

3.4 Conduct Viability Assessments on Two Single Dams in Other Regions Nationally

Two additional viability assessments for single dams are to be conducted in regions of the country where extreme precipitation is dominated by weather systems other than ARs, e.g., tropical storms/hurricanes, large clusters of long-lived thunderstorms, or Nor'Easters. These dams will not be located in the same regions explored in the assessment of system of dams. Selection of these dams is underway and is being coordinated with the results of the FIRO Screening Process.

4 KEY LESSONS LEARNED AND THE PATH FORWARD

The importance of having multi-disciplinary, multi-agency steering committees, partnered together with academia, to lead the evaluation of FIRO viability through the Viability Assessment process developed in the FIRO program cannot be overstated. Having the variety of backgrounds of those with interests in water supply, flood risk management, ecological concerns, and the difference in approach between researchers and operators brings a wealth of perspective and experience that greatly enriches the experience of seeking a better balance between competing objectives in water management. A fundamental rule of engagement with each FIRO steering committee is the principle that all parties are actively engaged with the goal of finding what will the science support. This principle has the effect of making the discussion of changing water operations – often a contentious and fraught topic, particularly in the western U.S. – significantly less threatening, particularly since there isn't a specific proposed plan. The exploration of what is possible within the boundaries of each organization's constraints and the physical limitations of the existing infrastructure helps create an atmosphere of institutional trust that has, for each of the viability assessments completed to date, produced consensus proposed changes to WCMs that are universally supported through the approval and public comment process.

The River Forecast Centers (RFCs) of the NWS play a key role for USACE in providing inflow forecasts to USACE reservoirs. While USACE does have some ability to generate its own hydrologic inflow forecasts from QPFs, USACE has enjoyed a fruitful partnership with RFCs in relying on their expertise in predicting hydrologic inflows. With the advent of FIRO within USACE and other federal and state agencies, the workload for RFCs to provide more detailed and extensive forecasts, particularly ensemble forecasts, has increased. In recognition of this, NWS has embarked on a restructuring of their RFCs nationwide to better support the workload demand for supporting FIRO. USACE and other federal and state agencies view this as a very positive development that is anticipated to provide an even closer and productive collaboration between NWS and USACE in realizing maximum benefits of implementing FIRO nationwide.

The FIRO program continues to enjoy strong support from the U.S. Congress through continued appropriations as well as advocacy from within senior leadership of the USACE and current and past administrations. Looking forward beyond the completion of FIRO Phase III, the focus will be on implementing FIRO at the dams with the highest suitability scores as prioritized by the FIRO Screening Process. Accelerating the viability assessment process through streamlined and expedited pathways will be key to implementing FIRO at an increased pace to deliver the benefits of improved balance between competing reservoir operation purposes across the entire USACE portfolio of flood risk management dams.

5 CONCLUSION

With the key policy update in May 2016, the USACE has entered a new phase of water management where forecasts can be officially incorporated into WCMs and other water management practices. The FIRO research and operations partnership has defined how this can safely and effectively be done and codified in WCM updates. The viability assessment studies conducted to date indicate from 5-20% increased water availability as well as improvements in flood risk management and ecosystem benefits at the reservoirs where FIRO has been studied. The results of Phases I and II of FIRO have demonstrated the value of assessing FIRO viability at candidate reservoirs and Phase III is exploring how these benefits can be realized in other parts of the country and at an accelerated pace. Results to date clearly indicate that FIRO provides an effective means of increasing the efficiency and resiliency of existing water resources infrastructure to achieve multi-purpose benefits and provide increased flexibility demanded by climate extremes, all without costly construction projects. FIRO viability assessments conducted by multi-disciplinary, multi-agency steering committees build institutional trust among participants that lead to increased collaboration and accelerated approval of WCM updates. Internal restructuring of NWS RFCs to support FIRO going forward will have a long-lasting positive impact on increasing the magnitude and value of FIRO benefits as it is implemented across the nation.

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