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Regionally Adaptive Assessment of Dams for Forecast-Informed Reservoir Operations Potential

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ABSTRACT

The U.S. Army Corps of Engineers (USACE) research and operations program Forecast-Informed Reservoir Operations (FIRO) seeks to use forecasts to add flexibility to dam release decisions, improving outcomes across objectives including flood risk management, water supply reliability, groundwater recharge, and environmental flows. Pilot sites for the program are on the west coast of the United States and are characterized by short travel times from dams to downstream control points and by relatively high predictability of extreme precipitation events, notably atmospheric rivers. Viability assessment studies of FIRO at several USACE-owned pilot sites are now informing water control plan updates. Deviations in operations using FIRO have demonstrated gains in flood risk management and water storage, leading to expanded demand for FIRO viability assessments and implementation at other reservoirs.

To assess the potential for FIRO implementation across the USACE portfolio of reservoirs, a nationwide screening process was developed. This screening considers the potential for benefits of increased operational flexibility weighed against the level of effort or difficulty to change operations and is underpinned by a multidimensional assessment of the skill of precipitation forecasting in the contributing watershed. FIRO screening is being conducted in stages, with a high-level elimination assessment of ~600 USACE reservoirs recently completed, and more in-depth assessments of site suitability by region underway through 2027. This second stage of the screening process has been applied across the southwest United States and is now being regionally adapted to consider the operational, meteorological, and hydrologic contexts of reservoirs in other parts of the United States. This paper discusses the development and application of this screening process, including results of the national first stage and regional second stage. The goal of the screening effort is to identify FIRO-suitable sites and inform next steps to scale up the modernization of USACE's reservoir operations where possible.

KEYWORDS: Reservoirs, Forecasts, Forecast-Informed Reservoir Operations, Screening Process

1 INTRODUCTION AND BACKGROUND

Dams and reservoirs are critical infrastructure for multiple, sometimes conflicting purposes, including managing flood risk, ensuring reliable streamflow and stored water supply, enabling navigation, and generating hydropower (Ho et al., 2017). Dams in the United States (U.S.) can impound an estimated volume of 1300 km^3 (Graf, 1999). Growing awareness of dams' disturbance to natural flow regimes and riparian ecologies has started to constrain operations and motivates both structure removal and improved operation of existing dams rather than new construction (McKay et al., 2020). Growing populations, shifting land use and hydrologic regimes, infrastructure aging, and increasing water stress all place demand on these critical infrastructures to be operated efficiently and effectively (Ho et al., 2017).

Forecast-Informed Reservoir Operations (FIRO) has emerged as a strategy to support more efficient management of dams (Dettinger et al., 2023). By allowing reliable forecasts of precipitation to be used in decision-making about when to retain or release water from reservoirs, more flexibility is introduced to operations at participating sites (Forbis and Ly, 2023). Where traditional reservoir guide curves require conservative preservation of a flood control space during flood-prone times of year, implementation of FIRO allows water managers to hold more stored water when forecasts are dry, improving supply reliability, or conversely to prerelease volumes in advance of forecasted precipitation, improving flood risk mitigation (Forbis and Ly, 2023). The FIRO research and operations program, led by the U.S. Army Corps of Engineers in partnership with the Scripps Institution of Oceanography's Center for Western Weather and Water Extremes (CW3E) has piloted the FIRO approach at five sites to date (Web-1). Together with investments in improving the forecast skill for predicting Atmospheric River (AR) events, the dominant driver of flood risk in the U.S. West Coast, FIRO has enabled benefits to water supply, fisheries health, recreation, and flood risk reduction at pilot sites (Forbis and Ly, 2023).

The success of this approach at the pilot sites induced expansion of the research program, including a nationwide screening of the USACE reservoir portfolio to determine where to invest in FIRO studies. At pilot sites, developing alternative forecast-based WCPs and assessing their safety and viability requires a rigorous, multi-agency assessment process that has taken up to five years, followed by a separate process to formally update the site's Water Control Manual for implementation. Pilot sites have so far been selected with reasonable expectation of FIRO viability, and the assessment process has been streamlined as more sites undertake assessment and implementation, but this approach is not efficiently applicable across a wide portfolio. In response to the demand for expansion, a multi-stage FIRO screening process (FIRO-SP) was developed to assess preliminary suitability across the portfolio of ~600 USACE reservoirs. The aim of the FIRO-SP is to efficiently remove from consideration sites with low or no FIRO suitability, and to preliminarily assess the remaining sites to identify where FIRO assessment and implementation would be most beneficial and would face fewer barriers. The resulting assessments and recommendations are meant to inform decisions about where to invest in viability assessments, and to document initial considerations for those more rigorous studies to use in scoping. This paper reports the development of the FIRO-SP, the nationwide results of its first stage, and its full application to 53 projects in the western U.S. Previous large-scale screening efforts for dams have been developed to assess potential for removal (McKay et al., 2020; Naslund et al., 2025) or prioritization for repair and maintenance (Concha Larrauri et al., 2022). The FIRO-SP is novel in attempting to screen for FIRO suitability.

2 METHODOLOGY

2.1 The FIRO-SP Approach

For initial development of the FIRO-SP, expert elicitation was used, taking advantage of the robust community of researchers and practitioners that had been developed through the pilot projects at Lake Mendocino, Prado Dam, and the Yuba-Feather system. Attendees at the CW3E FIRO Workshop in August 2020 provided input for key criteria of FIRO suitability, including precipitation forecast skill at lead times meaningful for operations; willingness of stakeholders to invest in the viability assessment and implementation process; availability of reliable operational models; and capacity of the project to buffer forecast uncertainty (Yeates et al., 2026a). A FIRO-SP steering committee was formed in 2021 consisting of representatives from USACE, the U.S. Bureau of Reclamation, CW3E, Portland State University, and Sonoma and Yuba Water Agencies. This committee determined that screening should take a staged approach and that the process should not be solely algorithmic but must allow for expert judgment. Screening is distinct from the highly rigorous FIRO Viability Assessment process: it does not determine whether or to what extent FIRO can be implemented at a site, but rather that there is potential for the strategy to be possible at and beneficial for operations at the site.

The staged approach is detailed in Table 1. Stage A was envisioned to quickly eliminate broadly unsuitable sites, allowing for more in-depth site assessments in Stage B. Stage C ensures that site-level expertise is reflected in the final scoring and recommendation, and builds a pathway from screening to FIRO viability assessment and implementation.

Table 1. Stages of the FIRO Screening Process

Stage	Description	Components	Products
A	High-level assessment of a large portfolio of reservoirs to eliminate clearly unsuitable sites and to sort the rest into those with standard or significant barriers to FIRO. Applicable to all reservoirs under consideration.	1. Water manager provision of data for lead time estimation 2. Calculation of forecast lead time requirements by site 3. Critical Success Index calculation by site 4. Water manager responses to an 8-question instrument (drop-down responses, optional notes) 5. Data review and scoring	Categorization of all sites into those with prohibitive barriers (eliminated), significant barriers (eligible but not prioritized for Stage B), and standard barriers (prioritized). Technical Report (Yeates et al., 2026a) and ArcGIS Storymap (Web-2)
B	In-depth assessment of the potential for benefit from FIRO, the level of difficulty to assess and implement FIRO, and the supporting forecast skill at each eligible site. Applicable to sites which pass Stage A and are chosen by stakeholders to undergo further screening.	1. Meetings with site stakeholders to review Stage A and decide which sites to progress further 2. Dry Forecast Failure Ratio and Forecast Error Tolerance calculations by site 3. Water manager responses to a questionnaire with 14 data entry items and 22 scored questions (ranked response and text entry) 4. Data review, scoring, and production of site reports	Draft site FIRO suitability reports, including recommendations about whether to pursue FIRO at each site. Technical Report (forthcoming)
C	Dialogues held between water managers, invited stakeholders, and the FIRO-SP team to discuss the results and to finalize scoring and site reports. Applicable for all sites which undergo Stage B.	1. Provision of draft site assessment reports to USACE water managers 2. Regional stakeholder meetings, averaging 30 minutes per site, to discuss results and site context 3. Modify any scoring based on stakeholder review and dialogue 4. Finalize site assessment reports	Site FIRO suitability reports which include scoring, recommendations, and document context. Support for next steps, if applicable, to scope a FIRO study.

Stages were developed by the FIRO-SP working group and tested with a subset of reservoirs in the USACE South Pacific Division (SPD), which includes California, Arizona, New Mexico, Utah, Nevada, and portions of Oregon, Idaho, Wyoming, Colorado, and Texas. SPD was chosen to pilot the FIRO-SP since at the time, all FIRO pilot sites were SPD projects, so there was a high familiarity with the concept among those water managers as well as known potential for FIRO suitability in those regions. Testing was conducted in 2022 for Stage A and in 2023 for Stages B and C. Instruments and methodology were then revised, including the addition of the forecast skill assessment into Stage A. The nationwide Stage A screening was conducted in the fall of 2024 through spring of 2025, and Stages B and C were conducted for 53 eligible reservoirs or reservoir systems in SPD in 2025. Application of Stages B and C is ongoing for USACE reservoirs in the Northwestern and South Atlantic Divisions and planned to be completed for all eligible sites by the end of 2027.

2.2 Stage A Methodology

The first stage was developed with the aim of eliminating from further consideration sites with clear prohibitive barriers to FIRO, and to do so without requiring extensive data elicitation from water managers or computation beyond the precipitation forecast skill assessment. The FIRO expert community was convened to provide input to the Stage A criteria at the FIRO workshops in 2020 and 2021. The USACE Sacramento District's internal Reservoir Modernization Framework and the Lake Mendocino FIRO Final Viability Assessment (Jasperse et al., 2020) were reviewed for criteria. Outcomes of Stage A are described in terms of barriers to FIRO. Prohibitive barriers eliminate a site from further screening, and significant barriers indicate lower priority for screening unless otherwise determined by site stakeholders. "Standard" barriers are so termed because while they were identified as FIRO suitability barriers, they have been successfully addressed in pilot projects. Stage A barriers are listed in Table 2.

Table 2. FIRO Screening Process Stage A barriers and their classifications

Prohibitive barriers	• Dam cannot hold an impoundment • No Water Control Plan • Insufficient forecast skill (both the CSI value is below the 0.33 threshold AND inflow forecasts are deemed insufficient) • Other identified prohibitive barriers
Significant barriers	• Indefinite forecast skill (either inflow forecasts are deemed insufficient OR the CSI value is below the 0.33 threshold) • Low or adverse stakeholder engagement • Legal or technical barriers including low dam safety classification • Other identified significant barriers
Standard barriers	• Part of a system • Section 7 project (i.e., USACE manages the dam for flood risk but does not own the project) • Other identified standard barriers

Forecast skill is assessed in Stage A by means of the Critical Success Index (CSI) for extreme precipitation. CSI describes the ratio of forecasts "hits", "misses", and "false alarms" for precipitation events at a selected percentile in a watershed area (Cordeira et al., 2025). Methodology to calculate CSI for this effort is as described in Cordeira et al. (2025), but for the FIRO-SP CSI was calculated for the precipitation integration period corresponding to an estimated necessary lead time for operational decision-making at each screened site. Lead time estimation assumed that a hypothetical additional stored volume associated with FIRO implementation will need to be evacuated past a downstream flood control point before an incoming flood event, based on reliable forecast information. This required lead time was estimated for each site using Equations 1 and 2, with site gross pool volumes, travel times to downstream control points, release outlet capacities and channel capacities provided by USACE water managers.

$$Release\ Rate = Minimum(Release\ Capacity, Downstream\ Channel\ Capacity) \quad (1)$$

$$Required\ Forecast\ Lead\ Time = \frac{0.05 \times Gross\ Pool\ Volume}{Release\ Rate} + Travel\ Time \quad (2)$$

Volumes were provided in acre-feet, release and channel capacities were provided in cubic feet per second, and travel times to downstream control points were provided in hours or days. Units were converted as necessary to calculate the required lead time in days to the nearest tenth of one day. For the FIRO-SP Stage A, the FIRO volume was assumed to be equal to 5% of the gross pool storage (a conservative estimate based on the 10% flexible FIRO pool assessed for Lake Mendocino (Jasperse et al., 2020)). CSI values for the integration period closest to the required forecast lead time were then calculated for the HUC-6 watershed in which the reservoir was located. A CSI value of 0.33 was chosen as the threshold for indicating some forecast skill (Weihs et al., 2026). Sites with CSI values below 0.33 were assigned a prohibitive barrier in Stage A if operators of the site also indicated that inflow forecasts were not available or were unreliable, and assigned a significant barrier otherwise. This condition to the interpretation of the CSI metric was intended to reduce the risk of eliminating sites if precipitation forecasts were not reliable enough alone to enable FIRO, but hydrologic response was well understood enough that precipitation forecasts together with inflow forecasts could enable modified operations.

Other Stage A barriers were all determined based on data provided by USACE site water managers via spreadsheets developed for each District's reservoir portfolio. These water managers then reviewed the resulting Stage A classifications, which were also published via an interactive ArcGIS Storymap (Web-2).

2.3 Stages B and C Methodology

Stage B assesses FIRO suitability in terms of the potential for forecast-based flexibility in operations to address water management challenges at that site (benefit), whether there are site factors that significantly inhibit the probability of successfully updating operations using FIRO (level of effort), and whether forecast skill may support operational change. Stage B is conducted by water managers providing quantitative and qualitative project information via an online questionnaire. Potential benefit includes factors such as how frequently operators request to deviate from the water control plan and how interested project stakeholders are in modifying operations to meet different objectives. Effort is assessed via items about stakeholder willingness to engage in the FIRO process, availability of forecast and operational modelling products, complexity of reservoir system operations, and presence of protected species which might be affected by operational change. Water management teams were given the opportunity to suggest additional items and factors based on regional operational conditions and challenges, and a series of workshops is planned to further develop regional methodology adaptative before more USACE divisions are assessed.

Alongside the questionnaire, the FIRO-SP team conducts assessments of a Dry Forecast Failure Ratio (DFFR) metric and a Forecast Error Tolerance (FET) metric in addition to the CSI assessed in Stage A. Benefit, effort, and forecast skill dimensions are all scored and used to calculate a composite FIRO Suitability Index score. These scores are associated with recommendation categories and are intended to inform prioritization of sites for viability assessment and implementation.

DFFR assesses the forecast's complete failure to detect precipitation when observed precipitation exceeds the 90th percentile. Forecast Error Tolerance assesses whether a reservoir's flood storage space can absorb estimated inflow resulting from the mean annual precipitation error over its contributing basin. Both metrics and the CSI are calculated using forecasts from Global Ensemble Forecast System Version 12 Reforecasts, and observational datasets vary by watershed and are reported in site suitability reports. The full instrument and Stage B scoring routines are provided in a forthcoming Technical Report (Yeates et al., 2026b).

Stage C entails the provision of draft scoring and site reports to USACE water managers followed by dialogues, virtual and in-person, to discuss results by site. These meetings have averaged about 30 minutes to an hour per site discussed. Water managers have the option to invite additional stakeholders. Scoring is revised as necessary following these dialogues, and any additional context provided is added to site suitability reports in hopes that it will support development of viability assessments where appropriate.

3 RESULTS

593 reservoirs were screened in Stage A. 184 of these (31%) were eliminated with prohibitive barriers, most commonly having no ability to impound volume (78 sites, such as lock system dams) followed by poor forecast skill. Half of the reservoirs (299 sites) exhibited significant but not prohibitive barriers, most commonly failing either, but not both, the CSI metric or the water manager assessment of inflow forecast sufficiency. 110 sites, 19% of the portfolio of USACE reservoirs, exhibited only standard barriers to FIRO. These sites were primarily in the South Pacific Division (39), Great Lakes and Ohio River Division (32), and Northwestern Division (19). Figure 1 shows the intersection sets of all barriers assessed in Stage A.

Figure 2 shows a histogram of the CSI forecast skill values for all sites assessed. More site-level detail is provided in the Storymap (Web-2).

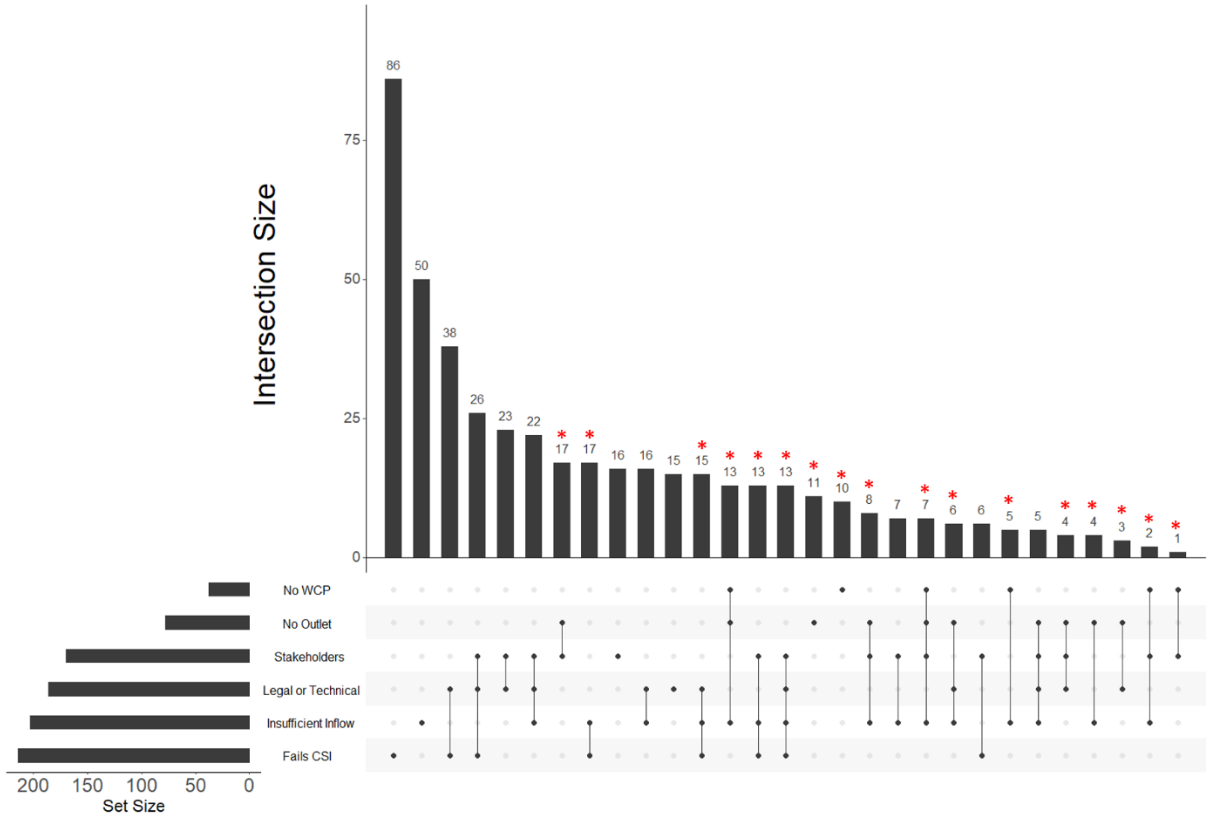

Figure 1: Intersections of barriers across all reservoirs assessed in Stage A. Intersections associated with the "Prohibitive Barrier" classification are denoted with a red asterisk (*).

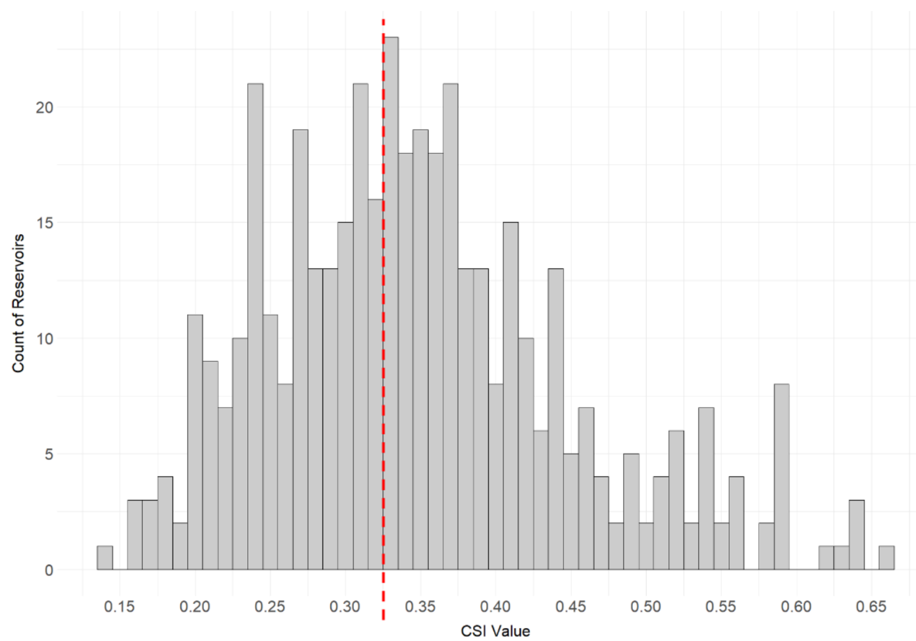

Figure 2: Histogram of CSI values in Stage A. The red dashed line indicates the CSI threshold value of 0.33, below which is considered CSI failure in the screening process.

Stages B and C were applied across 53 sites. The Effort and Benefit scores along with the Forecast Skill scores are plotted in Figure 3. Greener circles further to the right exhibit higher FIRO suitability.

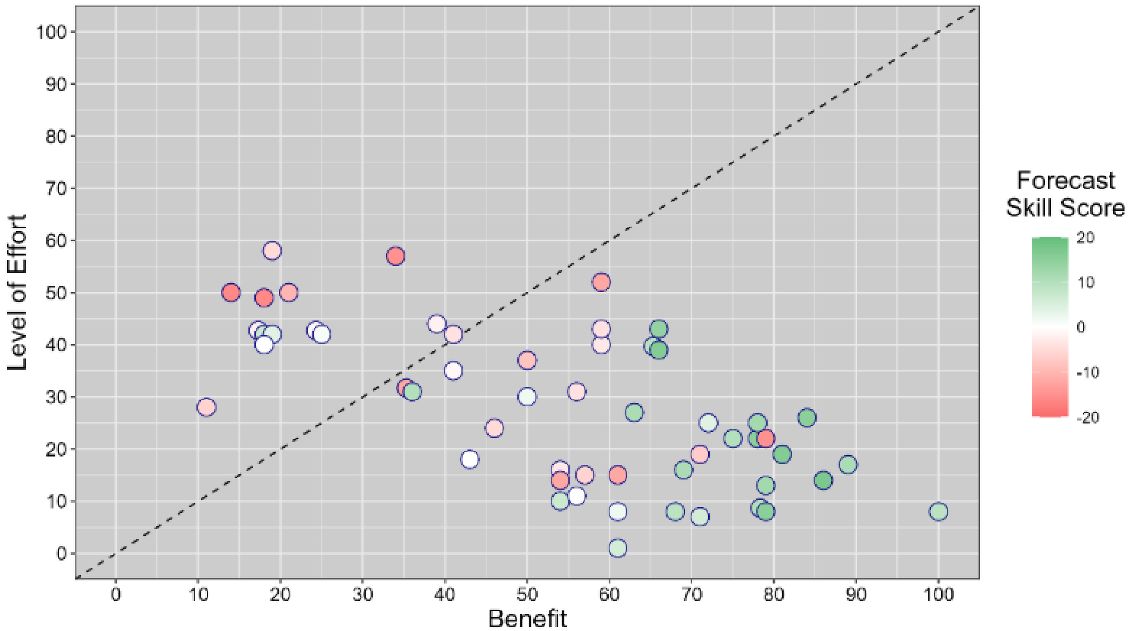

Figure 3: Plot of Stage B results for the South Pacific Division. Scores for the potential benefit from and level of effort to implement FIRO are plotted on the x and y axes, and the circles for each site are shaded by the Forecast Skill Score. The dashed line notes equality between benefit and effort scores, indicating that sites to the right of the line may be more suitable for FIRO.

Site counts associated with each of the four recommendation categories are provided in Table 3. Sites with higher FIRO suitability were further west, along the U.S. Pacific Coast, due to higher forecast skill scores. The current and prior FIRO pilot sites all fell within the highest recommendation category.

Table 3: South Pacific Division Stage B results

Recommendation	Number of Projects
Strongly consider pursuing FIRO	30
Consider pursuing FIRO	6
Make improvements before pursuing FIRO	7
Barriers to FIRO may be prohibitive; do not pursue until significant challenges are addressed	10

4 CONCLUSION

Water managers generally agreed with the initial scoring and recommendations, although most Districts did request minor adjustments to scoring. More substantial revisions were needed when the initial assumptions about forecast lead time requirements were not appropriate, leading to changes in the forecast skill scoring procedure. These are documented in site suitability reports. This upholds the importance of the site-specific dialogues in the FIRO-SP as an opportunity to correct mistaken assumptions and carefully consider the potential of updating operations at each site. Limitations included the exclusion of metrics for hydrologic inflow forecast skill, due to the high variability of inflow forecast models and availability nationwide. The heuristics used for potential benefit and level of effort are also simple, perhaps overly so.

Initial efforts to develop the Stage B methods included more complex value functions for individual scored items, which were later rejected due to the difficulty of communicating these to water management teams. Care was taken to keep the scope of the FIRO-SP simplified rather than veering into viability assessment territory, at the expense of analytical resolution.

The FIRO-SP will continue evolving as more regions are assessed and lessons learned from ongoing FIRO viability assessments are considered. It has served as a "first contact" between site water managers and the research program, providing an opportunity to grow the community of practice and promote two-way learning between researchers and practitioners.

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