Texas Forecast-Informed Reservoir Operations (FIRO): *Confluence of Interest and Path Forward*

Report from the 2023 Joint Workshop on Forecast-informed Reservoir Operations (FIRO) in the State of Texas

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List of Acronyms

ASR	Aquifer Storage and Recharge
BRA	Brazos River Authority
CIRO	Climatology-informed Reservoir Operations
CIROH	Cooperative Institute for Research to Operation Hydrology
CMU	Carnegie-Mellon University
CTB	Climate Testbed
CW3E	Center for Western Weather and Water Extreme
DRI	Desert Research Institute
DWU	Dallas Water Utilities
EFO	Ensemble Forecast Operation
FIRO	Forecast-informed Reservoir Operation
GEFSv12	Global Ensemble Forecast System Version 12
HEFS	Hydrologic Ensemble Forecast Service
NASA	National Aeronautics and Space Administration
NIDIS	National Integrated Drought Information System
NMME	North American Multimodel Ensemble
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
NWS CNRFC	National Weather Service, California-Nevada River Forecast Center
NWS CPC	National Weather Service, Climate Prediction Center
NWS OWP	National Weather Service, Office of Water Prediction
NWS WPC	National Weather Service, NWS Weather Prediction Center
NWS WGRFC	National Weather Service, NWS West Gulf River Forecast Center
NYCDEP	New York City Department of Environmental Protection
NOAA PSL	NOAA Physical Science Laboratory
QPF	Quantitative Precipitation Forecast
PMP	Probable Maximum Precipitation
S2S	Subseasonal to seasonal
TAMU	Texas A&M University
TWCA	Texas Water Conservation Association
TWDB	Texas Water Development Board
UFS	Unified Forecast System
USACE	US Army Corps of Engineers

USACE-ERDC	US Army Corps of Engineers Engineering Research and Development Center
USACE-SWF	US Army Corps of Engineers Fort Worth District
USBR	US Bureau of Reclamation
USGS	US Geological Survey
UT-BEG	University of Texas Austin Bureau of Economic Geology
UTA	University of Texas at Arlington
WPC	Weather Prediction Center (NWS)

Table of Contents

Executive Summary

First demonstrated and adopted for Lake Mendocino in California, Forecast-Informed Reservoir Operation (FIRO) has gained steady traction among states as a ***cost-effective*** strategy of managing water resources and reducing the threats of flooding. In September 2019, the Texas Water Development Board (TWDB), University of Texas at Arlington (UTA), and the National Integrated Drought Information Systems (NIDIS) jointly convened the first Texas-Oklahoma FIRO Workshop on UTA campus. The workshop served as a platform for showcasing FIRO practice and lessons learned, reviewing current forecast products from the National Weather Service (NWS) relevant to reservoir operations in the region, and identifying gaps between forecast issuers and potential users involved in reservoir operation and water resources management. The workshop produced four key recommendations for the National Oceanic and Atmospheric Administration (NOAA) and the State of Texas to facilitate the adoption of FIRO:

- Form a Task Force to coordinate FIRO-related initiatives in Texas
- Launch pilot projects that allow synergy among federal, state agencies, and reservoir operators
- Develop partnerships to broaden outreach and education to improve awareness of FIRO among water managers
- Prioritize development and operational transition of products at NOAA to facilitate FIRO adoption

The TWDB and regional stakeholders have heeded these recommendations. An informal working group was formed in 2021 consisting of personnel from TWDB, UTA, US Army Corps of Engineers - Fort Worth District (USACE-SWF), NWS, and NOAA's Office of Oceanic and Atmospheric Research. The group began with three initiatives, noted below, and continues to hold quarterly meetings focused on determining forecast requirements and improvements. Current initiatives underway include:

- A Texas FIRO Pilot project exploring the potential of FIRO for a system of reservoirs in central Texas, a multi-agency project being led by UTA
- A quarterly webinar series to highlight experiences of reservoir operators, forecasters, and researchers engaged in FIRO, led by UTA
- An assessment of the potential for employing forecasts to guide operations of a water supply reservoir near Houston, a project being carried out internally by TWDB staff

Building on this groundwork, three partnering entities (UTA, TWDB and NOAA) held the second joint Texas FIRO workshop on September 21 – 22, 2023 on the UTA campus in Arlington, Texas. The second workshop shared the same overarching goal as the first—namely to facilitate the adoption of FIRO in Texas by bridging gaps between forecasters, reservoir operators, researchers, and other stakeholders. Yet, it differed by featuring new foci, including reviewing outcomes from the Texas FIRO Pilot, building synergy among regional stakeholders for FIRO adoption, and identifying actions towards FIRO assessment.

Over one hundred participants from a wide spectrum of backgrounds attended the workshop in person or online. Key organizations at the workshop included TWDB, USACE-SWF, NOAA Research, NIDIS, and regional water suppliers. Other entities represented included engineering firms and not-for-profit organizations, an advocacy group (Texas Water Conservation Association), and academic institutions.

The workshop was held in hybrid mode with six sessions:

- Session 1: Opening remarks and background
- Session 2: Status of FIRO on a national level and lessons learned
- Session 3: NOAA's support of FIRO
- Session 4: Texas FIRO initiatives
- Session 5: FIRO: From operation to research
- Session 6: Synergistic activities and emerging themes

In addition to presentations, two panel discussions were held. The first panel was embedded in Session 3 and featured leaders from NWS forecast centers discussing ongoing and future efforts in the NWS to improve forecasts based on the decision support needs of FIRO. The second panel, during Session 5, featured discussions among water suppliers and forecasters on the value of forecast products for water planning and reservoir operation. In-person participants were able to join breakout discussions held at the end of Sessions 4 and 5 to identify interests and action items to facilitate FIRO assessment and adoption in the state of Texas.

This report documents key outcomes of the workshop and recommends specific actions for federal and state agencies to undertake in order to progress towards the assessment and implementation of FIRO. We use the term "FIRO paradigm" to designate practical situations where forecasts can be effective applied, reservoir operation strategies that incorporate forecasts, forecast products and time horizon, and workflow that translates forecasts into decisions. The FIRO paradigms for Texas likely depart from those established along the West Coast owing to the state's distinct climate, weather, drainage patterns, reservoir configurations, and risk appetite of stakeholders. The key recommendations include:

- Sustain and expand FIRO Pilot to deepen engagement with core stakeholders and collectively establish potential FIRO paradigms
- Establish an organizational structure and develop a statewide FIRO strategic plan that identifies reservoirs prioritized for screening and assessment
- Leverage state and federal resources to launch a preliminary phase of FIRO (or climatology informed operation) assessment over the FIRO Pilot in central Texas
- Create a regional testbed for the NWS Hydrologic Ensemble Forecast System to accelerate the operationalization of experimental forecast products to address critical challenges emerging from Texas FIRO Pilot and NWS operations at the West Gulf River Forecast Center.

The report is organized into three sections. Section 1 introduces the impetus of FIRO investigation in Texas and reviews key progress made since 2019. Section 2 offers an overview of sessions from the workshop, highlighting perspectives from key stakeholders. Section 3 summarizes findings and offers recommendations for follow-up actions to be taken to overcome barriers in FIRO adoption.

Introduction

Background

Forecast-informed Reservoir Operation (FIRO) is a proposed management strategy that employs weather, climate, and hydrologic monitoring and forecast information to help guide reservoir operations. By proactively managing storage and release, FIRO offers a potentially cost-effective mechanism to reduce the impacts of flooding and droughts. Systematic, consistent FIRO practice, however, only started to gain acceptance in recent years. Lake Mendocino in northern California was the first reservoir in the western United States (US) to undergo rigorous FIRO assessments (Delaney et al., 2020), and the associated successes demonstrated in the past few years have ignited wide interests among reservoir operators across the nation. Now, a national FIRO Program has been launched by the US Army Corps of Engineers, Engineering Research Development Center (USACE-ERDC), and a number of reservoirs along the Pacific Coast are undergoing FIRO assessments.

The state of Texas is the second largest economy in the US, and in the past two decades it has experienced explosive population growth that when combined with drought conditions can at times strain water supply (Fig. 1). Both present and anticipated shortages are the most severe over major urban centers (TWDB).

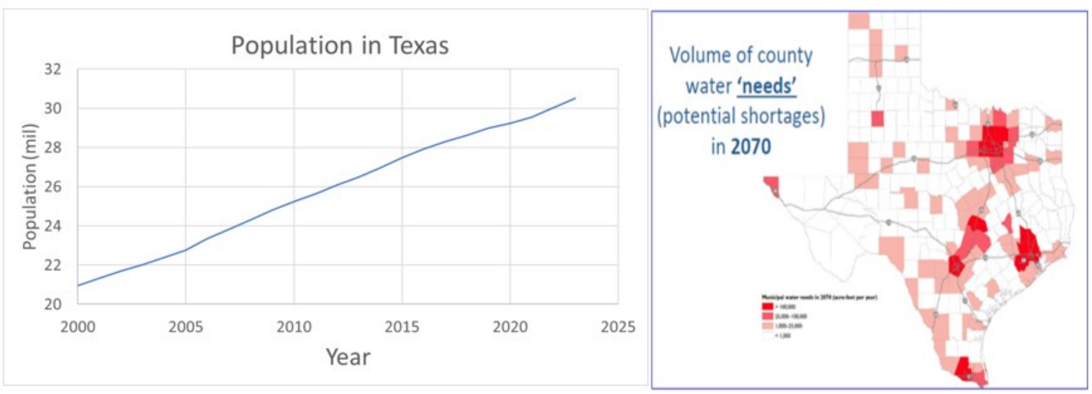


Figure 1: Population of Texas between 2000 and 2020 in millions (left); and a map of projected water shortages in 2070 per county (right). Source of projected shortage: Matt Nelson, the TWDB.

Texas is known for an abundance of weather and climate extremes with devastating consequences. The drought that developed in 2020/2021 has lingered through the fall of 2023 (Fig. 2). Its intensification in the summers of 2022 and 2023 led to severe depletion of water supply over the western and central parts of the state.

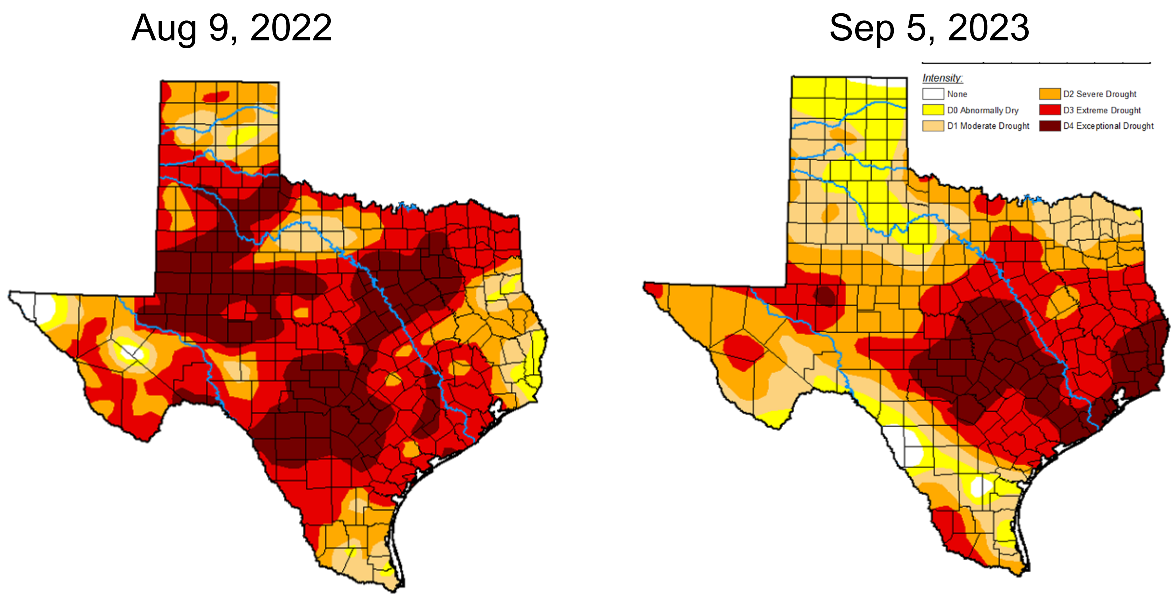


Figure 2: Drought conditions in the state of Texas from the National Drought Monitor released on August 9, 2022 (left) and September 5, 2023 (right).

The most severe impacts of the drought were consistently felt over the central parts of the state. Inflow to Lake Travis, a major reservoir that supplies water to the City of Austin, diminished to a historical low in mid-2022 since impoundment in the 1940s. Several reservoirs in central Texas, such as Lake Belton and Stillhouse Hollow, also reached their lowest level since the 1970s.

In the state of Texas, reservoirs, particularly multi-use reservoirs managed by the US Army Corps of Engineers Fort Worth District (USACE-SWF), have historically played indispensable roles in both managing flood risks and providing water supply across the state. The 2022 State Water Plan (TWDB, 2022) calls for construction of more than 20 new reservoirs by 2070 as one of the management strategies for closing the supply-demand gap in water supply. Yet, the prohibitively high cost of building and lengthy process of permitting new reservoirs have prompted state and regional stakeholders to seek alternative, interim strategies. FIRO is one such strategy being evaluated. Note that FIRO can take different forms that serve different purposes (henceforth referred to as FIRO paradigms), and the most probable one for Texas would entail temporarily retaining floodwater based on forecasts, climatology, or a combination of both, thus extending access to a greater amount of water supply than otherwise would be available.

USACE-SWF has employed forecasts in a few discrete circumstances to increase water supply. For example, USACE-SWF has coordinated with water suppliers to allow high pumpage rates from Stillhouse Hollow Lake to Lake Georgetown, in conjunction with high seasonal evaporation rates to act in place of gated releases and continue the evacuation of flood waters. This allowed both Georgetown and Stillhouse Hollow to increase water supply in anticipation of persisting drought conditions. After flooding events, reservoir operators at USACE-SWF in some cases choose to taper the scheduled release of flood waters, thereby extending access to 'extra' water supply. These practices, however, have so far been performed only on a case-by-case basis. They did not involve a systematic approach of incorporating monitoring and forecast information that could be easily replicated among events or on a regional scale. Given the diverse and unique hydroclimatic conditions of Texas, much needs to be done to identify practical situations where forecasts can be effective applied, the specific aspects of reservoir operations, forecast products and time horizon, and workflow that translates forecasts into decisions, which are collected referred to as “FIRO paradigm”.

2019 Joint Texas-Oklahoma FIRO Workshop

In September of 2019, the Texas Water Development Board (TWDB), University of Texas at Arlington (UTA), and National Integrated Drought Information System (NIDIS) convened the first Texas-Oklahoma FIRO Workshop on the UTA campus in Arlington, Texas. The workshop brought together FIRO practitioners across the nation, regional water suppliers, forecasters, policy makers, and researchers to explore the potential of adopting FIRO in Texas. Key outcomes from the workshop were summarized in a report published in 2020 (https://www.twdb.texas.gov/publications/reports/other_reports/doc/TWDB_UTA_NIDIS_forecasts_workshop_report.pdf).

Among the key findings are:

- There exists a clear knowledge gap between reservoir operators and forecast providers on the needs, availability, and skills of forecasts.
- There are interests among stakeholders in embracing FIRO but most express concerns about accuracy, spatial specificity, and delivery mechanisms of weather and climate forecasts.
- A lack of decision-support tools hinders the operational use of ensemble and probabilistic forecasts.

The report provides four recommendations to facilitate adoption of FIRO in Texas:

- Form a FIRO Task Force to coordinate FIRO-related initiatives in Texas
- Launch pilot projects that allow synergy among federal, state agencies, and reservoir operators
- Develop partnerships to broaden outreach and education to improve awareness of FIRO among water managers
- Prioritize development and operational transition of products at NOAA to facilitate FIRO adoption

Progress made from 2020 – 2023

Since the publication of the FIRO workshop report in 2020, the TWDB, UTA’s Hydrometeorology Research Group, USACE-SWF, and the NWS West Gulf River Forecast Center (WGRFC) have formed a consortium to prepare for FIRO assessment and potential adoption. The consortium has taken the following initiatives over the last three years:

Partnership with NOAA on Forecast Requirements

Since the fall of 2020, USACE-SWF has met regularly with WGRFC to discuss the use of Hydrologic Ensemble Forecast System (HEFS) forecasts in its reservoir operations. Concurrently, the Texas FIRO consortium started to hold quarterly meetings with NWS and NOAA Research to determine requirements for targeted efforts in forecast improvements and to determine FIRO approaches that can best meet the needs of various stakeholders. The NWS offices and centers engaged in Texas FIRO meetings include: NWS Climate Prediction Center (CPC), Weather Prediction Center (WPC), Office of Water Prediction (OWP), as well as four entities under NOAA Research, namely Physical Science Laboratory (PSL), Weather Program Office (WPO), Climate Program Office (CPO), and National Integrated Drought Information System (NIDIS). The meetings have provided opportunities for USACE-SWF reservoir operators to share concerns on forecast quality and needs; regional FIRO partners to stay abreast of ongoing NOAA forecast improvement activities; and aligning regional initiatives with national priorities while also providing feedback to NOAA on requirements.

Texas FIRO Pilot Project

In 2022, with support from the TWDB, USACE-SWG, NWS WGRFC and Brazos River Authority (BRA), the Texas FIRO Pilot was officially launched with Dr. Yu Zhang at UTA as the lead investigator and a team from the University of Texas Bureau of Economic Geology (UT-BEG) contributing. The Texas FIRO Pilot focuses on a reservoir system on the Little River, a tributary to the Brazos River that is situated to the north of Austin (Fig. 3), where water suppliers are grappling with securing water supply for a fast-growing population. The pilot is aimed at bridging knowledge and practice gaps between forecasters and reservoir operators, and explores potential FIRO strategies that will pave the way for FIRO assessments and adoption.

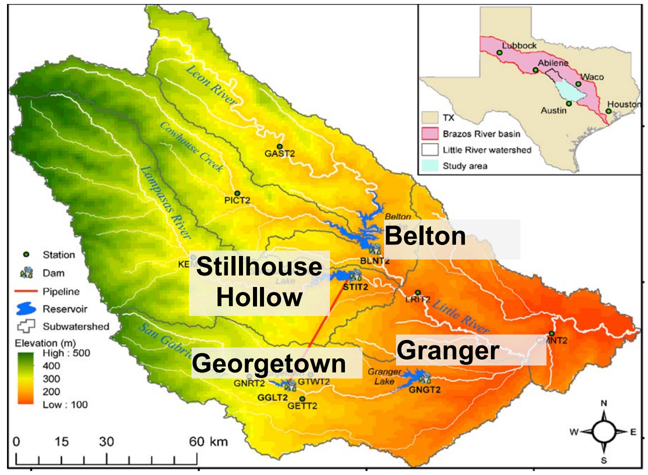


Figure 3: Map of the Little River system and reservoirs in the Texas FIRO Pilot, namely Belton Lake, Lake Stillhouse Hollow, Georgetown Lake, and Granger Lake.

Figure 4: Current Texas FIRO Pilot institution partners.

From its launch, the Texas FIRO Pilot allowed reservoir operators, forecasters, and researchers to collaboratively review the skills of current forecasts, identify forecast improvement needs, and determine opportunities and use cases of forecasts. The primary NWS forecast products undergoing evaluation are those produced by the WGRFC HEFS (Demargne et al., 2011). The Texas FIRO partnership has been expanding to include additional institutions (Fig. 4).

In 2021, the TWDB initiated an internal, complementary project assessing the use of forecasts in guiding operations of Lake Conroe, a water supply reservoir located outside of Houston in the San Jacinto River basin. The Texas FIRO Pilot team has coordinated closely with TWDB staff and is contributing to the latter project.

FIRO Webinar and Engagement Activities

The TWDB and UTA partnered to introduce a quarterly FIRO webinar series to inform regional stakeholders about FIRO activities, including the Texas FIRO Pilot and efforts taking place elsewhere in the nation. Webinars hosted until Fall 2023 featured talks from water suppliers, NWS forecasters, USACE operators involved in the Lake Mendocino FIRO project, and the lead researcher for the Texas FIRO Pilot project. TWDB staff have regularly engaged water suppliers in meetings hosted by the Texas Water Conservation Association (TWCA), a primary trade organization. The USACE-SWF representative has participated in the North American Multi-Model Ensemble (NMME; Becker et al., 2014) meeting as a stakeholder and presented forecast needs and challenges.

2nd Texas FIRO Workshop - Summary of Sessions

The second Texas FIRO workshop was a follow-up of the 2019 workshop. The motivation was to provide a platform for regional, state, and national stakeholders to share lessons from both national FIRO initiatives and the Texas Pilot project and to collaboratively determine pathways forward for FIRO adoption in the state of Texas. It comprised six thematic sessions, featuring talks, panel discussions, and breakouts. Key issues explored throughout these sessions included the following:

- Water supply and flood risk challenges: the role of FIRO in meeting these challenges from a policy perspective
- Lessons learned: the applicability of new initiatives and advances in FIRO practice from other parts of the nation to reservoir operation in Texas
- Impact of the Texas FIRO Pilot: potential FIRO strategies, forecast improvements, and planned activities
- Operational concerns of reservoir operators and water suppliers: identifying both interests and impediments to adopting forecasts and mechanisms to foster collaboration
- Research and development: activities that would contribute to FIRO adoption and enhance its beneficial use of FIRO water

The highlights of each session are summarized below.

Session 1: Opening Remarks and Background

This session included opening remarks by **John Dupnik, P.G., Deputy Executive Administrator for Water Science and Conservation at the TWDB**; welcome remarks from **Peter Crouch, Ph.D. Dean of Engineering at UTA**; a keynote address by **L'Oreal Stepney, P.G., Board Member of the TWDB**, and talks by **Matt Nelson, P.E. Deputy Executive Administrator at TWDB - Office of Planning, Todd Lericos, National Weather Service - Southern Region , Jerry Cotter, P.E. Chief of Water Resource at USACE - SWF, and Sarah Kirkle, Director of Policy and Legislative Affairs, TWCA.**

Nelson (TWDB) highlighted the challenge of meeting rising water demand in the state (Fig. 5). By 2070, the overall water demand across all sectors is projected to be 19.2 million acre-feet, with an unmet water need of 6.9 million acre-feet. Per the 2022 state water plan, twenty-five percent of the water management strategies proposed to meet this unmet need are surface water strategies. The flood planning process in Texas includes the need to identify projects that serve both flood control and water supply purposes (Texas Water Code § 16.062(e)). So far, projects falling within this dual-use strategy have proved to be elusive. FIRO could potentially be categorized as a dual use strategy. Target reservoirs would be those with both a conservation pool and a flood control pool. There is a need to consider FIRO in the long term, not just as a seasonal strategy. Areas that need further assessment include potential trade-offs in the strategy, the risk appetite of affected stakeholders, and the reliability of the strategy.

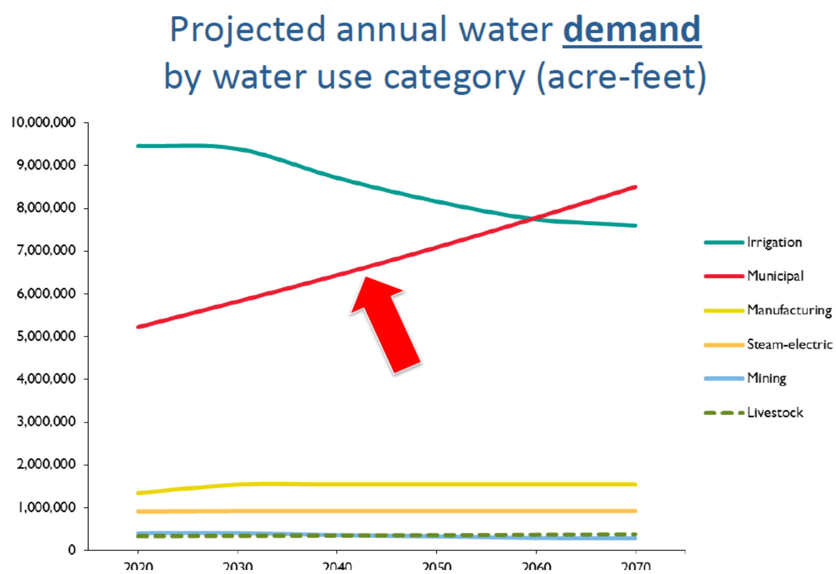


Figure 5: Projected water demand. Source: the TWDB.

Studies show declining trends in runoff in the Brazos and the Colorado River basins, two of the largest river basins in Texas. Texas has an in-migration of ~1,100 people per day, with much of the expansion of population centering along interstate 35 in Central Texas.

There is a need to lean into adaptive water management strategies to meet the growing water supply needs in the state. The talk by **Cotter (USACE-SWF)** centered on the role of USACE-SWF in this respect. For the last 15-20 years, USACE-SWF has been supporting the Water Supply community by generally starting a tapered release system as the USACE reservoirs approach 5% of flood pool or the last half foot of flood water, whichever is less. The goal of this tapered release system is to support water supply reliability, while also reducing erosion and sloughing issues downstream. Seasonality and watershed moisture conditions can affect this tapered release system. SWF Water managers are much more inclined to more slowly taper the release going into known dry periods or with dry watershed conditions, than going into known wet periods (Spring) or watersheds with wet soil conditions. At the request of water supply contract holders for temporary deviations, the USACE–SWF has, on a case-by-case basis, held a small percentage of the lower flood pool in certain reservoirs. These are one-off cases, rather than regular operational practice like the tapered release system mentioned previously. These deviations generally are requested to hold water greater than 5% of flood pool, often times 10-20% of flood pool. Adopting FIRO means taking such practice to the next level, with forecast-based deviations incorporated in normal operational strategy. Improving skills of forecasts at weather to subseasonal to seasonal (S2S) timescales are key to effective implementation of FIRO. Of particular importance are predictions on when conditions will shift from wet to dry and vice versa and how wet or how dry those conditions might be. The speakers also emphasized that collaboration is key to FIRO's success. NOAA Research and the National Weather Service are key partners in the Texas FIRO initiative, as are the state, river authorities, and water suppliers.

Session 2: Status of FIRO on a National Level and Lessons Learned

This session featured four speakers, **Cary Talbot, Ph.D., National FIRO Program Lead at the USACE - ERDC, Martin Ralph, Ph.D., and Christopher Delaney, P.E., from Scripps Institution of Oceanography, Center for Western Weather and Water Extreme (CW3E)**; and **Jerry Mead, P.E., the New York City Department of Environment (NYCDEP)**.

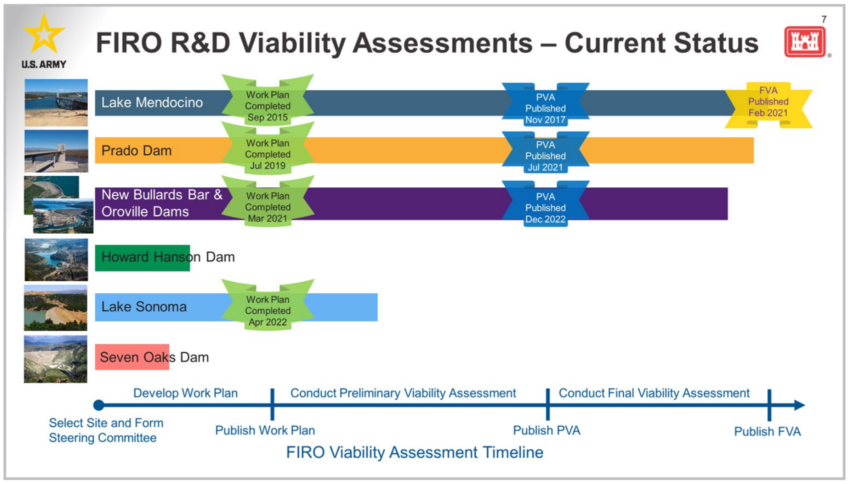
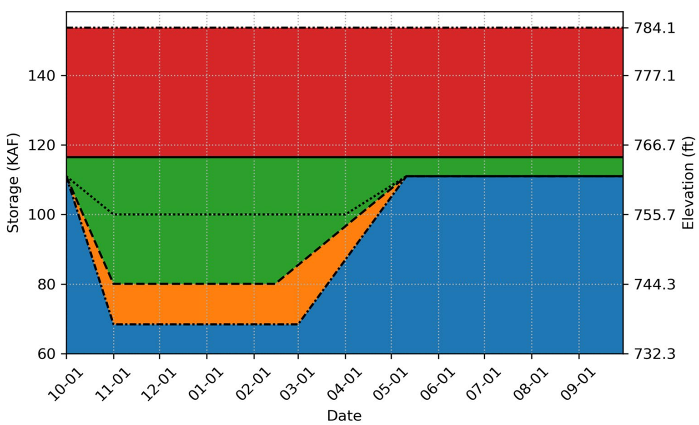


Figure 6: Status of the National FIRO Program's Research and Development Viability Assessments (USACE ERDC).

Talbot (USACE-ERDC) offered an overview of the National FIRO Program led by USACE-ERDC. The program coordinates among stake and local water agencies, USACE division and district water management leads, NWS forecasters, and researchers from NOAA Research and CW3E. Phase 1 of FIRO Research & Development successfully concluded in 2021, marked by completion of the Final Viability Assessment at Lake Mendocino (Fig. 6). The National FIRO Program is now in Phase II with ongoing assessments at three dams along the Pacific Coast (Prado Dam, New Bullards Bar and Oroville dams, and Lake Sonoma). The program is also expanding to the Willamette Valley System, a large drainage in Oregon which houses 13 USACE reservoirs and one US Bureau of Reclamation reservoir. In comparison to existing FIRO pilots, the Willamette Valley System features more complex upstream-downstream connections and longer travel times.



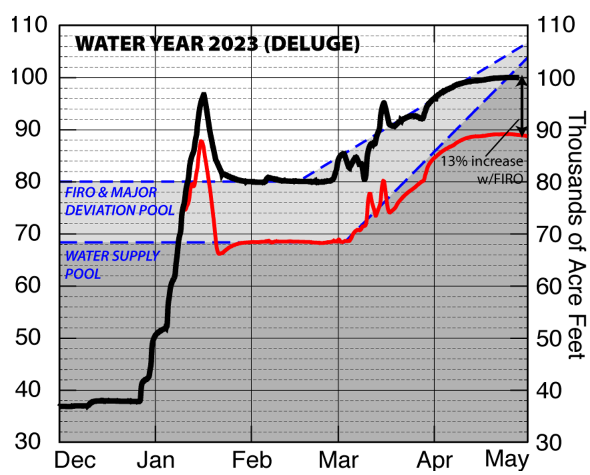


Figure 7: A default seasonal guide curve and FIRO pool for Lake Mendocino (left). Reservoir levels of Lake Mendocino during early 2023 under FIRO operations (*black*) and without (*red*) FIRO (right).

Ralph (CW3E) presented the FIRO experience during the deluge of late 2023 - early 2023, when a sequence of landfalling atmospheric rivers brought pulses of heavy precipitation and severe flooding across California. At Lake Mendocino, FIRO retained flood water and thereby substantially increased water supply storage (Fig. 7). It was noted by Ralph that evacuation of the FIRO pool of Lake Mendocino takes 2 days, and it takes 1-3 days for the releases to travel to the furthest downstream control point that is sensitive to flooding (Guerneville). Therefore, forecast skills at 1-3 day lead times are generally required for FIRO in its current form at Lake Mendocino.

Delaney (CW3E) recounted the use of ensemble flow forecasts produced by California-Nevada River

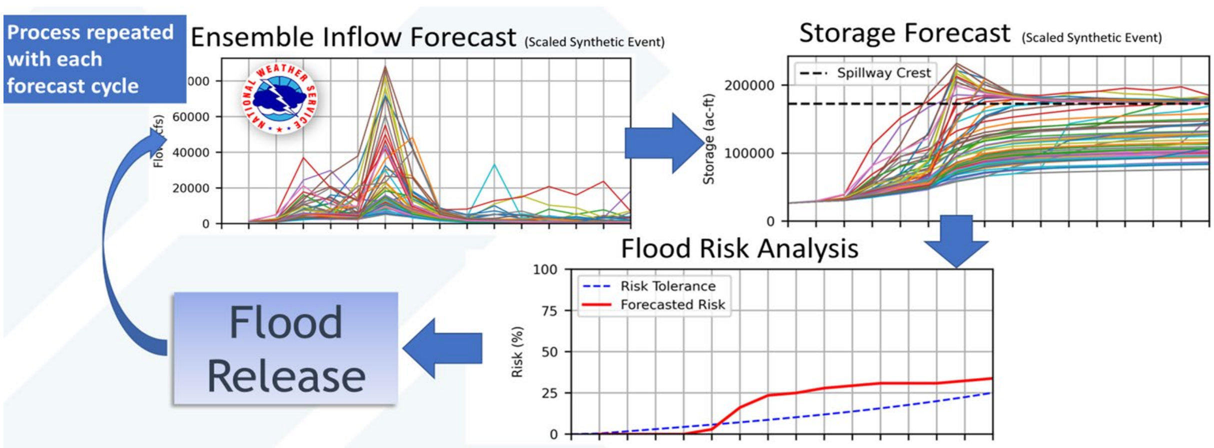


Figure 8: Ensemble Forecast Operation devised by CW3E. Source: Christopher Delany.

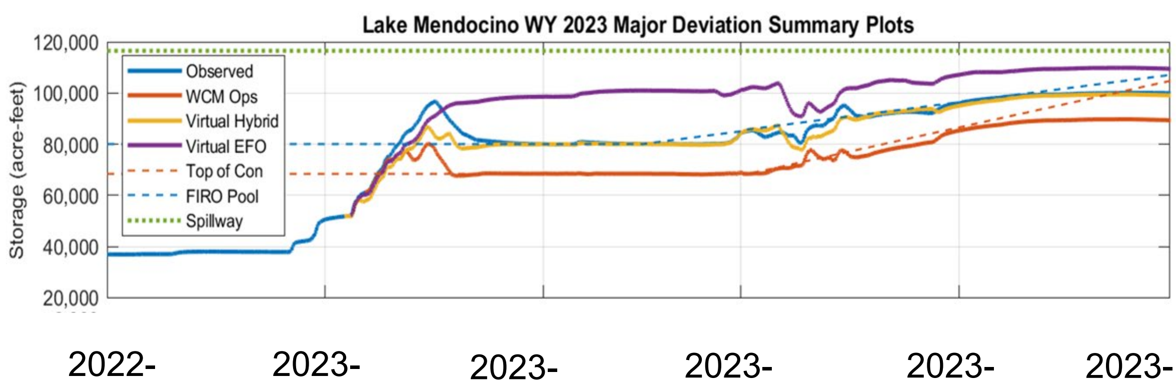


Figure 9: Time series of Lake Mendocino storage from December 2022 to May 2023 with actual water control manual (WCM) and virtual (hypothetical) operations.

Forecast Center (CNRFC)'s HEFS in guiding FIRO at Lake Mendocino using the Ensemble Forecast Operation (EFO) strategy outlined in Delaney et al. (2019; Fig. 8). The strategy compares ensemble inflow and storage forecasts against a predefined flood risk tolerance curve. This flood risk analysis creates a time series characterizing percentage risk of storage exceeding the spillway crest for a range of lead times. The result from the comparison leads to decisions on proactive flood release that is fed to HEFS to revise storage and downstream flow forecasts. Delaney demonstrated that using EFO does not increase flooding risk at downstream control points but rather yields large gains in storage relative to the current hybrid operation employed by USACE San Francisco District (Fig. 9). Delaney also showed the potential use of EFO at Prado Dam, for which a minor deviation was requested during early 2023. A key lesson learned from the pluvial events of 2023 is that forecasts were very dynamic and changed drastically between forecast cycles. This demonstrates that the practice of FIRO requires decision-support tools and personnel.

Mead (NYCDEP) entails the use of the Operational Support Tool for managing the major drainages from which New York City's water supply is drawn from (Fig. 10). The model accounts for all aspects of water supply, including water demand, water quality, releases, diversion, infrastructure status and construction support. The tool offers a position analysis mode, which ingests ensemble NWS forecasts. The multi-use reservoirs in the region implement seasonal guide curves to accommodate snowmelt-driven runoff during the spring (Fig. 11, left panel), and the agency actively uses probabilistic forecasts to manage the reservoirs. Mead provided an example of FIRO for one reservoir, the Ashokan, where additional storage is created in spring to store turbid inflow as a means to reduce turbidity. Releases from the reservoir to meet the seasonal storage objective are guided by HEFS forecasts. The agency's hindcast evaluations found that the skills of HEFS forecasts degrade substantially at longer lead times.

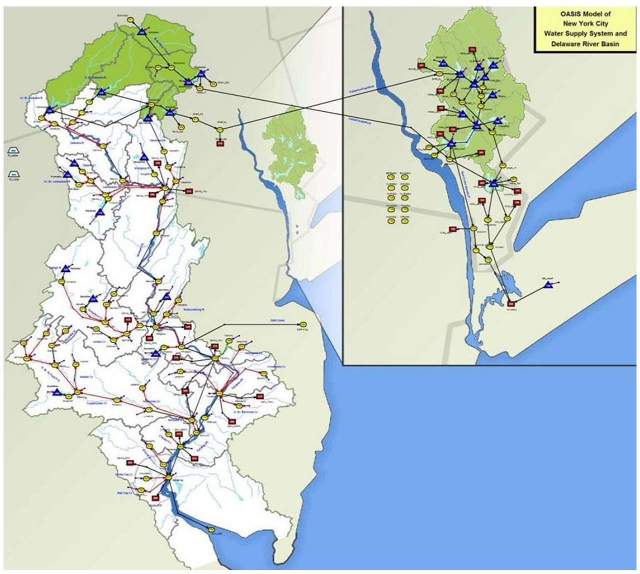
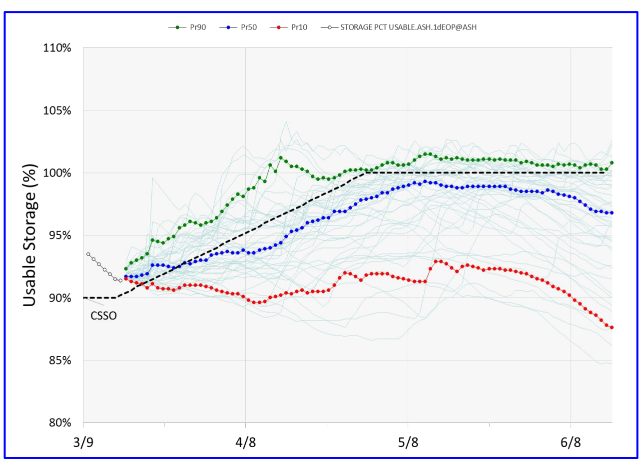
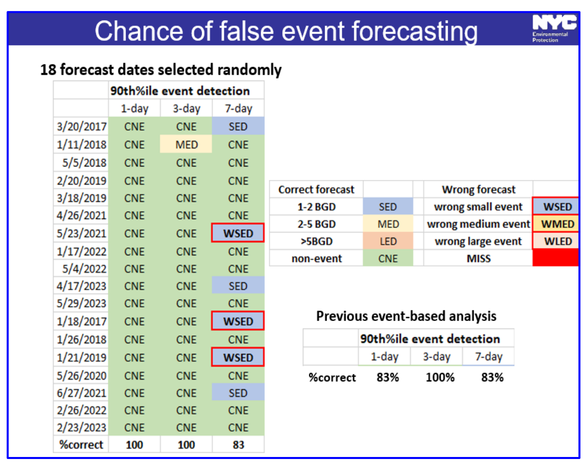


Fig. 10: Geographic coverage of the New York City water supply system modeled by the Operation Support Tool. Source: New York City Department of Environmental Protection.





Chance of false event forecasting

NYC Environmental Protection

18 forecast dates selected randomly

	90th%ile event detection		
	1-day	3-day	7-day
3/20/2017	CNE	CNE	SED
1/11/2018	CNE	MED	CNE
5/5/2018	CNE	CNE	CNE
2/20/2019	CNE	CNE	CNE
3/18/2019	CNE	CNE	CNE
4/26/2021	CNE	CNE	CNE
5/23/2021	CNE	CNE	WSED
1/17/2022	CNE	CNE	CNE
5/4/2022	CNE	CNE	CNE
4/17/2023	CNE	CNE	SED
5/29/2023	CNE	CNE	CNE
1/18/2017	CNE	CNE	WSED
1/26/2018	CNE	CNE	CNE
1/21/2019	CNE	CNE	WSED
5/26/2020	CNE	CNE	CNE
6/27/2021	CNE	CNE	SED
2/26/2022	CNE	CNE	CNE
2/23/2023	CNE	CNE	CNE
%correct	100	100	83

Correct forecast		Wrong forecast	
1-2 BGD	SED	wrong small event	WSED
2-5 BGD	MED	wrong medium event	WMED
>5BGD	LED	wrong large event	WLED
non-event	CNE	MISS	

Previous event-based analysis

	90th%ile event detection		
	1-day	3-day	7-day
%correct	83%	100%	83%

Fig. 11: Predicted traces of reservoir storage against usable storage (seasonal guide curve) at Ashokan Reservoir (left), with red, blue and green dotted lines representing the 10%, 50% and 9% quantiles. Chance of false forecasts of large inflows to Ashokan Reservoir at 1,3, and 7-day lead times for selected events from 2017 to 2023 (right). Source: New York City Department of Environmental Protection.

At 1- and 3-day lead times, HEFS offers reasonable rates of detecting moderate inflow events in the late winter-spring and features few false alerts; whereas, at a 7-day lead time, the skills are much lower (Fig. 11, right panel). HEFS skills also tend to be lower in predicting high inflow events. Improvements to HEFS are needed to guide operations in meeting storage targets for large events.

Session 3: NOAA's support of FIRO

Leaders from three NOAA NWS offices, Ed Clark, Director of National Water Center (NWS OWP); David Novak, Ph.D., Director of Weather Prediction Center (NWS WPC); and David Dewitt, Ph.D., Director of Climate Prediction Center (NWS CPC), provided overviews of their operation and research and development activities relevant to Texas FIRO. **Robert Webb, Ph.D., Director of NOAA PSL**, updated the audience on various initiatives to improve weather, water, and climate forecasts, as well as projects creating situational awareness products assisting with FIRO. **Joel Lisonbee, Ph.D., regional drought coordinator from NIDIS**, a NOAA affiliate, provided an overview of its Drought Early Warning System program.

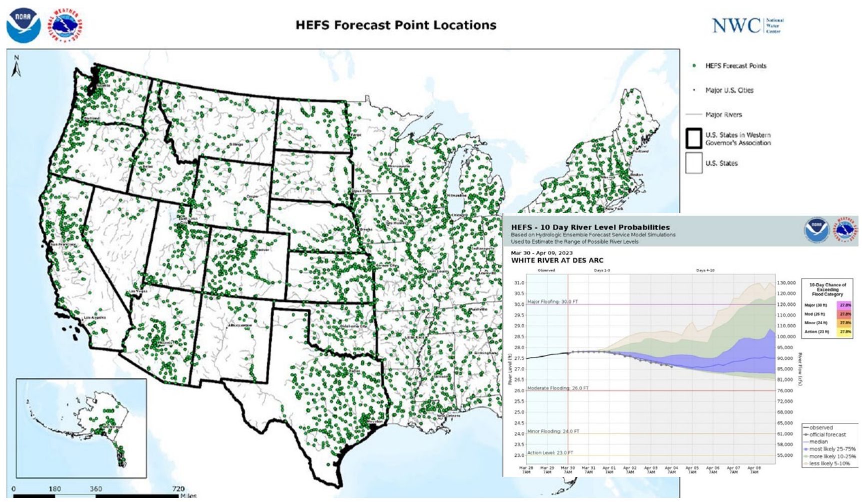


Figure 12: Current HEFS forecast points and example of a HEFS forecast. Source: Ed Clark, National Water Center.

Clark (NWS OWP) touched upon the status of HEFS deployment and the migration from Advanced Hydrologic Prediction Service to National Water Prediction Service. Fig. 12 shows current HEFS forecast points. The OWP is performing gap analysis for HEFS and plans on implementing a two-track approach for improving the system. Track 1 consists of short-term improvements, which include the introduction of methods to improve forecasts for large events, to add freezing level forecast, to eliminate artifacts, and to test the Ensemble Postprocessor. Track 2, or longer-term research and development efforts, will include testing alternative statistical postprocessors and using information from ensemble members of single and multi-model systems. NOAA established a cooperative institute (CIROH) managed by the NWS Office of Water Prediction that contributes to improving hydrologic forecasts.

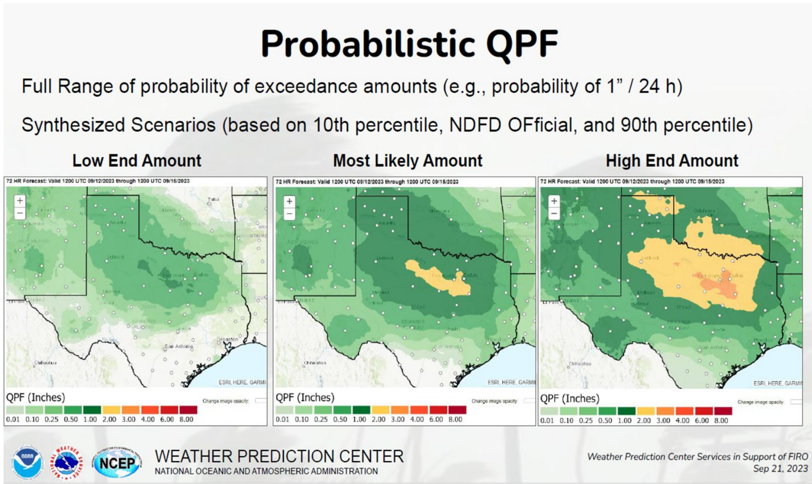


Figure 13: Examples of probabilistic quantitative precipitation forecasts (PQPFs) issued by NWS Weather Prediction Center. Source: David Novak, Weather Prediction Center.

Novak (NWS WPC) discussed the status of quantitative precipitation forecasts (QPF) issued by the NWS's Weather Prediction Center, which are now issued regularly and provide measures of forecast confidence (Fig. 13). He noted that prediction of precipitation remains a formidable challenge over Texas which encompasses a variety of climates and where diverse storm systems are responsible for heavy precipitation. Nonetheless, skills of QPFs have been improving, especially for the wintertime, and some storm systems are tied to topography which offer hope for improved predictability.

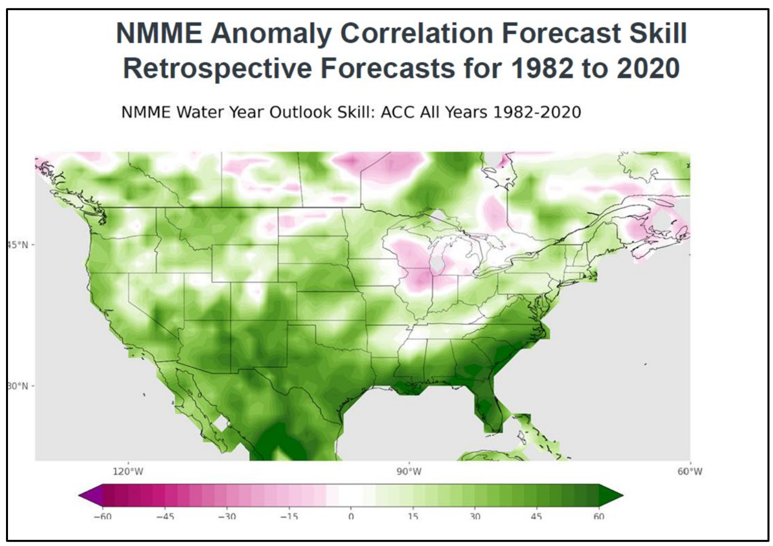


Figure 14: Geographic distribution of skill of National Multi-model Ensemble (NMME) forecasts as measured by Anomaly Correlation.

Dewitt (NWS CPC) addressed the potential use of CPC tools and products (deterministic and probabilistic) for water resources applications and specifically FIRO. It was assumed that HEFS is the primary forecast platform whereas CPC forecast products are integrated into HEFS as forcing (i.e., temperature and precipitation). CPC is interested in contributing to testing postprocessing tools for integrating first and second month lead time forecasts into HEFS. He also mentioned that advanced trace-weighting schemes that weight historical traces using forecast analogs can be explored as mechanisms of improving forecast skill. The CPC's assessment of National Multi-model Ensemble (NMME) precipitation indicates reasonably good skills over Texas (Fig. 14), but it was brought up that the skill resides mostly in periods when certain climate condition persists, whereas skill of foreseeing transition (e.g., pluvial transition) is limited.

Webb (NOAA PSL) offered a synopsis of the observational and modeling capabilities of PSL and their ongoing initiatives to support FIRO in California. A partial list of these is provided below:

- Advanced Quantitative Precipitation Information – a project that entails the deployment gap filling radar, soil moisture sensor, and other instruments to augment forecast systems for predicting variables ranging from precipitation, streamflow, to coastal inundation (Fig. 15).
- Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology – an integrated field campaign to improve the prediction and weather and surface variables.
- Monitoring with Evaporative Demand Drought Index – a project to better measure drought conditions.
- Assessments of potential changes in Western Hydroclimate over the coming decades.
- Postprocessing of precipitation forecasts to improve probabilistic QPF from National Blend of Models and could also be applied to HEFS.
- Probable Maximum Precipitation (PMP) – the Bipartisan Infrastructure Law is providing funding support to NOAA to modernize the PMP.

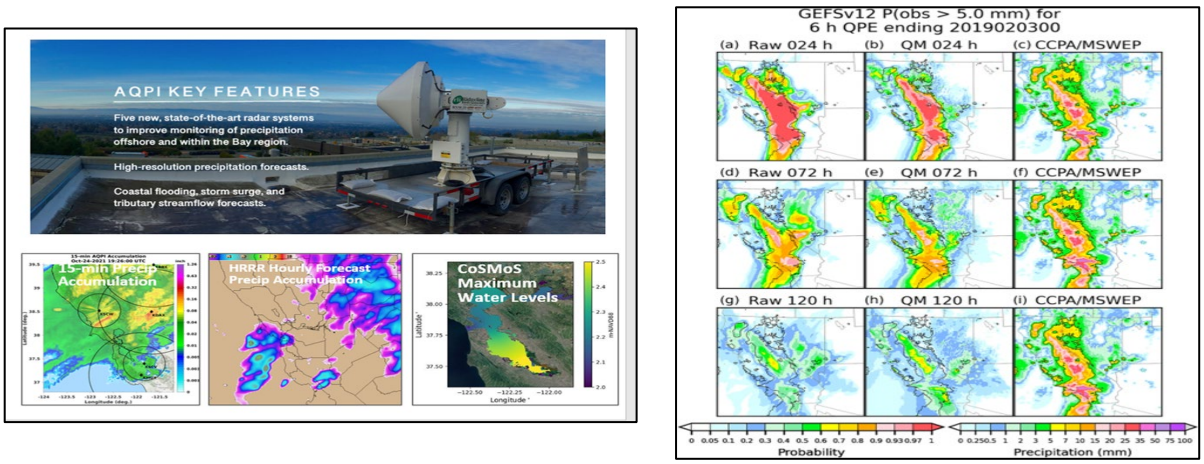


Figure 15: PSL's Advanced Quantitative Precipitation Index project highlights and experimental probabilistic precipitation forecasts. Source Robert Robin, PSL.

Lisonbee (NIDIS) emphasized that the drought early warning system is not only about forecasting or warning of droughts but rather is intended as a framework for partners to collaborate in responding to droughts (Fig. 16). The 2021 - 2025 strategic plan for Southern Plains includes investigating the expansion of FIRO over Texas as a key priority. In addition, Lisonbee discussed the increasing incidence of abnormally elevated temperatures during recent drought episodes and how this likely intensifies drought impacts and brings to fore the necessity of seeking countermeasures to preserve and increase water availability.

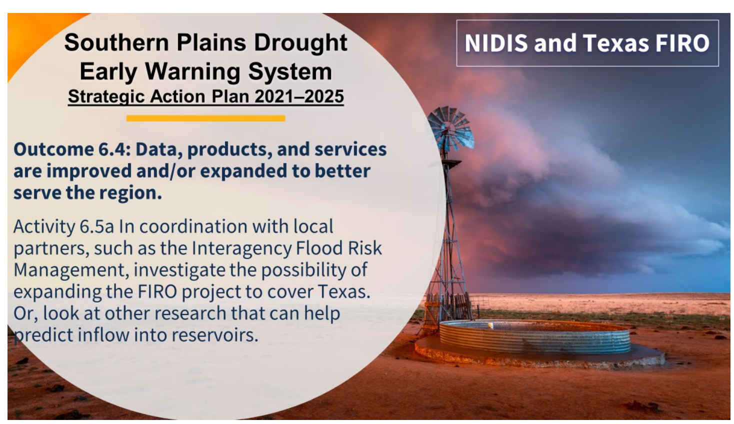


Figure 16: NIDIS Southern Plains Drought Early Warning System strategic plan lists Texas FIRO as one of their key objectives.

Presentations were followed by a brief panel Q&A with the audience.

Session 4: Texas FIRO Initiatives

In this session, **moderator Nelun Fernando, Ph.D.,from the TWDB** reviewed the history of Texas FIRO and progress made since the first workshop held in 2019. This was followed by presentations from core partners of the Texas FIRO project, namely **John Hunter, P.E., and Max Strickler, P.E. from USACE-SWF, Kris Lander, P.E. from NWS WGRFC, Yu Zhang, Ph.D. from UT Arlington, John Malito from UT-BEG**, and **John Zhu, Ph.D., P.G., from the TWDB**.

Hunter and Strickler (USACE-SWF) offered the perspective of the district and discussed FIRO-related plans and activities. The district currently operates 27 multi-purpose reservoirs in the state of Texas that serve water supply, navigation, hydropower, environmental, and recreation interests (Fig. 17). These reservoirs in total offer 6.5 million acre-feet of water supply storage. Drought vulnerability of the state has risen in recent decades, marked by downward trends in runoff in the Brazos and the Colorado River Basins. The [2022 State Water Plan for Texas] includes over 2,400 water management strategy projects, including an additional 23 reservoirs, with a total projected cost of $80B for all projects. With the adoption of adaptive management approaches, including FIRO, there is potential for the USACE-SWF to utilize 5-20% of flood storage (~13.4 million acre-feet) for water supply, thus offering significant savings.

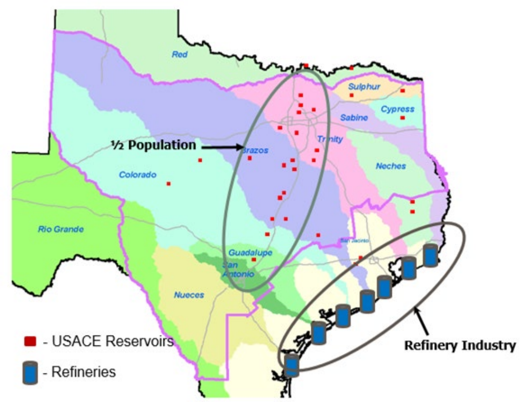


Figure 17: Location of USACE-SWF multi-purpose reservoirs within the state of Texas and distribution of major refinery facilities along the Texas coast.

Strickler presented an overview of the Trinity Operations Study, an ongoing project led by USACE-SWF involving partnerships with water suppliers in the Upper Trinity Watershed. The project aims to identify flexible reservoir operation plans for the Trinity River Basin, where eight USACE multi-purpose reservoirs are located. The project commenced in the fall of 2023 and will last for three years; it comprises three phases: Outreach, Planning, and Modeling/Analysis. Through re-evaluation of Reservoir Operation Plans in the Water Control Manuals, the project is expected to identify system weaknesses and potential adjustments that can maximize flood reduction, water supply, environmental, and recreation benefits (Fig. 18).

Figure 18: Partners for the Trinity Operations Study (left) led by USACE-SWF and potential tasks (right). These tasks include control point flow analysis, analysis of potential of implementing seasonal guide curve, environmental/low flow analysis, and water supply resilience/FIRO analysis.

Lander (WGRFC) presented the status of HEFS implementation and FIRO decision support activities. The HEFS forecasts from various RFCs are now published in a portal hosted by Colorado Basin RFC (Fig. 19). For the WGRFC service area, HEFS forecasts for 342 locations have been published and validated on

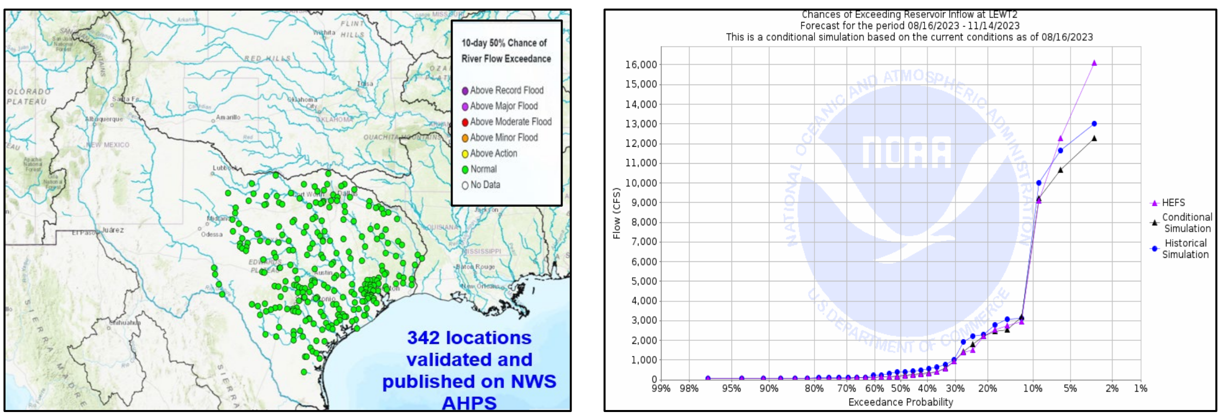


Figure 19: Experimental portal of HEFS and forecast points where HEFS forecasts have been validated and published (left), and an example of exceedance probability derived from HEFS and ESP forecasts (right). Source: Kris Lander from NWS WGRFC.

NWS Advanced Hydrologic Prediction Service (AHPS) website (Fig 19, left panel). WGRFC meets regularly with the USACE-SWF on HEFS and shares risks of high flow derived from HEFS and ESP forecasts with USACE-SWF. WGRFC is now a key partner in the Texas FIRO consortium and has been working closely with the FIRO Pilot team to assist with hindcast experiments, validations, and model improvements. Lander also summarized key challenges going forward in applying HEFS for FIRO. These include limited skills of precipitation forecasts beyond 2-7 days and reliance on climatology for longer-term forecasts. He highlighted the importance of partnerships with OWP and the FIRO Pilot team in improving HEFS performance.

Zhang (UTA), the principal investigator of Texas FIRO Pilot, reviewed the scope of the central Texas Pilot project and the preliminary findings. He noted that, for some recent storm episodes, forecast skills for heavy precipitation from the medium-range GEFS ensemble are higher over the Texas rather than California (Fig. 20), pointing to the potential of using forecasts to guide operations over a 1 - 7 day range. The current phase of the pilot has focused on evaluation of streamflow, reservoir inflow, and reservoir level forecasts generated using HEFS and the NWS CHPS, where the WGRFC HEFS configuration uses a combination of medium-range precipitation forecast and resampled climatology. Outcomes show that HEFS forecasts from the current WGRFC operational configuration outperform those based on resampled climatology at high and moderately high flow thresholds (95% and 90% quantiles); whereas for low flow thresholds, HEFS skills are lower than climatology.

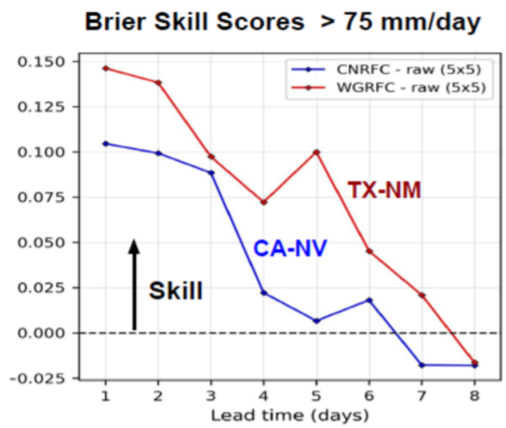


Figure 20: Skills of ensemble precipitation forecasts from the GEFSv12 as measured by Brier Skill Score over the lead times of 1 – 8 days, for service areas of California-Nevada (blue) and West Gulf (red) River Forecast Centers. Source: Yu Zhang from

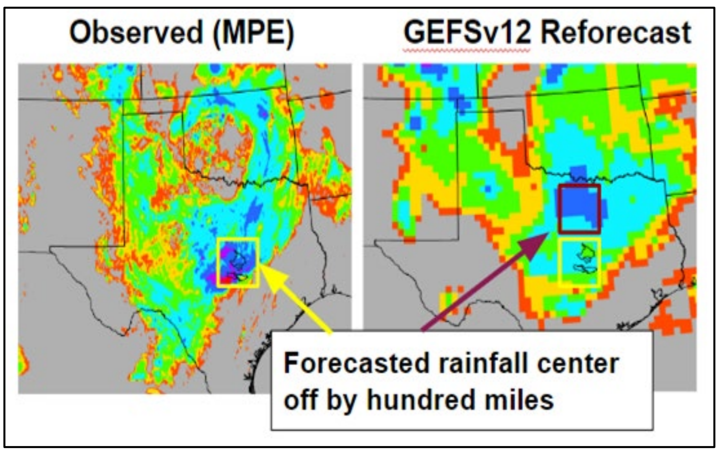


Figure 21: Observed and forecasted precipitation valid on June 27, 2007. Source: Zhang at UTA.

Zhang's presentation underscored critical limitations of current HEFS methodologies that warrant specific attention. A key limitation stems from its inability to explicitly account for forecast uncertainty resulting from displacement errors. An example was an organized convective system that produced heavy rain in the vicinity of the Texas FIRO Pilot in late June of 2007, for which the GEFSv12 control run depicts a storm center nearly 200 miles to the north of actual location (Fig. 21). This location mismatch resulted in a severe negative bias in the ensemble mean of the HEFS precipitation forecast which in turn suppressed forecasted streamflow. The second limitation relates to inadequacy in hydrologic model calibration that compounded the negative bias in precipitation forecasts for the 2007 event.

The FIRO Pilot project team completed a preliminary examination of the seasonality of inflow which serves as the first step in determining risks and returns associated with the application of a seasonal guide curve. The results appear promising. For Lake Georgetown, adding a hypothetical seasonal pool on top of the conservation pool, starting from the end of June, leads to additional storage in 10 out of the past 43 years. An example was shown for 2015 when there was considerable flood storage by late spring that could be captured. It was shown that, only in 2002, the seasonal pool may complicate flood operations due to the occurrence of a high-flow pulse in July of that year (Fig. 22).

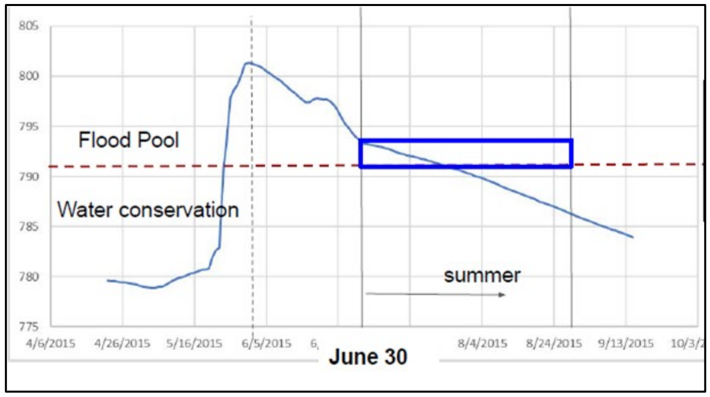


Figure 22: Reservoir level of Lake Georgetown over April – October 2015. A hypothetical, temporary elevation above conservation pool in late June provides a small gain in storage, partially alleviating the subsequent summertime deficit in conservation pool. Source: Zhang at UTA.

Malito (UT-BEG) presented the integration of HEFS seasonal inflow forecasts into the BRA planning model, which currently uses historical flow traces only (Fig. 23). The experiment explores the potential of using HEFS forecasts to aid planning operations (e.g., pumping). The outcome suggests that seasonal forecasts need improvements to capture abnormally low and high inflows to the reservoirs. It also shows that some forcing components of the model (e.g., lake evaporation) need to be updated to reproduce the severity of drawdown during the drought of 2011.

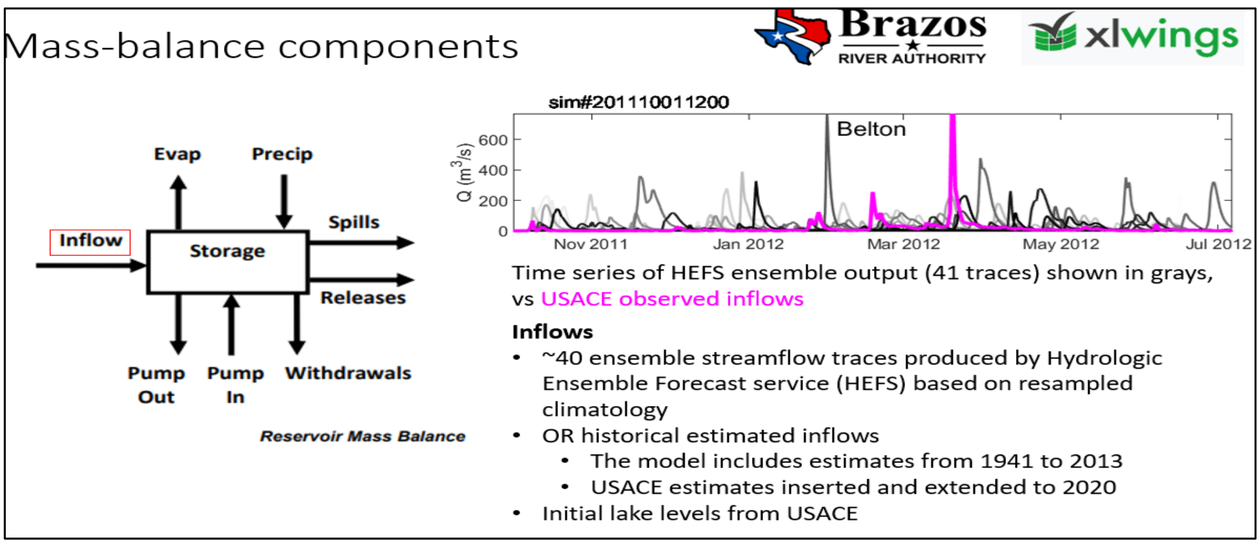


Figure 23: Ensemble HEFS inflow forecasts to the four reservoirs in FIRO Pilot for 2011 (left), and water balance components used by the BRA model as well as the model simulated release and storage. Source: John Malito at UT-BEG.

Zhu (TWDB) discussed the Lake Conroe FIRO project. Lake Conroe is a water supply reservoir outside Houston that is operated by the San Jacinto River Authority. After Hurricane Harvey in 2017, the Texas Legislature requested SJRA to consider allocating flood storage. (The reservoir currently only has water supply storage.) The current plan calls for establishing a seasonal guide curve with a lower target conservation pool level during September, which is the peak of the hurricane season, thus allowing for the capture and storage of flood water (Fig. 24). The investigation focuses on assessing the potential of applying NWS seasonal outlook and medium-range QPF to guide the pre-release of water from conservation storage to create space for flood control. The modeling system consists of a HEC-RTS model that produces inflow forecasts from a combination of seasonal outlook and medium-range QPF (for lead time of 1-3 days) and a Riverware model of Lake Conroe that utilizes inflow forecasts to generate storage and release forecasts (Fig. 24). The current model configuration specifies a range of target pool elevations based on outlook/forecasts. The schematic will be refined to incorporate Lake Houston, a downstream reservoir that takes release from Conroe.

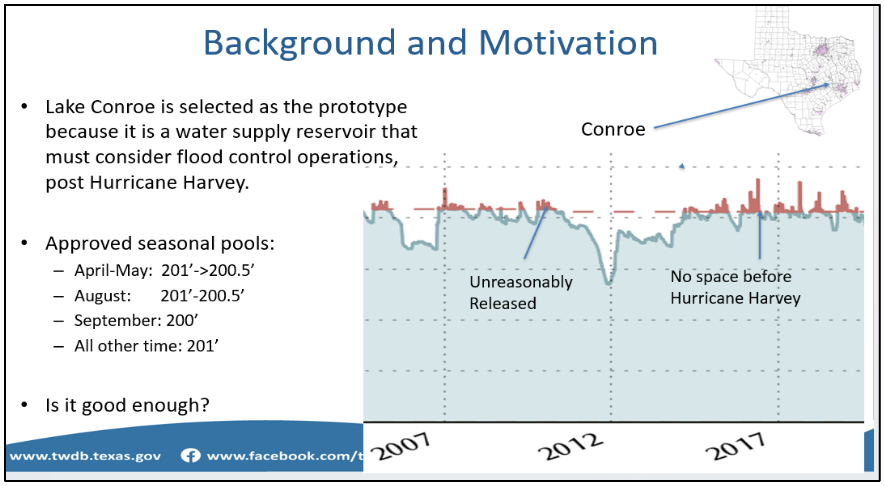


Figure 24: Proposed seasonal pool for Lake Conroe for applying forecasts to guide pre-release operations for flood control purpose.

Session 5: From Operation to Research

This session started with a panel discussion featuring water suppliers and representatives of NWS, followed by presentations on forecast needs and various research and development initiatives aimed at improving forecasts and creating new products to facilitate FIRO.

Panel Discussion: Matching forecast needs by water suppliers with NWS R&D activities

The panel included three representatives of regional water suppliers: **Denis Qualls, P.E., D. WRE. from Dallas Water Utilities (DWU), Aaron Abel from BRA, and Webster Mangham, from Trinity River Authority (TRA)**, plus two technical leads from NWS, **Kris Lander, P.E., from NWS WGRFC and Matthew Rosencrans, PhD, from NWS CPC**. **Victor Murphy from the NWS Southern Region Headquarters** moderated the discussion focusing on the following issues:

- Water suppliers' water planning and operations and the roles of NWS forecast/outlook products
- Current and future R&D efforts aimed at producing new products and improving existing forecasts at NOAA
- Making forecasts more useful and actionable for water suppliers

The three water managers described the impacts of past droughts, the process of water planning as water suppliers, current drought preparation process, and the situations in which forecasts and outlook products are applied. Water suppliers' operation and planning typically targets long-term horizons (3 – 50 years), and at present it is done using historical flow exclusively at most agencies. Water suppliers' plans are updated every ten years to cover worst-case scenarios (e.g., the drought of record in the 1950s). Nonetheless, water suppliers track CPC outlook products regularly for situational awareness and to prepare for potential "regime change" and will take actions based on forecasts. As an example, in

November 2020, BRA submitted a request to USACE-SWF for a deviation partly based on the long-range drought outlook. Water suppliers also indicated that they seek forecasts on drought intensification. Though CPC outlooks provide “drought development” as a scenario, a specific category on drought intensification is lacking.

There is a consensus among water suppliers, for those presenting and, in the audience, that the pre-release of water supply storage for flood control is not an option to entertain. Qualls emphasized the critical importance of ensuring water supply reliability and explained that using forecasts to guide operations is not currently viable, because a wrong forecast may have grave consequences on municipal water supply. He further stressed that forecasts need to achieve very high reliability (e.g., > 99%) to be useful in the context of planning, where reliability is defined as the percentage of time a forecast is validated. Rosencrans at CPC noted that this definition differs from the reliability metric used by forecasters, which depicts the consistency between the chance that a certain event is forecasted to occur and the empirical frequency of occurrence in the observation data set when similar forecasts are issued. Mangham from TRA noted that while it is challenging to incorporate forecasts in the context of water planning, other missions such as environmental flow release and flood preparedness have the potential of being informed by forecasts. In addition, the risk appetite (say for pre-release) may change when circumstances change (e.g., deteriorating drought conditions).

WGRFC is taking several initiatives of potential interest to water suppliers: including an expansion of HEFS coverage to forecast points upstream of smaller reservoirs; producing inflow forecasts at the subseasonal-seasonal range (1 – 3 months lead time); and forecast enhancements under the Next-gen National Water Model umbrella led by the National Water Center and CIROH. Rosencrans pointed to the CPC initiatives, including better resolving the upper and lower tails in forecasts through the expansion of ensemble traces; refining the spatial resolution of subseasonal forecasts to better capture high-end events; and the ongoing development of the Unified Forecast System (UFS). He also took note of the gap on drought intensification.

Additional issues discussed included:

- An interest by water suppliers to visualize past forecasts and their verification against real-time operation, tracking how forecasts fared through an event would provide confidence in the quality of upcoming forecasts
- The large displacement errors of precipitation forecasts which result in heavy rainfall occurring outside of the reservoir’s catchment region
- The difficulty of acting on probabilities of inflow forecasts alone and that inflow quantity is important for release decisions

The panel discussion was followed by presentations from **Yu Zhang, Ph.D., UTA; Matthew Rosencrans Ph.D., NWS CPC; Mark Olsen**, **Ph.D., NOAA Weather Program Office (WPO), Mimi Hughes, Ph.D., NOAA PSL; and Christopher Hain, NASA Applied Research Science Program.**

Zhang (UTA) underscored key limitations of HEFS and priorities for improvements, some of which were identified through the Texas FIRO Pilot project and the FIRO experience in California. These included:

- Under-forecast of rainfall amounts for major storm events and over-forecast for moderate events (Type-II conditional bias) in raw NWP forecasts and the amplification of such biases in the postprocessed forecasts

- Large spatial displacement errors in the location of heavy precipitation, which partially contribute to the under-forecasts and are not explicitly accounted for in the current HEFS Meteorological Ensemble Forecast Processor (MEFP)
- Lack of robust mechanisms for generating ensemble streamflow forecasts at the seasonal range
- Difficulty in calibrating/tuning HEFS for semiarid western Texas due to the limited number of rainy days and limited streamflow observations

He further pointed to potential remedies to the foregoing limitations, such as:
- Implementing a gridded version of a postprocessor to address displacement errors in precipitation forecasts
- Applying mechanisms such as forecast analogs to translate outlook products into daily or sub-daily series of precipitation
- Mitigate negative conditional bias using a technique developed at UTA.

Rosencrans (NWS CPC) offered an overview of the Climate Testbed (CTB), its missions and funded projects, and potential connections to FIRO. The CTB comprises both Research to Operation (R2O) and Operation to Research (O2R) function, the latter of which entails informing the research community of the current state of operational applications and workflows. Some of the FIRO-related projects include supporting development of a NOAA flagship subseasonal model, next-generation ensemble for Day 1 – 46 outlooks, and diagnostics for ENSO forecasts. CTB also manages the operational portion of the NMME and held a user's workshop to identify service gaps. Rosencrans pointed to several promising developments such as the development of Water Year outlooks, improved trace weighting strategies, creating downscaled forecasts, postprocessing forecasts for RFCs (currently limited to CNRFC and Ohio River Forecast Center), and experimentation with machine-learning/artificial intelligence to create improved week-2 and week 3/4 outlooks.

Olsen (NOAA WPO) presented the NOAA strategic plan for improving precipitation forecasts. In particular, he highlighted the challenge of seasonal precipitation prediction, as NMME is often unable to accurately foresee occurrence of heavy precipitation (examples shown in Fig. 25). Improvement to precipitation forecast skills has been "painfully slow." The presentation cites several sources of errors in model representations of convective initiation and propagation. NOAA has initiated the precipitation prediction grand challenge. Targets include improving forecasts of extreme events, subseasonal and seasonal forecasts, forcings to hydrologic models, and drought early warning.

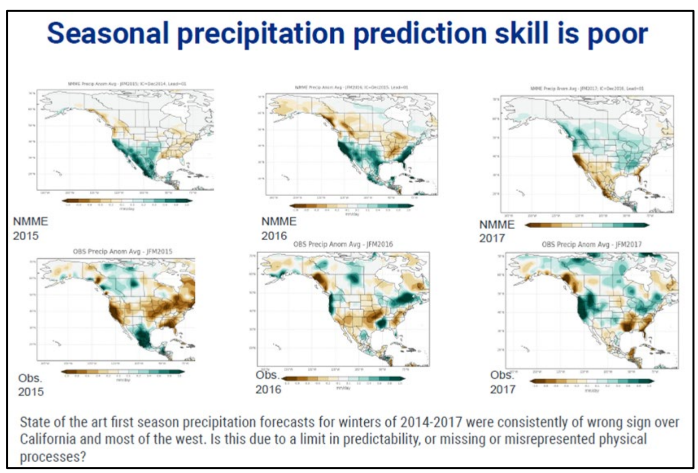


Figure 25: Inability of NMME first season forecast to predict precipitation in North America for winter (January-February-March) of 2015 – 2017. Source: Mark Olsen, NOAA WPO.

NOAA has launched two regional S2S pilots under precipitation prediction grand challenge to address needs from water management communities: a) Winter S2S Precipitation Forecasts for Water Management over the Western US and b) spring-summer S2S Precipitation Forecasts for Agriculture for the central US. PPGC also comprises an element to enable *multi-decadal forecasts* of water availability across the western US. Olsen also touched upon the two-fold goals of NOAA's S2S program, namely to improve forecast skill and to enhance products for stakeholders, and the four elements of the approach (Fig. 26), including a) gather stakeholder requirements; b) jointly determine metrics of forecast skills; c) communication of forecast uncertainties; and d) co-develop forecast products. Olsen also showcased the FY23 projects funded by the S2S program, discussed development of NOAA Seasonal Forecast System and of Seamless System for Prediction and Earth System Research ensemble, and described the path forward for which stakeholder engagement is a crucial component.

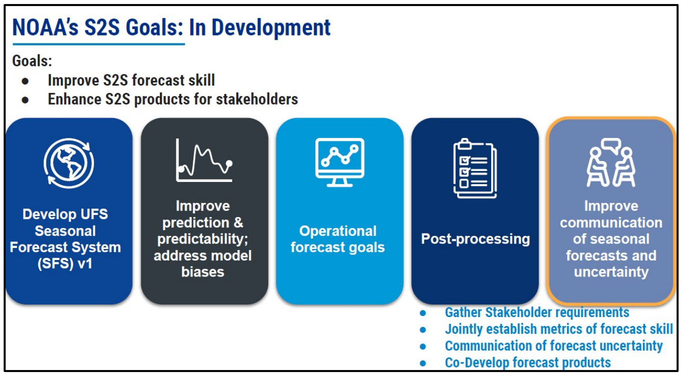


Figure 26: NOAA's S2S program goals and elements. Source: Mark Olsen, NOAA WPO.

Hughes (NOAA PSL) presented PSL's past and current activities in improving water forecasts. The Bipartisan Infrastructure Law directs PSL to "support and contribute to the transformation of NOAA water prediction tools", which will entail the development of hybrid machine-learning and processed-based techniques. The lab has worked on several initiatives in collaborating with partnering agencies, including improving ensemble forecasts of forcing to HEFS (with NWS OWP) and drought characterization, early warning, and forecasts (with NWS CPC). An example product is experimental ML-based monthly and seasonal precipitation forecasts developed by Archaya (Robetson et al., 2021) and disseminated through a web portal (Fig. 27).

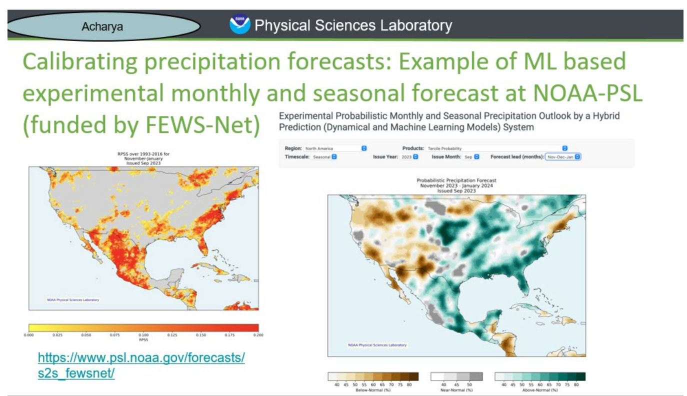


Figure 27: Experimental extended range precipitation forecasts hosted at NOAA PSL. Source: Hughes at NOAA PSL.

NOAA PSL is actively working to introduce and test alternative postprocessing techniques, including those developed for the National Blend of Models, and it will leverage the HEFS capability at UTA for the FIRO pilot. The ultimate goal is to improve risk-based decisions by stakeholders, particularly reservoir operators.

Hain (NASA) shared an overview of NASA Applied Science's Water Resource Program, the portfolio of projects and the range of capabilities it has built or is in the process of building. Hain highlighted NASA

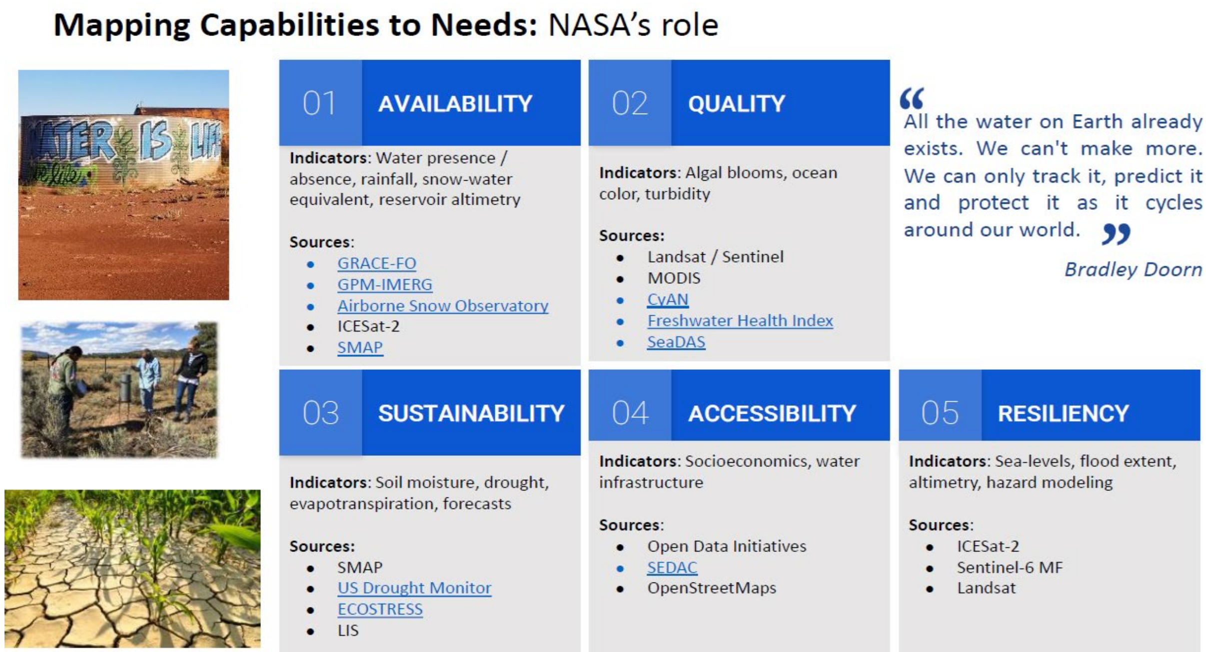


Figure 28: NASA's role in mapping capabilities to user needs. Source: NASA Applied Sciences Water Resource Program.

missions and their contributions to different water-related needs (Fig. 28). He also brought attention to the NASA Earth Information System whose focus includes flooding and water security, and he mentioned two projects relevant to Texas FIRO, including a project led by UTA on estimating precipitation losses in forecasting reservoir inflows and a project led by Texas A&M University on producing forecasts of reservoir evaporation. Hain emphasized the focus of the program is to facilitate applications, which are distinct from operations as defined by NOAA but nonetheless have lasting impacts on stakeholders' decision process.

Session 6: Synergistic Activities and Emerging Themes

This session provided an opportunity for regional stakeholders and researchers to showcase projects and discuss ideas that contribute to and/or benefit from FIRO. It comprised seven presentations delivered by nine speakers from eight organizations, namely **Jonathan Quebbeman, PhD, PE, RTI International; Denis Qualls, P.E., DWU; Bridget Scanlon, PhD, UT-BEG; Sarah Fakhreddine, PhD, Carnegie Mellon University; Huilin Gao, PhD, Texas A&M University; Farhad Hassani, UTA; and a team consisting of Diana Hanbali and Eric Van Vleet (USACE-SWF), Glenn Harwell and Monica Yesildirek (USGS).**

Quebbeman (RTI) presented three projects related to FIRO, including a project on establishing a decision support system for the New Hampshire Department of Environmental Service (NHDES), a NASA-ROSES project on economic benefits of improving streamflow forecast skills, and an ongoing project funded for CIROH on experimental FIRO operation using NexGen modeling frameworks and forecasts. The last project involves the development of a data-driven reservoir operation model that ingests experimental forecasts from the NexGen framework. The aim of the FIRO experiment is to determine the potential of reducing flood damage and increasing storage through the use of medium-range streamflow forecasts. Quebbeman highlighted the need of guiding forecast selection by reservoir operators, and the importance of economic and risk considerations in FIRO implementations.

Qualls (DWU) presented on DWU planning and operations. DWU has a dual mission of managing water supply and stormwater/flooding, which often have contradictory needs. While the water supply plan includes projects to improve water supply under "drought of record" conditions, the flood plan considers projects whose primary aims are to reduce flood risk. Qualls used "walking the tightrope" as the metaphor of the challenge in decision-making and illustrated that there is potential room for projects that could benefit both missions, namely water supply projects that provide incidental flood storage and flood projects that provide water supply benefits (Fig. 29). He further discussed the city's interest in Aquifer Storage and Recovery as a key strategy for water planning and shared thoughts on FIRO in the region.

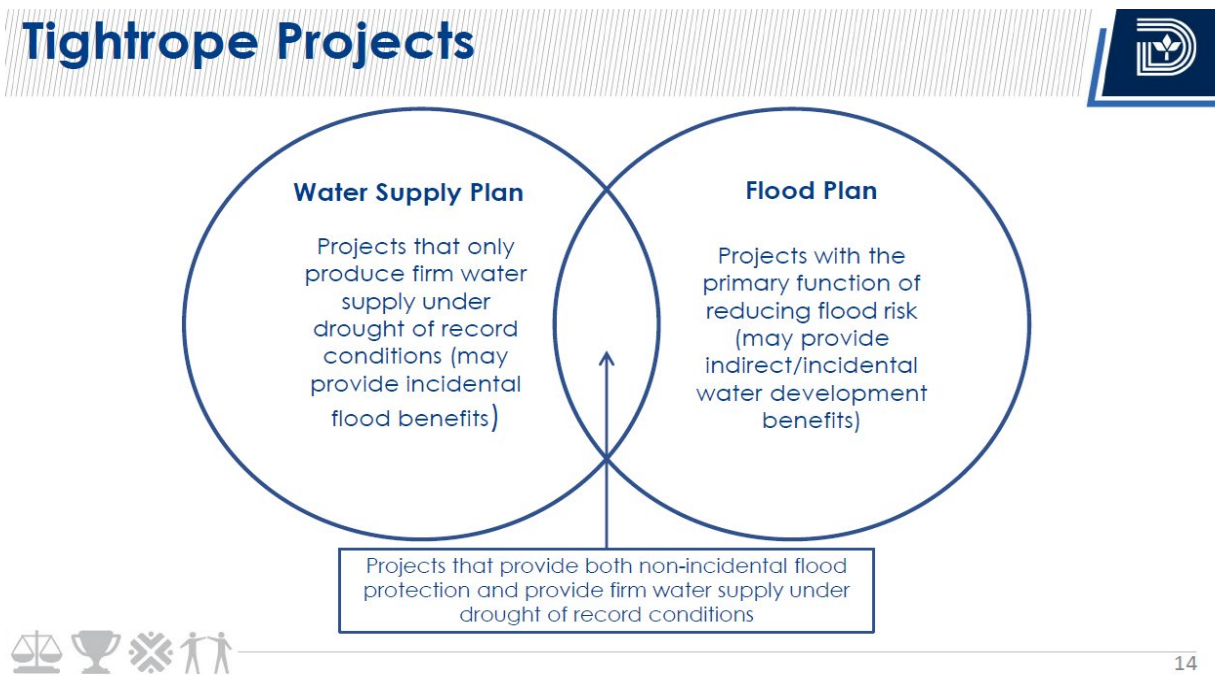


Figure 29: Objectives of water supply and flood planning and potential room for projects that could benefit both missions. Source: Qualls, Dallas Water Utilities.

Scanlon (UT-BEG) reviewed the feasibility study of Aquifer Storage and Recharge (ASR) for 91 public water supply systems in the state, which accounted for sources of contaminants, regional geology, and alternative groundwater sources. The naturally occurring contaminants include arsenic, fluoride, radionuclides, and nitrates, and implementing ASR requires facilities for treating these contaminants.

Fakhreddine (CMU) described a new initiative to predict water demand. This initiative is part of a broader project funded by NOAA to facilitate the adoption of forecasts for reservoir operations and planning over the service area of WGRFC. A key motivation of the work is the large variability in water withdrawal as identified in the Pilot project (Fig. 30). As the reservoir models used by the BRA and by

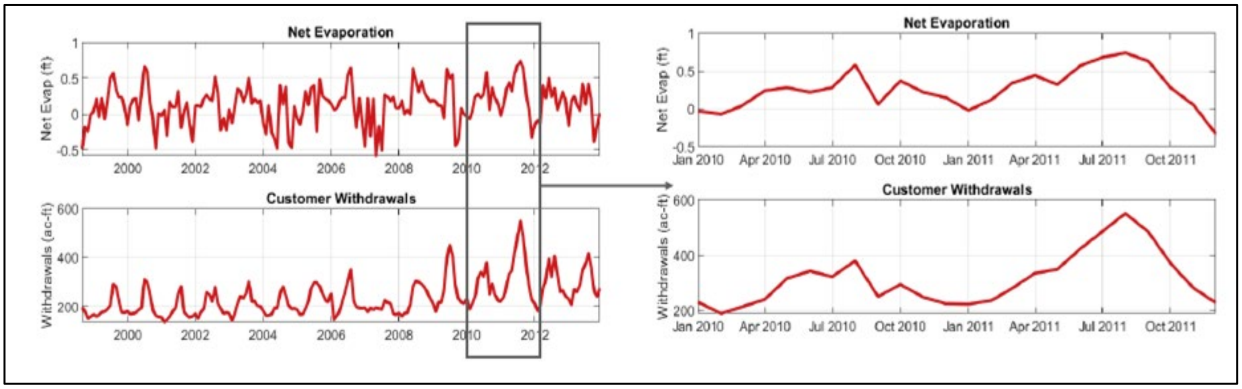


Figure 30: Departure of lake evaporation and withdrawal from climatology at Lake Granger during the 2011 drought.

WGRFC both employ static, monthly withdrawals, they are unable to foresee the severity of depletion during major droughts, such as the drought of 2011. The project element being spearheaded by CMU entails the development of a predictive tool to determine water demand on the basis of population and weather conditions. The predictions will be experimentally integrated into HEFS to yield forecasts of reservoir levels.

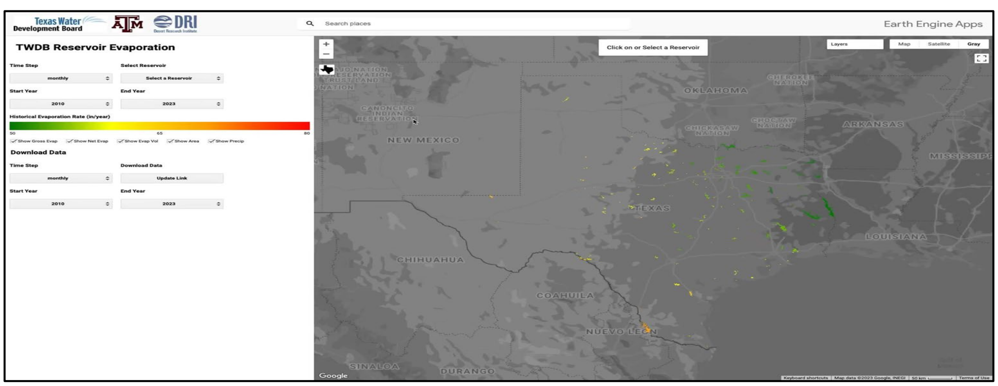


Figure 31: Portal for displaying lake evaporation for reservoirs in Texas. Source: Huilin Gao at TAMU.

Gao (TAMU) presented the reservoir evaporation efforts led by TAMU and Desert Research Institute (DRI). The TAMU team introduced a modified version of the Penman Equation that incorporates water surface temperature to calculate lake evaporation. The method is superior to the current estimates based on adjusting pan evaporation in that it accounts for reservoir heat storage and yields daily, rather than monthly, estimates of evaporation. A portal has been established at DRI to display the lake evaporation data (Fig. 31). In a current NASA Applied Sciences project, the TAMU-DRI team is developing forecasts of lake evaporation for reservoirs over the western US using weather and climate forecasts as drivers.

Hassani (UTA) presented work on rainfall loss estimation that was sponsored by the NASA Applied Sciences program. The project aims to supply rainfall abstraction to event-based models used by USACE and river authorities for reservoir inflow prediction and therefore touches on the situational awareness aspect of FIRO. UTA adapted the algorithm developed by WEST Consultants which uses soil moisture anomalies to estimate initial loss and a combination of soil moisture and rainfall amount to determine constant loss. Owing to issues in the existing operational soil moisture products, e.g., long latency in the NLDAS-2 and wet bias in the National Water Model root-zone soil moisture product, UTA developed a modified version of the Noah-MP Land Surface Model to produce near real-time, gridded soil moisture for Texas. The project team also created a bias-corrected Analysis of Record for Calibration precipitation product that was used to drive the UTA-LIS to produce retrospective soil moisture analysis and soil moisture anomaly products. Comparisons with the NWM real-time soil moisture product confirmed that UTA-LIS root-zone soil moisture is closer to bias-neutral, and this helps better represent drought conditions in the past few years (e.g., 2022; Fig. 32)

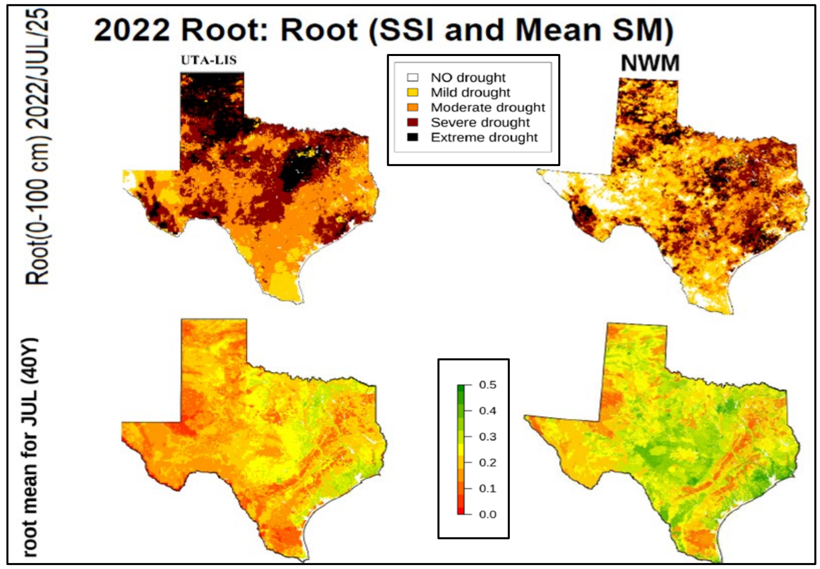


Figure 32: Root-zone soil moisture anomalies and mean soil moisture for July of 2022 from UTA-LIS (left) and National Water Model (right). Source: Hassani (UTA).

A team consisting of **Diana Hanbali** and **Eric Van Vleet (USACE-SWF), Glenn Harwell** and **Monica Yesildirek (USGS)** presented an ongoing USGS-USACE project titled “Precipitation Probability Distribution, Percent Runoff, and Trend Analysis for 25 U.S. Army Corps of Engineers Reservoir Basins in Texas from 1980 to 2019”. The project seeks to redefine the climatology of precipitation and runoff into USACE reservoirs in Texas. The resulting information may be used to guide reallocation of flood storage, an approach that is referred to as “Climatology-informed Reservoir Operation”. The project has produced monthly precipitation at different recurrence intervals (5, 20, 50-year) for each drainage basin, trends in the maximum 2-day precipitation total, and quantiles of monthly runoff under dry vs. wet conditions. The first phase of the project provided validation of the summertime trough and spring/fall peaks in the occurrence of heavy-to-extreme rainfall over the Brazos and Trinity River Basins (Fig. 33) and the highly variable runoff yield over the drainage systems. The runoff distribution is highly skewed with a conspicuous number of outliers. The follow-on phase will determine how reservoir inflows and streamflow are related to physiographic factors and drought conditions.

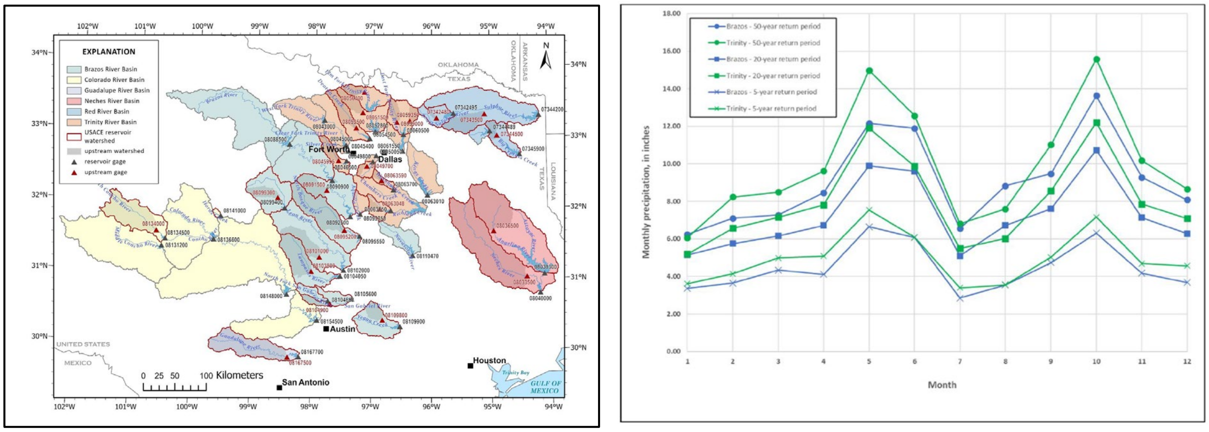


Figure 33: Map of drainages upstream of 25 USACE reservoirs in Texas (left) and monthly precipitation accumulation at different recurrence intervals in Brazos and Trinity Basins (right). Source: USACE-SWF and USGS.

Takeaways from Breakout Sessions

Two breakout sessions were held where the participants discussed the feasibility of FIRO given the current state of forecasts and reservoir operations, opportunities of more effectively applying forecasts in guiding reservoir operations, critical forecast improvement needs, and the future direction of Texas FIRO in general. This section presents the major takeaways compiled from the discussions.

FIRO's feasibility in Texas: perceptions of stakeholders

Most stakeholders expressed interest and enthusiasm in pursuing FIRO investigations. There was clear recognition of the benefit of FIRO to water supply and drought resilience by regional stakeholders, and participants showed a cross-disciplinary commitment to further exploration of the technology. A summary of key points emerging from the discussion is provided below:

- Some forms of FIRO **were already practiced de facto** by USACE-SWF. The water control manual grants flexibility in reservoir operations. For example, tapered releases and institutional wisdom of the operators allow for enhanced water supply reliability and anticipation of weather events. In several historical cases, USACE-SWF performed temporary deviations in response to requests from water suppliers to provide additional water supply storage. These experiences offered confidence to reservoir operators and stakeholders in the feasibility of the practice. USACE-SWF has also communicated to water supply stakeholders that unlike FIRO in California, USACE-SWF is not considering pre-releasing water supply storage from the water conservation pool in preparation for a high inflow event. USACE-SWF is interested in supporting the water supply community by managing the reservoirs within a flexible FIRO pool that will be located within the present-day flood pool.
- As in California, stakeholders need to be the drivers for Texas FIRO. FIRO ought not be forced on reservoir operators from a government or scientific entity, rather those entities enable and support FIRO in development and practice. FIRO should be an option for reservoirs where

viability and simulations support it. At present, a key obstacle to moving forward is that stakeholders are reluctant to assume more risks in order to protect institutional interests. Texas FIRO as a program should aim at overcoming the inertia and changing the dynamic towards addressing critical questions, forecast skills, lead times, predictability of different events, travel times; it should be a concerted, group effort to learn what the science supports.

- FIRO strategies need to be fine-tuned to suit the needs of key regional stakeholders. Several attendees brought up the possibility of pre-release as a strategy to prevent flood damage (e.g., for reservoirs upstream of Houston). However, pre-release of water supply storage for flood prevention remains contentious and water suppliers in attendance all voiced strong reservations about this practice. On the other hand, water suppliers are generally supportive of storing excess runoff in the flood pool to improve water supply reliability. Temporary reallocation of flood storage, as one water supplier pointed out, provides additional storage and in some cases helps reduce pumping costs. Additionally, water quality forecasts may be desirable to inform downstream customers about chloride levels.
- The viability of FIRO depends on a combination of forecast skill and operational constraints. The viability assessment at Lake Mendocino took into consideration frequency of high flows, spillway configuration, and riprap (erosion protection), in addition to forecast skill. Evaluating the impacts of elevated pool levels for Texas reservoirs may also account for hypothetical changes to spillway and mitigation measures (e.g., adding riprap to strengthen shorelines) that would reduce potential damage from elevated water levels. Release capacity is a critical parameter determining viability.
    - As most water supply reservoirs (in Texas) are fill-and-spill reservoirs, FIRO will focus on reservoirs equipped with flood pools and controlled release.
- There are major challenges to overcome to adopt FIRO strategies as practiced in California. Some stakeholders expressed concerns that temporary reallocation of the flood pool would elevate flood risks if the extra storage cannot be evacuated in a timely manner. For FIRO to be viable, the current consensus is that forecast skills need to extend to lead times commensurate with the aggregate of release time and travel time. Most USACE reservoirs in Texas have longer flow travel times than those being examined for FIRO operation in California. For example, the travel time for flow released from Lake Georgetown to the Gulf is ~6 days, whereas most California reservoirs are ~3 days. The travel time is further compounded by the release time, resulting in much longer lead times for which skillful projection of flooding risks is necessary. At present, however, forecast skill for heavy precipitation over Texas is often limited and tends to degrade rapidly with lead time. Noting the distinct hydroclimate of Texas and the challenges with respect to predictability, attendees suggest the following:
    - evaluate data-driven reservoir operations (e.g., static quantities such as climatology of precipitation) before embracing forecasts
    - prioritize assessment of reservoirs with shorter travel time
    - address the risk of errors in hypothetical FIRO operations (guiding operations with forecasts that went wrong)
    - weigh risks of action vs. inaction under different forecast scenarios
- ASR was brought up as a complementary measure to FIRO to reduce flood risk, by recharging reservoir storage into groundwater rather than/in addition to releasing it downstream. However, the feasibility of this approach is debatable given the infrastructural constraints (transport and recharge capacity and timeliness).

Current state of forecasts and critical improvement needs

The discussion related to forecasts revolved around accuracy of precipitation and streamflow forecasts, limitations and gaps, and needs for improvements to overcome the barrier of applying forecasts in reservoir operations. Notably, there has been increasing interest in experimenting with the use of HEFS in reservoir operations. For example, Tarrant Regional Water District has been exploring the possible use of HEFS forecasts to foresee flooding conditions in reservoirs. USACE-SWF has been holding regular meetings with WGRFC on HEFS. Below is a summary of feedback concerning forecast products and quality:

- A key concern raised by users (or potential users) is that HEFS tends to under-forecast rainfall for major, impactful events, and there should be an effort to mitigate or correct this conditional bias.
    - Related to this, there is also a concern about the inability of HEFS to account for errors in the spatial location of heavy rainfall.
- Forecast accuracy needs to be sufficiently high for months when FIRO may be practiced, i.e., months in which sizable inflow takes place. In Texas, May and October are critical windows for potential FIRO operation and forecast skills for these months appear to be the lowest.
    - Some pointed out that a more nuanced depiction of forecast skills is warranted — forecast skill for rainfall produced by tropical storms has much improved whereas forecast skill for convective rainfall events is lacking.
- Forecasting regime transition (wet to dry or vice versa) needs to be given high priority for FIRO to be practical and effective. On the other hand, there should be ancillary data provided to the users indicating the chance that a forecast fails.
- As forecast skill varies among different types of storm events (tropical, convective, frontal, etc.), there should be a breakdown of forecast performance across storm categories commonly seen in the region.

Users also expressed interest in closer engagement with forecast producers, namely NOAA Research and NWS in product design, development, and delivery. Points related to this topic include the following:

- Thus far, new forecast products have rarely, if ever, been evaluated for their impact on stakeholders' operations. There should be opportunities afforded to users to participate in product design, development, and testing to ensure the usability of the products.
- Delivery of forecast data and products appears fragmented, giving users the impression of oversaturation. NWS maintains a heap of websites and products with various acronyms that can be overwhelming, and there is not a clear pathway for using these products by reservoir operators.
- Reservoir managers point to the need for tracking how forecasts evolve in real time alongside performance of forecasts (of streamflow and reservoir inflow). Current forecast delivery platforms do not offer displays of forecast traces issued hours earlier and this needs to be corrected.

Compared to the first workshop, users demonstrated a higher level of receptiveness to ensemble/probabilistic forecasts. Users offered further suggestions on how to make forecasts more actionable by reservoir operators:

- **Consolidation:** Streamlining delivery of available forecast data through consolidated venues and highlighting products reservoir operators can act upon.
- **Improved decision support:** This can be achieved through the following efforts:
    - Providing training opportunities to help operators understand the purpose, interpretation and use cases of each product and metrics for evaluation.
        - For example, communicating what each ensemble trace represents to help users effectively consume the forecast information.
        - Users require training to interpret metrics for evaluating ensemble forecasts against climatology.
    - Creating customized products for reservoir operators with involvement of a subject matter expert.
        - A dashboard that allows users to extract metrics from a multi-ensemble dataset by setting different thresholds (such as the probability of exceeding 4” of rain).
        - Forecast products on transition from wet to dry periods: e.g., when the last inflow pulse will occur in a rainy month, like May, before an extended dry period decisively commences.
    - Establishing a risk-based decision support dashboard and metadata for reservoir operators. The system should provide the ability to parse out weather information (i.e., current conditions, short-range forecasts, etc.) and climate context (i.e., long term trends, historical records, etc.). An example to model after is the US drought monitor, which features both real-time data and time series that allows users to get a snapshot of present conditions and long-term context.
    - Providing on-demand, real-time decision support to reservoir managers, assisting the latter by parsing out the details of products useful for situational awareness and foreseeing future conditions
        - For example, New York water managers meet with the river forecast centers regularly. Tarrant Regional Water District meets with regional centers that provide very helpful data.
        - Time and manpower are critical constraints.
    - Augmenting the HEFS to allow rapid generation of hindcasts to assist with FIRO investigations.
- **Establishing Use Cases**: Use-cases of forecasts in reservoir operations will serve as valuable templates for future action. These cases should show the specific operational scenario/context, how a reservoir operator identified and employed available forecast data from NWS/NOAA to take actions, and the overall outcome.

Moving forward with FIRO: ideas and actions

Stakeholders discussed various mechanisms to build confidence in reservoir operators and stakeholders to overcome hesitancy of stakeholders to adopt FIRO. These discussions centered on launching studies demonstrating FIRO feasibility, measuring risks and stakeholder tolerance of risks, and outreach/education to obtain stakeholder buy-ins. Ideas of note are summarized herein.

- There was a call for FIRO viability studies to be undertaken to demonstrate the risks/rewards of FIRO. “Less talking, more showing”, as several participants put, would be an effective way of convincing the stakeholders and public about the potential of FIRO operations in Texas. Each viability study should

    - for each reservoir system under consideration, identify and include stakeholders who will be impacted by changes to reservoir operations
    - identify risks, risk tolerance of stakeholders (acceptable level of risks), risk of inaction, and avoid compound risks (risks of aggravating flooding downstream from release from flood storage)
    - use hindcasts and take into account risk tolerance
    - produce quantitative outcomes on water supply reliability enhancement, reduction in pumping costs, etc.
- To modify the water control manual to make alternative operation strategy a reality, there should be targeted outreach efforts to understand and reconcile the competing interests of stakeholders and minimize potential detrimental impacts, such as:
    - impacts of flood pool storage on recreation (boating, fishing), hospitality (restaurants) industries, and lakeside properties
    - capital expenditures by regional entities (for clearance of lakeside properties affected by elevated water level)
    - dam safety/maintenance considerations: for example, to allow FIRO storage, it may be necessary to raise the dam or build auxiliary spillways to speed up the release.
- To make FIRO adoption a reality, it is necessary to incorporate both bottom-up and top-down approaches, which include:
    - establishing “Champion groups” – a stakeholder, such as the Brazos River Authority, or a group of stakeholders that can adopt FIRO and provide an example.
    - soliciting champions who may represent the interest of the broader public, e.g., reservoir users, industries, conservation groups, etc.
    - establishing mechanisms to inform and engage administrators at county and state levels and providing assistance to entities that lack sufficient technical capacity to determine a path forward
    - holding more workshops or coordinating other stakeholder meetings (e.g., informal gathering at professional society meetings or webinars) to share concrete outcomes of FIRO investigations

Closing Thoughts and Recommendations

While the first Texas FIRO Workshop served as the catalyst for interagency dialogue and led to the launch of the Texas FIRO pilot, the second workshop is a culmination of the initiatives taken by the FIRO project team. It showcased findings from the Pilot project as well as FIRO initiatives in other parts of the nation, and fostered discussion among stakeholders on steps forward. Overall, this workshop demonstrated a clear confluence of interest and a strong cross-disciplinary commitment to the technology by regional stakeholders. To paraphrase a participant, FIRO can, and likely will be successful in Texas, where the science allows it to be successful.

In comparison to the workshop held in 2019, there is a broader awareness of FIRO and its implementation among reservoir operators in the region. The quarterly webinars have helped inform regional stakeholders about the FIRO initiatives and outcomes in California. The 2023 workshop offered more panoramic and in-depth overviews of FIRO-related activities and outcomes over the nation. Highlights include the following.

- Lake Mendocino, the first official FIRO pilot, has moved beyond the assessment stage in 2021, and its water control manual has undergone modifications.
- FIRO is now in the President's Budget as the single largest Civil Works R&D effort within USACE. The USACE National FIRO Program led the expansion of FIRO assessments on new pilots in California and launched its pathfinder program to bring FIRO to other regions.
- The sequence of rare-to-extreme storms and floods experienced in California starting from late 2022 till mid 2023 served as an exemplary test case that attested the risk/reward afforded by FIRO.
- FIRO practitioners in California and New York have accumulated critical operational experiences on the efficacy of using ensemble forecasts under different operational scenarios.
- NOAA has launched several forecast improvement initiatives aimed at closing the gaps between forecasts and needs of water managers over the western US.

These developments, in particular the successes, demonstrated through the Lake Mendocino Pilot, instill interest and guarded hope among regional stakeholders on the prospect of FIRO in Texas. Past and ongoing efforts in California and New York further serve as illuminating examples on how to initiate FIRO investigations, potential FIRO paradigms, and the ingredients necessary for successful implementation of FIRO.

The central Texas FIRO pilot, commenced in 2022, has made strides in building cross-institutional synergy, in narrowing the knowledge gaps between the forecast agency and users, and in delineating potential directions to materialize a Texas flavored FIRO. The project has thus far focused on the potential of temporarily reallocating flood storage for water supply, and its primary findings include:

- HEFS ensemble forecasts overall outperform climatology for moderate and high flow pulses in the medium range (0-15 days).
- Despite their overall superior skills to climatology, HEFS forecasts are limited in their ability to predict high inflows, particularly those produced by convective events. This poses perhaps the greatest challenge to its routine use in FIRO. Under-forecasts of precipitation and issues in model calibration contribute to the skill limitations.
- There are a substantial number of historical years in which using a seasonal guide curve could have led to increased water availability and only a few years in which it may have complicated flood operations. Judicious use of forecasts can help release this extra storage and thereby reduce flooding risks.

Though the FIRO Pilot covers a limited spatial domain in central Texas, the outcomes broadly echo the experience from NWS forecasters over other parts of the state, or even other regions in the US. Indeed, the concern with under-forecast, particularly over longer lead times (> 3days), is shared by NYCDEP.

The TWDB-led Lake Conroe initiative features objectives complementary with those of the central Texas Pilot, namely appraising the potential use of forecast and outlook products to improve reservoir management in general. After Harvey, water suppliers along the coast have been under pressure to adopt a seasonal rule to allow flood storage in water supply reservoirs during the hurricane season. Though forecast-guided pre-release remains a contentious topic among water suppliers in Texas, it presents a potentially viable alternative to the seasonal rule by averting unnecessary releases.

Feedback from the breakout sessions points to a clear, converging interest of regional stakeholders in launching FIRO investigations. Specifically, stakeholders expressed interest in launching feasibility/viability studies that can produce quantitative assessments of risks and returns associated with FIRO strategies, establishing working groups and champions for FIRO adoption, and expanding outreach efforts. Experience from California indicates that strong stakeholder involvement is a key ingredient to any successful FIRO assessments. As in California, Texas FIRO investigation may follow a similar, bottom-up approach that involves coordination among stakeholder groups to review risks/rewards, identify and address competing interests, and collectively determine/advocate for the course of actions necessary for modification of water control manuals.

The workshop highlights challenges that must be overcome to introduce and adopt forecasts in reservoir operations. Most of these echoed those summarized in the 2019 workshop report and will not be repeated here ad verbatim. It is important to recognize that the hesitancy of reservoir operators to adopt forecasts stems from three interrelated concerns, namely 1) limitation in skills of forecasts and potential risks arising from embracing alternative operation strategies; 2) distinctive geographic layout of reservoirs, long travel time, limited release capacity that may compound and amplify risks related with forecast errors; and, 3) a lack of experience and technical skills in using forecasts, particularly ensemble forecasts, to guide operations. Reservoir operators remain skeptical about the applicability of the FIRO paradigm established in California, i.e., the FIRO pool and its forecast-guided release, considering the challenges in forecast skills for heavy precipitation and long travel times for several reservoirs in Texas. An alternative approach floated by the USACE-SWF is the use of climatology, rather than forecast to guide operations. This climatology-informed reservoir operation (CIRO) essentially involves the application of a seasonal guide curve in lieu of the current, uniform guide curve, allowing for expanded storage only during months featuring low probabilities of heavy rainfall and high inflow. Note that the majority of USACE multiuse reservoirs, those in the Texas FIRO Pilot included, feature relatively long travel time (> 7 days to the most downstream control point), at which forecast skills for heavy rainfall tend to be marginal. Thus, CIRO appears to be an appealing intermediate solution. Indeed, preliminary analysis conducted through the FIRO pilot suggests that switching to a seasonal guide curve can help increase water supply for the four pilot reservoirs in some of the years. Nonetheless, there remain questions on whether and how flood pool storage impacts flood operations as high flow did occur in several past years.

To close, though major progress has been made by Texas FIRO partners that provided material for discussion, much remains to be done to systematically address the remaining concerns from reservoir operators and stakeholders. Below is a list of recommendations for state and federal partners to consider overcoming barriers.

Recommendation 1: Sustain and expand the Texas FIRO Pilot and outreach activities

The Texas FIRO Pilot led by UTA has made strides in facilitating dialogues, building partnerships, and identifying a common course of action among NWS forecasters, reservoir operators, water suppliers, and researchers in NOAA and academic institutions. In some ways mimicking a NOAA testbed project, the Pilot serves as a bridge between the forecast purveyors and users, and has helped identify limitations in current forecast products, directions of improvements, and use cases. The FIRO webinar series hosted by UTA has helped connect regional stakeholders with FIRO practitioners in the nation and brought awareness of FIRO paradigms and implementation among water managers across the state. Workshops served as capstones for FIRO investigations by synthesizing outcomes from concurrent FIRO activities and soliciting stakeholder input.

It is recommended that state and federal partners (i.e., TWDB, NOAA, USACE, UTA) collaborate to sustain and expand the FIRO Pilot and outreach activities. Specific recommendations include the following:

- Incorporate FIRO and the FIRO Pilot in the strategic plan of TWDB, a primary sponsor of the FIRO pilot, and partnering agencies.
- Expand the current FIRO pilot projects by assessing forecast-guided, hypothetical operations to include CIRO and hybrid FIRO-CIRO paradigms to closely align with the priorities of the USACE.
- Broaden the purview of the FIRO Pilot to address the information fragmentation brought up by workshop attendees and develop a document summarizing decision support tools needed by reservoir operators and matching them to potential solution providers.
- Identify resources to assist the FIRO Pilot team in hosting webinars, conducting stakeholder surveys, preparing workshop reports, and planning for a FIRO assessment.

It was raised in the workshop that more frequent workshops will be helpful to share outcomes and compel action. At present, facing manpower and resource constraints, the FIRO Pilot team intends to host workshops biennially rather than annually, though this is subject to change depending on stakeholder needs, the cadence of FIRO assessment efforts, and availability of resources.

Recommendation 2: Establish FIRO organization and develop a state-wide strategic plan

The 2019 workshop report recommended the establishment of a task force coordinating FIRO activities across the state. While the FIRO Pilot team and partnerships in some ways fulfill this function, it remains important to build broader consensus across major stakeholders in the state, and to garner resources to launch FIRO assessments as advocated by workshop attendees. There have already been discussions among USACE, TWDB, and regional water suppliers on creating a state-level body that oversees FIRO-related efforts and identifies and advocates for resources to support FIRO assessment. It is recommended that existing FIRO partners work with key regional entities to develop an organizational structure conducive to future FIRO investigations. The TWDB, which had played an instrumental role in launching the FIRO Pilot, may lead the effort in coordinating among the stakeholders, FIRO partners, and the FIRO pilot project team.

Another important need identified through the FIRO Pilot and the workshop is a strategic plan for FIRO in the state of Texas. As noted earlier, FIRO paradigms for Texas may differ somewhat from those established along the West Coast owing to the state's distinct climate, weather, drainage patterns, reservoir configurations, and risk appetite of stakeholders. It is therefore critical to determine a process to identify reservoirs for potential screening while laying out potential, alternative operation strategies in the meantime. Note that the USACE National FIRO Program has established a set of criteria in screening reservoirs for potential FIRO assessment. These criteria may be tailored according to situations and stakeholder needs within the state of Texas. The strategic plan may be developed by a technical team in consultation with key stakeholders; it should be based on outcomes from Texas FIRO Pilot, Lake Conroe project, and concurrent FIRO efforts across the nation, and should offer an in-depth exposition of the FIRO paradigms, engagement strategies, and R&D needs for Texas. The plan also should be reviewed by the state committee prior to publication.

Recommendation 3: Prepare for Preliminary FIRO assessment

As many stakeholders expressed interest in pursuing FIRO assessment, the time is perhaps ripe for the current FIRO partnering agencies to prepare for a preliminary FIRO assessment while the strategic plan is being developed. It is recognized that FIRO investigations will be an iterative process and the experience from the assessment itself will help shape the formulation of eventual FIRO strategies and plans. As noted earlier, the reservoir system in the Texas FIRO Pilot features travel time beyond the 7-day window normally considered to be the maximum for FIRO investigation by the National FIRO Program. Nonetheless, there is a good possibility that CIRO (seasonal guide curve), or a hybrid strategy combining forecast and CIRO, may be effectively applied to yield beneficial results. Alternatively, priority may be given to a few multi-use reservoirs in the state that do have shorter travel times, e.g., Lake Somerville in the Brazos River Basin.

It is recommended that the FIRO project team and partners determine and undertake necessary steps for a preliminary FIRO assessment. The scope of the assessment and reservoirs of interest should be identified in consultation with key partners. As illustrated in past and ongoing assessments in California, the essential ingredients include the modeling system capable of integrating forecasts, workflow that would mimic potential FIRO practice, and stakeholders' risk tolerance.

Recommendation 4: Create a regional HEFS testbed to coordinate forecast improvement activities and facilitate research to operation transition

While the FIRO pilot fulfills several functionalities of the testbed as recommended in the 2019 workshop report, it is limited by its scope and geographic extent. To address current and emerging forecast needs from reservoir operators across the state, a state-wide HEFS testbed is necessary. This testbed will assess enhancements to existing modules in HEFS and explore potential alternatives that will overcome critical limitations that were documented by the FIRO Pilot project team and shared in the workshop (see presentation summary by Yu Zhang at UTA). It will also serve as a conduit to channel the needs of users to developers and researchers within and outside NOAA.

There are several efforts aimed at improving HEFS led by UTA, NOAA PSL, and NWS OWP. These initiatives range from developing novel mechanisms for postprocessing heavy-to-extreme precipitation forecasts (UTA, PSL, OWP), testing alternative seasonal forecasts for potential integration in HEFS (UTA, PSL), developing HEFS parameter estimation schemes for semiarid regions (UTA), and establishing algorithms for predicting water use and availability (UTA and CMU). A testbed environment will help coordinate these R&D efforts, avoid duplications, and facilitate integration of enhancements proven effective into the WGRFC workflow.

The UTA team has been using operational HEFS for development and testing over the years. The experience, however, indicates that the system in which HEFS is implemented is difficult to tailor for testing alternative modules. The NextGen framework being developed at NWS OWP provides a promising alternative platform that will allow for rapid prototyping, fast integration of new modules, and automated hindcast workflow. Moreover, the newly established Cooperative Institute for Research to Operation Hydrology (CIROH) offers opportunities to academic institutions to contribute to the development and operationalization of new concepts and modules. It is recommended that the NWS OWP works with the Texas FIRO partners to identify and leverage CIROH resources to establish the regional testbed. The regional testbed shall coordinate with concurrent activities sponsored by the NWS testbeds and, potentially, infuse new products emerging from these activities into HEFS. It shall also be closely connected with the ongoing FIRO investigations and feature clear research to operation pathways.

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