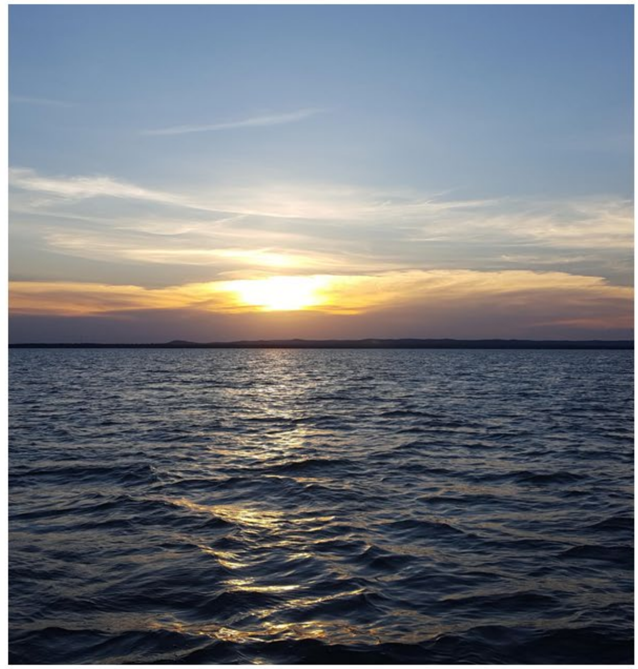
Forecast-informed Reservoir Operations (FIRO) and Water Resources Management in Texas



Report by the Texas Water Development Board, the University of Texas at Arlington, and the National Integrated Drought Information System.

December 2020

Acknowledgments

We thank Elizabeth Weight (National Integrated Drought Information System), Mark Fresch (National Weather Service – Office of Water Prediction), James Porter (New York City Water Supply – retired), Jonathan Quebbeman (RTI International), Thomas Zimmerman (Tennessee Valley Authority) Matthew Rosencrans (National Weather Service – Climate Prediction Center), Fiona Horsfall (National Weather Service – Climate Services Branch), Kris Lander (National Weather Service – West Gulf River Forecast Center), Carla Guthrie (Texas Water Development Board), Ron Anderson (Lower Colorado River Authority), and Aaron Abel (Brazos River Authority) for reviewing drafts of the workshop report and providing constructive feedback.

Yu Zhang (University of Texas at Arlington) and Nelun Fernando (Texas Water Development Board)

Cover images:
Upper left: Hurst Creek Arm of Lake Travis (Colorado River, Lakeway, Texas, courtesy of Mark Wentzel)
Bottom left: Floodgates at Tom Miller Dam (Colorado River, Austin, Texas, courtesy of Mark Wentzel)
Right: Lake Buchanan (Colorado River, Burnet and Llano Counties, Texas, courtesy of Josh Duty)

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List of acronyms

ABRFC	Arkansas-Red Basin River Forecast Center
AR	Atmospheric River
BRA	Brazos River Authority
CFSv2	Climate Forecast System version 2
CNRFC	California-Nevada River Forecast Center
CPC	Climate Prediction Center
CPO	Climate Program Office
CSGD	Censored-Shifted Gamma Distribution
CSTAR	Collaborative Science, Technology, and Applied Research
CW3E	Center for Western Water and Weather Extremes
ECMWF	European Center for Medium-Range Weather Forecasts
ENSO	El Niño Southern Oscillation
EnsPost	Ensemble Postprocessor
ESRL	Earth System Research Laboratory
FIRO	Forecast-informed Reservoir Operations
GEFS	Global Ensemble Forecast System
HEFS	Hydrologic Ensemble Forecast Service
HRRR	High-resolution Rapid Refresh
JTTI	Joint Technology Transfer Initiative
LCRA	Lower Colorado River Authority
MAPP	Model Analysis, Prediction, and Projections
MCMC	Markov Chain Monte Carlo
MEFP	Meteorological Ensemble Forcing Processor
NAEFS	North American Ensemble Forecast System
NCAR	National Center for Atmospheric Research
NIDIS	National Integrated Drought Information System
NMME	North American Multi-model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NWM	National Water Model
NWS	National Weather Service
NYCDEP	New York City Department of Environmental Protection
OAR	Oceanic and Atmospheric Research
OWAQ (now, WPO)	Office of Weather and Air Quality (now Weather Prediction Office)
OWP	Office of Water Prediction
PQPF	Probabilistic Quantitative Precipitation Forecasts
RFC	River Forecast Center
S2S	Subseasonal to Seasonal
SARP	Sectoral Applications Research Program

SCIPP	Southern Climate Impacts Planning Program
SP-DEWS	Southern Plains Drought Early Warning System
SubX	Subseasonal Experiment
TRA	Trinity River Authority
TRWD	Tarrant Regional Water District
TVA	Tennessee Valley Authority
TWDB	Texas Water Development Board
USACE	U.S. Army Corps of Engineers
USACE - SWF	U.S. Army Corps of Engineers - South West Division, Fort Worth District
USBR	U.S. Bureau of Reclamation
USDM	U.S. Drought Monitor
UTA	The University of Texas at Arlington
WFO	Weather Forecast Office
WGRFC	West Gulf River Forecast Center

Executive Summary

The Texas Water Development Board (TWDB), the University of Texas at Arlington (UTA), and the National Oceanic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS) jointly convened a workshop on *Forecast-informed reservoir operations (FIRO) and water resources management in the states of Texas and Oklahoma* from September 12−13, 2019 in Arlington, Texas. The goals of the workshop were to: i) identify gaps and obstacles that hinder the operational use of forecasts in reservoir management, and ii) spur actions to facilitate the adoption of forecast-informed reservoir operation paradigms demonstrated to be beneficial in other parts of the nation, particularly in the context of drought and flood preparedness. The workshop brought together reservoir operators, water suppliers, state agencies in the states of Texas and Oklahoma, private sector, and providers of forecasts, namely NOAA's National Weather Service (NWS), and university researchers.

The workshop was organized into four sessions. The first session focused on perspectives from state and federal agencies, and featured talks on water plans and priorities from agencies including the Texas Water Development Board, the Oklahoma Water Resources Board, and NOAA's National Integrated Drought Information System. The second session focused on the experiences of entities that have integrated, are in the process of integrating, or have helped with integrating forecasts into routine reservoir operations. The third session focused on the state of forecasts and offered an overview of climate and hydrologic forecast products from NOAA's line offices and from academic researchers. The fourth session focused on challenges to the application of FIRO and opportunities for collaboration. It featured talks from reservoir operators and water suppliers in Texas on their current state of operation, their perception of forecasts, and the overall challenges in integrating forecasts into operations. Given the limited representation of entities from Oklahoma at the workshop, this report focuses on challenges and opportunities for the application of FIRO in Texas.

A key finding of the workshop is the diversity of FIRO practices among reservoir operators in and outside of Texas. Though most reservoir operators that have implemented FIRO have used some form of forecast, the sources of forecasts, forecast types, and the method of using forecasts vary widely. A few operators with mature FIRO paradigms offered illuminating examples of how forecasts from various sources and lead times can be integrated into decision making. As an example, the Tennessee Valley Authority (TVA) maintains its own forecast system for streamflow and energy demand, while ingesting various weather and hydrologic forecasts from the NWS to guide its hydropower generation operation. Another example is the New York City Department of Environmental Protection, which actively uses ensemble forecasts for many aspects of its operations, including maintenance of infrastructure, for decisions on modifications to reservoir releases prior to storm events and droughts, and to guide decisions on water supply diversions from the multiple reservoirs comprising the system. Regional operators, including the US Army Corps of Engineers (Fort Worth District), the Lower Colorado River Authority (LCRA), and the Tarrant Regional Water District (TRWD) in North Texas, use climate and streamflow forecasts at different lead-times for real-time operations and long-term planning purposes.

The challenges for the adoption of FIRO in Texas, as identified by workshop participants, are multifold:

1. There are numerous mismatches between the type and quality of forecasts needed for reservoir operation versus what forecasts are currently available. For example, many floods that concern operators in Texas are driven by fast-moving storm systems for which skills of current forecasts are limited. Similarly, reservoir operators have keen interest in forecasts of onset, duration, and severity of droughts, yet skillful prediction of drought over the region remains a major challenge.

2. Another impediment to the application of FIRO is limited knowledge of relevant forecast products tools that are available. Most regional reservoir operators do use - and therefore are familiar with - the NWS's deterministic streamflow forecasts and rainfall products produced by the West Gulf River Forecast Center. However, their knowledge and experience of other NWS products, such as the longer-range outlooks, drought monitor products, and ensemble streamflow forecast, vary. Some entities are either not aware of the existence of these products, or they lack prior experience and confidence in using these products, or they are driven away by the lack of precision as well as by the challenges of interpreting forecast uncertainty. The issue of forecast uncertainty, or confidence, was repeatedly brought up in discussions of forecast application for reservoir management. While some agencies, including the New York City Department of Environmental Protection, have fully embraced forecast uncertainty in their decision making, few, if any, operators in Texas are currently doing so. Even for organizations with a desire to use uncertainty in the decision-making process, there is limited capacity and knowledge base to establish operational paradigms.

3. There are infrastructure challenges and practical constraints. For example, many water supply reservoirs are not equipped with flood pools (i.e., water that lies above the conservation pool in reservoirs that have flood storage functions) for flood risk management, and pre-release based on forecasts may exacerbate downstream flooding and incur revenue losses to the operators.

Despite these challenges, many participants at the FIRO workshop expressed interest and enthusiasm about FIRO paradigms showcased during the workshop. For example, the experience of the New York City Department of Environmental Protection of using ensemble forecasts for a wide array of decision processes generated audience interest in the potential to adopt similar paradigms. Furthermore, lessons learned from the Lake Mendocino pilot project addressed the concerns of operators that the use of flood pool storage for water supply purposes might compromise flood risk management.

Recommendations that emerged from workshop discussions for advancing forecast-informed reservoir operations in Texas include:

- Form a FIRO Task Force to coordinate FIRO-related initiatives in Texas;
- Establish a testbed and initiate pilot projects that promote synergy among federal, state agencies and reservoir operators;
- Broaden outreach and education to improve awareness of FIRO among water managers;
- Prioritize development and operational transition of products to facilitate the adoption of FIRO.

1. Introduction

Reservoirs have been indispensable infrastructure in many parts of the world for hundreds of years, serving various functions including water supply, flood control, power generation, recreation, and/or multiple water uses (e.g., domestic, irrigation, ecological). With recent improvements in the availability and precision of climate, weather, and hydrologic predictions, many water agencies around the globe are expanding the use these predictions into reservoir operations as a potentially ***cost-effective*** measure to alleviate the impacts of severe floods and droughts on societies. The broad practice of leveraging weather and streamflow forecasts to aid decisions in reservoir operations is often referred to as *forecast-informed reservoir operations* (FIRO). Recently, Wilson et al. (2019) offered a more precise definition of FIRO to reflect the need of any forecast-based strategy to address multiple targets:

> "*Forecast Informed Reservoir Operations (FIRO) is a proposed alternative management strategy that aims to use data from watershed monitoring and state-of-the-art weather and water forecasting to adaptively match available water with available storage to improve water supply reliability without impairing flood protection*."

The two major aspects of FIRO - forecasts and operational rules - have been under development since the 1990s by research institutions (e.g., Georgakakos and Yao, 1993; Mullusky and Georgakakos 1993). The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) developed the Extended Streamflow Prediction (Day 1985) program in the 1970s, a precursor to the present-day Ensemble Streamflow Prediction (ESP) program, with the primary aim of supporting reservoir operations. At present, NOAA offers a wide array of digital forecasts and guidance products, including climate outlooks, ensemble medium and short-range weather forecasts, deterministic and ensemble hydrologic predictions, and drought information. The operational adoption of these products in reservoir management, however, has been uneven geographically and varies among individual reservoir operators and water managers. Some entities on the west and east coasts have fully embraced these products. For example, New York City Department of Environmental Protection (NYCDEP), which oversees the management of 19 reservoirs and three lakes, has been actively incorporating NWS ensemble hydrologic forecasts with weather and climate forecasts in its daily operations. In the state of California, a pilot FIRO project for Lake Mendocino was launched jointly by the U.S. Army Corps of Engineer (USACE) and Sonoma Water in 2016; the project entails a temporary change to the established operating rules to allow the use of forecasts to determine reservoir releases. The Lake Mendocino project thus far has demonstrated the possibility of using forecasts to improve water supply reliability while reducing flood risk (Delaney et al., 2020). Many institutions, however, remain uncommitted to the adoption of FIRO due to a variety of factors ranging from lack of awareness of the availability of forecast information, lack of capacity to ingest ensembles in an operational system, license or regulatory limitations, to concerns about forecast accuracy and budgetary constraints.

The southern Great Plains is known for an abundance of extreme weather events. Droughts and floods in recent years have exacted a heavy toll in the region. Examples include the following: the Texas drought of 2010–2015 included the driest water year (i.e., October 2010 through September 2011) on record across the state and some areas experienced new record drought conditions (i.e., worse than the benchmark 1950s drought of record); Memorial Day flooding in 2015 caused death and destruction in South Central Texas; Hurricane Harvey in 2017 unleashed record rainfall and unprecedented floods across coastal Texas; and intense rain and flooding in October 2018 on the Colorado River led to the first-ever boil water notice in the history of the City of Austin because water treatment plants had limited capacity to handle the extreme sediment load that was transported downstream by floodwaters. In the wake of these disastrous events, there is an increased interest among federal and state agencies in FIRO as a potential strategy to address the challenges of water supply and flooding as posed by these weather and hydrologic extremes.

Against this backdrop, the Texas Water Development (TWDB) and the University of Texas at Arlington (UTA) jointly convened a workshop titled "Forecast-informed reservoir operations (FIRO) and water resources management in the states of Texas and Oklahoma" with support from NOAA's National Integrated Drought Information Systems (NIDIS). The workshop took place in Arlington, Texas on September 12 and 13, 2019. The overarching goals of the workshop were to i) identify gaps and obstacles that hinder the operational use of forecasts, and ii) spur actions to facilitate the adoption of FIRO paradigms demonstrated to be beneficial in other parts of the nation, particularly in the context of drought and flood preparedness. The workshop brought together reservoir operators, water suppliers, state agencies in the States of Texas and Oklahoma, private sector, and providers of forecasts, namely the NWS, and university researchers. It featured the following four theme sessions:

Session 1: Broad perspectives from state and federal agencies
This session featured talks on water plans and priorities from agencies including the TWDB, the Oklahoma Water Resource Board, and NIDIS.

Session 2: FIRO Initiatives and Operational Experience
This session focused on the experience of entities that have integrated, are in the process of integrating, or have helped with integrating forecasts into routine reservoir operations. These entities include regional reservoir operators in Texas and other parts of the nation, consulting firms, the U.S. Bureau of Reclamation (USBR), and one academic institution (Scripps Institution of Oceanography).

Session 3: State of Forecasts - Operational and Emerging Products
This session offered an overview of operational and emerging forecast and monitoring products. The operational products include those produced by NWS Climate Prediction Center (CPC) and River Forecast Centers (RFCs), whereas the emerging products include new hydrologic prediction technologies from the NWS Office of Water Prediction (OWP), and experimental products from NOAA Physical Sciences Laboratory (PSL) and academic institutions. The session informs reservoir operators about available forecast data and information and the opportunities for providing feedback to NOAA on forecast delivery approaches.

Session 4: Challenges in FIRO and opportunities for collaboration.
This session featured talks from reservoir operators and water suppliers in Texas on their current state of operation, their perception of forecasts, and the overall challenges in integrating forecasts into operations. The session concluded with a discussion on mechanisms for cross-agency collaboration to facilitate the adoption of FIRO.

This report summarizes the key findings of the workshop. It is organized into three sections corresponding to the themes of sessions 2–4. Section 2 focuses on the state of FIRO in and outside Texas, and the lessons learned from operators that have adopted FIRO. Section 3 reviews current forecast products that could be applied within a FIRO context, and the concerns raised by the workshop participants relating to forecast availability, accuracy, and method of delivery. Section 4 summarizes the challenges that need to be overcome for FIRO to be widely adopted by reservoir operators, particularly in the state of Texas, and offers an outlook of follow-up actions to be taken to facilitate FIRO adoption.

2. Current FIRO Practices and Lessons Learned from Operators

In Sessions 2 and 4 of the workshop, speakers from agencies that have adopted FIRO shared their experiences of, and lessons from, the use of forecasts in reservoir operations and reservoir management. Some speakers provided overviews of current and planned future FIRO pilot projects. This section first summarizes the types of forecasts used, the operational context, and how forecast use varies among entities. It then synthesizes the major lessons learned by operators. Pilot FIRO studies are described along with major points raised during the discussions.

2.1 FIRO as practiced by various entities

Table 1 provides an overview of the organizations represented, primary business models, and forecasts being used, as well as decision support tools used to interpret and translate forecasts into actionable information. The lead times for different forecast ranges shown in Table 1 are as follows: short (0.5–2.5 days); medium (0.5–15 days); subseasonal (15–60 days), seasonal (3–9 months).

Table 1: Organizations actively using streamflow forecasts in reservoir management

Organization	**Main Reservoir Functions**	**Context of forecast use**	**Forecasts Involved**		
			Types and Sources	**Lead Time**	**Use of Deterministic and ensemble forecast**
U.S. Bureau of Reclamation (USBR)[1]	Water supply	Real-time operation	Internally maintained streamflow prediction	Short-medium range, Subseasonal, Seasonal	N/A
			NWS weather forecasts	Short-medium range	
			NWS streamflow forecasts	Short-medium range, seasonal	
			Drought outlook	Subseasonal-seasonal	
U.S. Army Corps of Engineers (USACE)-Fort Worth District (SWF)	Flood control	Real-time flood operation	Internally maintained streamflow prediction,	Short-medium range	N/A
			NWS weather forecast		
			NWS streamflow forecast		
New York City Department of Environmental Protection (NYCDEP)	Water supply, flood control, environmental flow	Real-time decision	NWS weather forecasts	Short-medium range	Yes, ensemble streamflow traces used
			NWS streamflow forecast		
			NWS climate forecast and outlook		
		Planning and system maintenance,	Climate scenarios	Subseasonal-seasonal range	

		Watershed developments	Internally maintained streamflow prediction,	Annual and decadal	
Tennessee Valley Authority (TVA)	Water supply, power generation, Flood control, navigation	Real-time operation	NWS weather forecast	Short-medium range	N/A
			Drought outlook		
			Internally maintained streamflow prediction, NWS weather and streamflow forecasts	Subseasonal-seasonal	
Lower Colorado River Authority, Texas (LCRA)	Water supply, power generation, flood control	Real-time operation	NWS weather forecast	Short-medium range	N/A
			NWS streamflow forecast		
			HEC-RTS flood forecast and reservoir simulation system		
			Proprietary long-range forecast		
		Planning	Internally maintained streamflow prediction	Annual, decadal	
Tarrant Regional Water District, Texas (TRWD)	Water supply	Real-time operations, planning	NWS weather forecasts	Short-medium range	N/A
			NWS streamflow forecasts		
			Proprietary long-range forecasts		
		Planning	NWS streamflow forecasts	Interannual-decadal	
Brazos River Authority, Texas (BRA)	Water supply	Real-time operation	NWS streamflow forecasts	Short-medium range	N/A
City of Houston	Water supply	Pre-release	NWS weather forecast	Short-medium range	N/A
Sonoma Water, USACE, Scripps[2]	Water supply, flood control	Experimental real-time operation	NWS streamflow forecast	Short-medium range	Yes, ensemble forecast used

[1]Planned pilot project
[2]Ongoing pilot project with experimental, or shadow operations.

According to NYCDEP, the operational applications of FIRO can be broadly categorized as:

1) Guidance for routine reservoir operations
2) Emergency response
3) Long-term infrastructure planning
4) Watershed development and policy evaluation

Flood operation is a critical function for operators whose reservoirs contain flood pools, e.g., USACE-SWF, TVA, and NYCDEP. TVA, which has a substantial hydropower portfolio, uses forecasts (of weather, water, and energy markets) to guide hydropower generation and flood management decisions. The NYCDEP uses forecasts for all aspects of operations, including maintenance of infrastructure (aqueducts, pumping stations, etc.), modifications to reservoir releases prior to storm events and droughts, and to guide decisions on water supply diversions from the multiple reservoirs comprising its system. The TRWD in North Texas uses a proprietary statistical forecasting system, based on global meteorological fields and resampled historical hydrology traces, to optimize reservoir storage and to make decisions on when to move water through a distribution pipeline to terminal storage reservoirs. The TRWD uses short-range streamflow forecasts only for reservoir surcharge operations, i.e., operations that entail opening the spillway to make extra storage available.

2.2 Types of forecasts used in FIRO and the use of uncertainty information

Most organizations that have implemented FIRO have used some form of NWS forecasts. All participating reservoir operators, except for the TVA, use NWS streamflow forecasts. The TVA creates streamflow forecasts using its own version of the Flood Early Warning System based on the Sacramento Model to achieve interoperability with NWS RFCs, where identical systems are employed. The TVA monitors meteorological forecasts of rainfall and temperature from multiple sources [e.g. the North American Ensemble Forecast System (NAEFS), the High-resolution Rapid Refresh (HRRR) Model, and forecasts from the European Center for Medium-Range Weather Forecasts (ECMWF) model].

Several organizations, including the USACE-SWF and the LCRA, generate inflow forecasts at hourly intervals using in-house systems that supplement NWS inflow forecasts, which are issued at 6-hour intervals. Regional water suppliers, such as the LCRA and the TRWD, also rely on proprietary long-range predictions and outlooks for planning purposes. The LCRA uses El Niño Southern Oscillation (ENSO) indices published by NOAA ESRL for seasonal outlooks that supplement the outlook products from the NWS CPC. Specifically, it uses a proprietary model that is based on Markov Chain Monte Carlo (MCMC)-based monthly transitional probabilities, 9-month forecasts of the ENSO and current conditions (e.g. antecedent conditions, inflow for the last two-month period, etc.) to generate water supply forecasts out to a 60-month period. Operations are adapted on March 1st and July 1st of a given year based on current conditions on the ground and forecast conditions. The TRWD follows a similar paradigm.

Among all the organizations that participated in the workshop, only the NYCDEP has been actively incorporating ensemble forecasts in its current operations. The NYCDEP uses the ensemble streamflow traces generated by the NWS Hydrologic Ensemble Forecast Service (HEFS; Demargne et al., 2014) to gauge uncertainty in the forecast, and supplements that information using longer-range climate forecasts and outlooks.

The ongoing FIRO pilot project at Lake Mendocino incorporates HEFS forecasts from the California-Nevada River Forecast Center (CNRFC) as well as experimental forecasts from ESRL [Probabilistic Quantitative Precipitation Forecasts (PQPFs), and atmospheric river prediction supplied by Scripps Center for Western Weather and Water Extremes (CW3E)]. The project established four operational scenarios that are implemented in parallel: 1) actual; 2) ensemble forecast-based; 3) hybrid; and 4) perfect forecast operations. This ongoing parallel operation helps gauge the risk of adopting forecasts and determine effective ways for integrating the forecast into operations.

The U.S. Drought Monitor (USDM; Svoboda et al., 2002) maps are used by NYCDEP, whereas in the state of Texas, the reservoir operators in attendance have yet to actively incorporate drought information in their operations. Some organizations at the workshop were not aware of the drought products available.

Forecast lead times relevant to decision making vary by use case. For example, the TVA typically relies on forecasts within a three-day lead time, but this requirement varies based on which watershed receives rain. Among agencies represented at the workshop, few decisions are based on forecasts of five-day or longer lead times. Lead-time requirements also vary based on the time of year and reservoir level. For example, in Central Texas, a 3−4”/day rainfall event during the summer may have little or no impact on inflows; however, in the winter or during a wet season, such an event could lead to flooding. For water supply planning, a lead time of at least six months is needed to adjust water supply operations. In some instances, such as is the case with the TRWD, long-range forecasts of six months or more are needed to make operational changes.

2.3 Lessons learned from the application of FIRO

Workshop attendees shared many valuable lessons learned from the application of FIRO, summarized as follows:

- The NYCDEP uses ensemble forecasts as the basis for establishing a proactive drought watch, which allows for more conservative operations and the curtailment of deliveries if a drought is forecast. The agency also used forecast information to avoid a drought declaration in March 2015, and to issue a proactive drought declaration during the 2016–17 drought episode (Fig. 1). The agency further planned on system maintenance using ensemble forecasts.

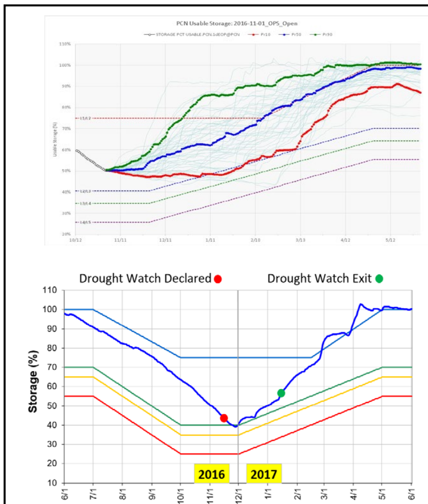

Figure 1: Ensemble storage forecast for Delaware River Basin over the 2016-2017 drought episode by NYDEP (top panel), and corresponding observed storage (bottom panel). The drought levels are superimposed. Source: NYDEP.

- The NYCDEP’s experience shows that forecast uncertainty information is useful, and sometimes critical in decision making, but making use of the ensemble forecast for uncertainty characterization requires a paradigm shift — operational agencies need to adopt a risk-based decision-making process that accounts for the chances associated with different scenarios. In addition, the NYCDEP also demonstrates that it is important to account for seasonal variability in forecast skill in its operations — the skill of forecasts tends to be higher during winter due to snowmelt-driven runoff, and lower for the warm season when runoff is driven by precipitation that is less predictable.

- Observations for situational awareness are critical complementary information to forecasts. For example, NYCDEP monitors snowpack closely in the winter as snowmelt is a major source of inflow.

- The TVA relies on forecasts of not only weather and streamflow, but also forecasts of the energy market, to generate as much revenue as possible from hydropower generation. The TVA has a range of flexibility built into the system to hedge downside risk if a forecast has significant error. An incorrect forecast might lead to a decrease in hydropower generation capacity in the short term. The TVA has been able to avert big dollar damages from flooding throughout their reservoir system by incorporating forecast information.

- The Lake Mendocino project shows that improving water supply reliability and reducing flooding risks are not always contradictory aims, that it is possible to use forecasts judiciously to achieve both aims. The implementation of “shadow operations” helps build operator confidence in using forecasts and in identifying the least risky operational strategies.

- The TRWD uses proprietary long-range forecasts to inform a variety of decisions, from moving water between storage reservoirs to holding reservoirs ahead of peak demand, with the ultimate objective of minimizing costs incurred in transporting water.

- The City of Houston uses rainfall forecasts (specifically if a 3” rainfall event is forecast over a 48-hour period) to drop the level of Lake Houston by one foot for flood mitigation purposes. This is a change in operating rule that was instituted in the aftermath of Hurricane Harvey.

- The Trinity River Authority (TRA) was well informed of the forecast rainfall amount from Hurricane Harvey about 3 days ahead of time, but it chose NOT to perform pre-release from its Lake Livingston reservoir because any release would have taken several days to reach Galveston Bay and could have exacerbated downstream flooding. The decision was in retrospect a prudent one given that much of the rainfall from Harvey fell downstream of the reservoir and over coastal watersheds. The size of the reservoir and the imprecision and limited range of forecasts, in terms of exactly where the heaviest rain would fall, make it difficult to adopt a proactive FIRO approach for Lake Livingston ahead of a major rain event such as Hurricane Harvey.

3. Forecast Products from NOAA and User Feedback

Several NOAA line offices were present during the meeting and provided a relatively comprehensive review of their products and services that are relevant to FIRO. Researchers from Scripps CW3E and UTA also spoke about their experimental forecast products and outreach efforts. Table 2 offers a condensed overview of organizations and products/services each offers.

Table 2: NOAA line offices and associated organizations involved in forecast product generation and dissemination

Organization	Line Office	Roles	Forecast Relevant to FIRO
NOAA/NWS	West Gulf River Forecast Center (WGRFC)/Arkansas-Red Basin River Forecast Center (ABRFC)	Issues hydrologic predictions and assists with decision-support at regional and local levels	Deterministic and ensemble streamflow predictions; probabilistic quantitative precipitation forecast, flash flood products including those for dam breaks; HEFS (generation/dissemination)
	Office of Water Prediction (OWP)	Conducts hydrologic operational, development, and field support functions and coordinates hydrology-related programs in NWS; umbrella organization for National Water Center	National Water Model (NWM) predictions; HEFS (development and implementation)
	Climate Prediction Center (CPC)	Issues and disseminates subseasonal to climate-scale outlooks	Subseasonal, seasonal, and longer-term outlooks

	Weather Forecast Offices	Issue and disseminate warning and watches; support local and regional decisions	Precipitation forecast, river flood warnings and watches, flash flood warnings and watches
NOAA/Oceanic and Atmospheric Research (OAR)	ESRL	R&D on weather models and post-processing mechanisms	Experimental post-processing systems; GEFS reforecast; ENSO and other climate indices
	Weather Prediction Office (WPO), formerly Office of Weather and Air Quality (OWAQ)	Funds development of observational and forecast tools	Short-medium range, subseasonal (0-60 days), and observational products
	NIDIS	Funds research to advance drought forecasts, monitoring, impacts; dissemination of drought information; coordinates regional entities for drought early warning, planning, and response	Drought monitor and outlook products through drought.gov portal
Scripps CW3E	N/A	Develops experimental atmospheric river (AR) products, situational awareness tools;	AR and related products
UTA	N/A	Develops HEFS enhancements; experimental snowpack assimilation system for NWM; soil moisture products for event-based forecast; collaborates with national and regional entities on decision support	Enhancements to HEFS, including streamflow post-processing schemes; meteorological ensemble processor; snow and soil moisture products; enhancement to NWM's data assimilation capabilities

3.1 NWS streamflow forecasts and their application in FIRO

The NWS produces a suite of hydrologic forecasts and products. These include deterministic and ensemble streamflow forecasts, probabilistic quantitative precipitation forecasts, and flash flood products. These products are being generated mainly at the NWS River Forecast Centers (RFCs), and to a lesser extent at the Weather Forecast Offices (WFOs). The WGRFC and the ABRFC interface directly with reservoir operators and the public. The tools and infrastructure for producing the forecasts are maintained and supported by the Office of Water Prediction (OWP). The three hydrologic products that were described during the workshop were the 15-day deterministic streamflow forecasts and the ensemble forecasts generated using the Ensemble Streamflow Prediction (ESP) and HEFS.

Deterministic streamflow forecast: WGRFC provides special 15-day deterministic streamflow forecasts to the BRA. At times, these forecasts are utilized in BRA's near-term decision process for managing the BRA water supply system. The 15-day forecasts are primarily used to assist BRA with allocating water use among its multiple water rights. The BRA and USACE-SWF provide WGRFC with release projections for a 1–5 days lead time whereas persistence forecasts are used for the 5–15 days lead time.

National Water Model Forecast: The National Water Model (NWM; Cosgrove et al., 2016) is a nation-wide forecast system that became operational at the NWS in 2015. At present, NWM provides ensemble and deterministic streamflow forecasts for gauged and ungauged locations across the Conterminous US and Alaska, and these forecasts supplement the forecasts generated at RFCs. Major improvements have been made to the accuracy of the forecasts over the last five years (Cosgrove et al., 2020).

Ensemble streamflow forecast: The WGRFC and ABRFC produce ensemble streamflow forecasts through the ESP and HEFS (Fig. 2). The ESP is based on historical flow traces and does not integrate weather or climate forecasts, though enhancements have been made to account for outlooks based on climate indices (Warner et al. 2005). HEFS is a more modern system that is able to integrate medium-range meteorological forecasts from the RFC quantitative precipitation forecast (QPF), Global Ensemble Forecast System (GEFS; 0–15 days lead time); seasonal climate forecasts from the Climate Forecast System version 2 (CFSv2); and climatology. The WGRFC's validation efforts so far indicate that HEFS forecasts outperform the ESP by 10–60%, and most of the skill improvements occur for lead times less than or equal to 12 days.

The HEFS is actively used by the NYCDEP and in the Lake Mendocino pilot project. The WGRFC has been collaborating with UTA in experimentally using HEFS for reservoirs managed by the TRWD through a project funded by NOAA's Climate Program Office (CPO) through the Sectoral Research Application Program (SARP). The WGRFC is in the process of expanding the forecast points covered by HEFS over its forecast domain (much of Texas and parts of New Mexico). Thus far, the adoption of HEFS by reservoir operators in Texas and Oklahoma has been slow due to a combination of factors. These include a lack of awareness of the product by operators, a lack of operational tools for ingesting the ensemble information, and inexperience in interpreting the uncertainty information.

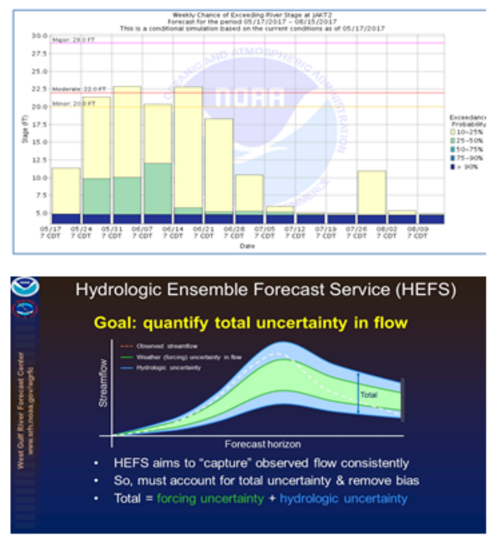

Figure 2: An example of ESP forecast from WGRFC (top panel), and schematic of HEFS forecast (bottom panel). Source: WGRFC.

3.2 Products from CPC and USDM

The CPC provides a broad suite of subseasonal and climate-scale products through its web interface, and it contributes the US Drought Outlook (USDO) to the USDM. The CFSv2 plays a central role while it is being augmented by the North American Multi-model Ensemble (NMME; Zhang et al., 2011; Kirtman et al., 2014) system, which has been shown to outperform CFSv2 over the southern Great Plains in several situations (Fig. 3).

The CPC climate outlook products are widely used by water suppliers but there is also some confusion experienced by users. For example, operators mentioned that CPC outlooks are often not sufficiently precise to act on, and products at different lead times sometimes contradict each other. In addition, operators (e.g., NYCDEP) cited the lack of data on the skills of CFSv2 forecast for all points in their operational domain as a concern.

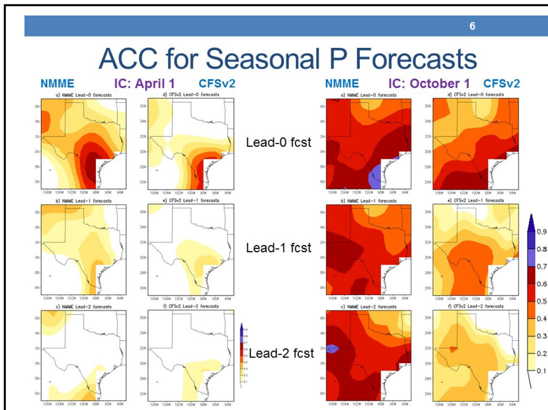

Figure 3: Comparisons of NMME and CFSv2 seasonal precipitation forecast over Texas. Source: CPC.

The USDM portal is well-known among water managers, who use the drought intensity for planning purposes. In the meantime, however, the role of NIDIS as an aggregator of drought products and a hub for collaborative drought planning, is not as well known among regional stakeholders.

3.3 Roles of experimental products from research institutions

Several FIRO-related applications supplement the official forecasts produced and disseminated by NWS line offices with experimental products created and maintained by NOAA labs and also by academic institutions. Such experimental products include the AR forecasts produced by Scripps CW3E, the Censored-shifted Gamma Distribution (CSGD) post-processing scheme that produces the PQPFs maintained by ESRL, various upgrades to the HEFS at UTA, including those to the Meteorological Ensemble Forcing Processor (MEFP) and Ensemble Postprocessor (EnsPost). Note that ESRL maintains the reforecast from the GEFS that the HEFS relies on. More recently, UTA has completed a project sponsored by NOAA that combines medium-range stream forecasts from multiple operational sources, including RFC deterministic forecasts, NWM forecasts, and HEFS forecasts to create more accurate streamflow forecasts that can be readily used by RFCs to assist with FIRO. In addition, UTA also has implemented an advanced blending mechanism to fuse radar and satellite-based precipitation products that show promising potential for improving real-time rainfall estimates for rare to extreme storm events. These products, once transitioned to operation, will also benefit FIRO applications.

The AR products and CSGD-based PQPF have been both applied in the Lake Mendocino pilot project, whereas various prediction tools and situational awareness products that UTA maintain either have been or are in the process of being tested out for reservoir-related applications. Through a NASA-sponsored project, UTA is working closely with the LCRA and the USACE-SWF to integrate some of the experimental products (e.g., precipitation, soil moisture) to the prediction systems that the two organizations employ.

The subseasonal (SubX; Pegion et al., 2019) project, sponsored partly by NOAA, offers potential improvements to synoptic scale patterns which in turn lead to improved precipitation and temperature forecasts over the subseasonal range. As of today, however, there has not been any dedicated effort to clearly demonstrate the utilities of SubX forecasts in the context of FIRO for the southern Great Plains and the south-central United States.

4. Applying FIRO in Texas: Challenges and Opportunities

This section summarizes the specific challenges to applying FIRO in Texas, highlights opportunities for expanding the adoption of FIRO, and recommends follow-up steps to be undertaken by the state and federal agencies to advance and facilitate the application of FIRO in this state.

4.1 Challenges

The challenges for FIRO adoption in the state of Texas are multifold. Being a large state with diverse climates, the state's needs for forecast information vary greatly depending on the climate, the size and functions of reservoirs, downstream conditions, and the experience and training of operators. Broadly speaking, the challenges fall into the following categories: 1) limitations in forecast accuracy and specificity; 2) infrastructure and operational constraints facing reservoir operators; and 3) information gaps between the forecast providers and operators.

Limitations in forecast accuracy and specificity
The key extremes that drive storage-release decisions in Texas are droughts and floods, and both are challenging to forecast. Droughts often are large in scale, develop slowly, and can last for several years. The key variables of any drought over the region, including the onset, duration, and severity, are all challenging to predict. The view from reservoir operators is that accurate long-range (e.g., at the lead time of 1–3 months to one year) drought outlooks are needed to prepare for droughts. At present, however, long-range forecasts from NOAA or other sources do not have sufficient skill to be useful for drought preparation.

An important distinction between Texas and other western states where FIRO is practiced is the predictability of streamflow. In California, rainfall systems are dominated by atmospheric river events for which skill in prediction beyond the 3-day lead time is now possible. In addition, snowpack over the Sierra Nevada plays a dominant role in water supply over the region, and the predictability of streamflow tends to be high as it often depends as much on current snowpack conditions as on future weather conditions. By contrast, storm systems responsible for runoff and flooding in Texas vary widely and are often challenging to predict at lead times that is sufficiently long for actions. Ideally, forecast information of relevance to flood operations must include details on rainfall intensity and location, yet the skill of current quantitative precipitation forecast (QPF) produced at NWS is limited beyond the very short range (< 6 h), especially for convective storms.

Given the geography of Texas, and the fact that big rain-bearing weather systems move inland from the Gulf of Mexico, knowledge of where in a river basin (i.e., upstream or downstream of a major reservoir) a big rain event might occur is critical to avoid, for example, coastal basin flooding due to reservoir flood releases coinciding with downstream inundation from stalled Gulf storm systems (e.g. Hurricane Harvey). The need for geographic specificity regarding the exact location and timing of rain events is essential if releases are to be made (for the purpose of increasing flood storage) from multi-purpose reservoirs in Texas ahead of major rain events.

Lake Livingston and Toledo Bend Reservoir are good examples of large, water supply reservoirs in Texas without a dedicated flood pool capacity, where spatially explicit rainfall forecasts are needed if forecast-based pre-releases are to be implemented to minimize flood impacts to downstream communities. It is currently difficult to make long-range forecasts of summer rainfall over Texas. A medium range (3- to 7-day lead) forecast of the location where a 1” rainfall event may not occur relative to multi-purpose reservoirs could be useful for FIRO applications in Texas, but such information is not directly available from NWS forecast products. It is currently difficult to say at what lead times such a forecast is needed because the lead times needed would vary based on antecedent soil moisture conditions and the decisions that the forecast would inform. The WGRFC has recently taken a proactive approach to providing user-friendly, graphical warnings that depict the likelihood of where forecast rains will fall relative to the locations of saturated soils and swollen rivers. Investments in improving the skill of these forecasts, both in terms of rainfall magnitude and spatial distribution of intense rainfall at the medium- to long-range lead time, is needed if FIRO is to gain traction in Texas.

Infrastructural and operational constraints facing reservoir operators
Most reservoirs in Texas are water supply reservoirs that are designed to store, not release, water and thus offer limited capability to mitigate flooding. Moreover, reservoir operators are often reluctant to

perform pre-releases due to: a) a lack of confidence in forecasts, b) impacts on revenue generation and the ability to supply water to customers, and c) infrastructure limitations to releasing water in a timely fashion.

Two examples, Lake Houston and Lake Livingston, offer large storage capacities for water supply but were not designed for flood control. Post-Harvey, given the historic flooding and resulting political pressure, the City of Houston agreed to lower Lake Houston by 1' if a rain event of more than 3" is predicted over a 48-hour period. However, because Lakes Houston and Livingston are designed to store water releasing sufficient water out of the reservoir in time to create increased capacity to store flood flows has been a problem. A massive infrastructure project is currently underway in Lake Houston to install new flood gates so that water can be released faster. As mentioned earlier, the TRA's decision to not pre-release from Lake Livingston prior to Harvey was based on the consideration of the long release and travel times that were likely to exacerbate the risk of downstream flooding. For these water supply reservoirs, in cases where predicted inflow does not materialize, pre-releases would incur revenue losses for reservoir owners due to the depletion of water supply storage.

All the USACE reservoirs in Texas are multi-purpose reservoirs, which include those in the Brazos, Trinity-San Jacinto, and Sabine-Neches river basins. These reservoirs have flood control in their operations manuals and their management requires coordination between USACE and river authorities. At present, flood operations at USACE rely on both NWS streamflow forecasts and forecasts generated using internally maintained models based on observed rainfall.

Information and knowledge gaps between providers of forecasts and operators

During the workshop, several gaps were identified in relation to forecast product availability and knowledge of and confidence in products. There are clear mismatches between the type and quality of forecasts needed for reservoir operations versus that which is currently available. Most reservoir operators who participated in the workshop were familiar with NWS deterministic streamflow forecasts and rainfall products, which are created primarily by the WGRFC. Yet, the knowledge and experience of operators about other NWS products vary; these products include the CPC longer-range outlooks, drought monitor products, and ensemble streamflow forecasts. Some agencies are either not aware of the existence of these products, or they lack experience and confidence in using these products, or they are hesitant given the lack of precision and the complications of interpreting forecast uncertainty. As an example, the CPC outlook products depict the probability of below-, near-, and above-normal precipitation, and this information is often not sufficiently precise for actions. Moreover, not all reservoir operators have the resources or technical skills to incorporate forecast information in order to improve their operational decisions.

The issue of forecast uncertainty, or confidence, was repeatedly brought up in the discussions of forecast application. While organizations such as the NYCDEP have fully embraced forecast uncertainty in their decision making, few, if any, operators in Texas are currently doing so. While the WGRFC is working on expanding HEFS coverage, few reservoir operators indicated readiness to adopt HEFS in operations. It appears that most reservoir operators in Texas are accustomed to operating on absolute statements and have not had experience using probability. Even for organizations with a desire to use uncertainty in the decision-making processes, there is limited capacity to use it. It is also important to note that the use of uncertainty information could vary vastly depending on the system and the operational scenario being considered. For example, in planning for flooding operations during a major flood, operators are likely to focus on the extreme scenarios in the forecasts. By contrast, to determine water supply release at longer lead times (say > 4 days), operators may utilize the ensemble mean that represents the consensus of forecasts as the basis for decisions.

Finally, there may be water suppliers or city utilities that need forecast information for flood or drought management measures not pertaining to reservoirs. Flooding impacts can occur when major rivers rise, and tributaries cannot drain into the major river. For example, about 70% of flooding in the Trinity River basin takes place in storm drain areas. This has nothing to do with reservoir operations. It is unclear how forecasts could be utilized for flood early warning along tributaries and storm drains. From the perspective of emergency management and flood mitigation planning, it would be useful to have forecasts of rainfall occurrence over these watersheds at least 24 hours in advance.

4.2 Opportunities

Despite the challenges described above, many participants expressed interest in, and enthusiasm for, the FIRO paradigms showcased during the workshop. The NYCDEP's operational experience demonstrating the use of ensemble forecasts in a wide array of decision processes generated keen interest from the audience in potentially adopting similar paradigms. Furthermore, the lessons learned from the Lake Mendocino pilot project address the concerns of operators that the use of flood pool storage for water supply purposes compromises flood risk management – flood risk management and water supply management do not have to be mutually exclusive. Indeed, many regional entities have already incorporated flavors of FIRO in their operations and/or long-range planning; these include the USACE, some river authorities (e.g. the LCRA and the BRA), and wholesale water providers (e.g. the TRWD). These entities are, in general, open to the possibility of enhancing the use of forecasts in their operations. The TRWD, for example, has been collaborating with UTA to ingest forecasts from HEFS as an alternative basis for reservoir operation.

A key advantage of FIRO is that its judicious use can enhance the operational efficacy of existing infrastructures, and in some cases it may event present a potentially lower-cost complement to structural measures for flood and drought management. As Texas has been severely impacted by floods and droughts, several entities are looking to upgrade structural flood control measures and develop new water supply sources and storage infrastructure. Recently, Texas launched a regional and state flood planning process and initiated a flood infrastructure financing program. New programs have been established for flood science and flood planning at the TWDB. There is a need to advance the science related to flood resiliency planning. While FIRO should not be considered a wholesale substitute for infrastructural upgrades, its judicious application can help increase the efficiency and resilience of water infrastructure, and thereby help contain the costs associated with new projects.

As FIRO is gaining national attention, federal agencies, including NOAA, USACE, and USBR, are taking the initiative to identify and establish federal-state partnerships to facilitate the adoption of FIRO. For example, NWS has adopted the new paradigm of "enhancing impact-based decision support for deep-relationship core partners" (NWS, 2018), and core partners now include state and local water resources managers. This new paradigm opens many new opportunities for establishing partnerships between the state of Texas and NOAA, and to address the disconnects between the needs of water resource managers and forecasts currently offered by NWS. Additional opportunities involve working with USBR and energy producers who have a vested interest in maintaining water supply reliability.

4.3 Recommendations on actions to advance the application of FIRO in Texas

Based on the workshop findings, the workshop organizers recommend the following actions:

- <u>Form a FIRO Task Force to coordinate FIRO-related initiatives in Texas.</u>
  The composition of the task force would need to be determined but would likely consist of the major players in the water sector in Texas, such as the TWDB, the USACE-SWF, the USBR – Oklahoma Texas Area Office, representatives from academic institutions in Texas undertaking FIRO-relevant research, the Texas State Climatologist, the WGRFC, river authorities that manage and operate multi-purpose reservoirs, and city utilities interested in FIRO applications. The task force would coordinate FIRO initiatives and identify projects that facilitate the adoption of FIRO. Some of the initial tasks may include a survey on the state of FIRO and forecast awareness among reservoir operators and water resource managers; planning for workshops and training sessions to disseminate FIRO paradigms to stakeholders; and screening reservoirs in Texas for their suitability for FIRO adoption.

- <u>Establish a testbed-like program and initiate pilot projects that allow synergy among federal, state agencies, and reservoir operators.</u>
  Key obstacles to using forecasts in reservoir operations are the limited skill of rainfall forecasts for Texas and the Southern Plains beyond the weather timescale, and unfamiliarity of reservoir operators about existing forecast products. To facilitate the adoption of FIRO, it is recommended that the state of Texas and NOAA collaborate to establish a testbed-like program. This program will be modeled after various NOAA testbeds and proving grounds that have played critical roles in transitioning research outcomes to operation products. The collaborative effort will advance the NWS goal of "Enhancing impact-based decision support for deep-relationship core partners". It will allow and encourage water resource managers to experiment with operational and emerging products in quasi-operational settings as forecasters do in, for example, the Hazardous Weather Testbed. These emerging products include, but are not limited to, the ensemble streamflow forecast from HEFS, outlook products at S2S range, and drought monitor products. It will provide valuable feedback to NWS and OAR to prioritize research to development efforts.

  The workshop organizers have conferred with a few water suppliers about the possibility launching a pilot project. A pilot project for one, or some of reservoirs will provide a platform for building partnerships among federal, state and local stakeholders, and will serve as a concrete first step towards a full-scale implementation of the FIRO program. It is recommended that the task force work with NIDIS to examine the possibility of leveraging the latter's Southern Plains Drought Early Warning System (SP-DEWS) to kickstart the initiative.

- <u>Develop partnerships to broaden outreach and education to improve awareness of FIRO among water managers</u>
  NOAA line offices have made commendable efforts to reach out to stakeholders and inform them about products and services through various forms of activities. Nevertheless, the workshop underscored a lack of awareness and understanding among water managers of both existing and emerging products and services. This is particularly evident for smaller utilities and reservoir managers. There is a need for increased transparency and training on current operational NOAA products. For example, quarterly meetings of the WGRFC and the LCRA helps bridge the gap between the forecast producers and users; this approach could be expanded to other organizations and locations.

Considering the diverse backgrounds and needs of water managers in Texas, it is best for NOAA to consider partnering with the state to broaden outreach efforts. Both the state and NOAA may consider dedicating resources to allow for concerted, sustained efforts of outreach and education led by the task force. These efforts can include hosting workshops where experiences of reservoir operators can be shared, conducting training on forecast products, software, and methods of FIRO, and field trips. The state or NIDIS may consider providing support to small operators to participate in these activities so that resource limitations do not pose an obstacle to FIRO adoption. These efforts may be undertaken in coordination with NIDIS SP-DEWS, the Southern Climate Impacts Planning Program (SCIPP), the NWS Southern Region Headquarters Operational Service Division, OWP, and CPC.

- Prioritize development and operational transition of products to facilitate FIRO adoption

  A key finding of the workshop is the disconnect between product development and the needs of reservoir managers, which goes beyond the issue of product awareness. The subseasonal to seasonal (S2S) initiative, for example, addresses important science gaps such as deficiencies of the Global Forecast System in predicting the Madden-Julien Oscillation. However, its current scope does not directly address the need for improved precipitation and streamflow forecasts needed by reservoir operators. As an example, an effort, funded by NOAA's Modeling, Analysis, Predictions, and Projections (MAPP), at the National Center for Atmospheric Research (NCAR) produced downscaled seasonal forecasts and validation statistics on a watershed scale by 2018. These products are closely relevant to reservoir operators, but thus far the effort is yet to be fully operational at the CPC. It is also recommended that the Weather Prediction Office (formerly the Office of Weather and Air Quality, OWAQ), which is currently in charge of S2S and Climate Testbed, consider allocating resources to help support initiatives that could bridge the gaps between current forecast products and the needs of reservoir operators. Such initiatives include, but are not limited to, assessing predictability of different systems that cause flooding in Texas, improving hydrometeorological and hydrologic ensemble forecasting mechanisms, and refinement of methods for conveying uncertainty and forecast confidence. The USBR coordinated the Forecast Rodeo in which groups across the country submitted forecasts of precipitation and temperature at the sub-seasonal range (15-42 days) for evaluation (https://www.usbr.gov/research/challenges/forecastrodeo.html). A few promising machine learning-based prediction mechanisms emerged from the competition. NOAA may consider working with the USBR and other partners to prioritize the transition of these prediction schemes into operations at the CPC.

  It is also recommended that NWS Office of Science and Technology Integration (STI) and OAR offices offer more opportunities for cross-NOAA collaboration and private-public-academia partnerships. A past example of this partnership is a UTA-led project funded through the CPO's Sectoral Application Research Program (SARP). The project focused on the use of ensemble hydrologic forecasts for drought preparedness and was conducted in partnership among UTA, TRWD, WGRFC, SCIPP, and NIDIS. NWS, for example, could place FIRO-related product enhancements as a key priority in its Collaborative Science Technology, and Applied Research (CSTAR) program. Researchers proposing ideas may collaborate with the testbed-like FIRO program to ensure that products and mechanisms emerge from the proposed research can undergo thorough evaluation in quasi real-world operations.

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Appendix: Recommendations for NOAA

Recommendation 1:
NWS needs to consider dedicating resources to improving transparency and training on current operational products, which include the outlook products from CPC and hydrologic products produced by RFCs and NWC. The quarterly meetings of the WGRFC and the LCRA are a good example that can be expanded to include other water suppliers, and similar paradigms can be adopted by other forecast centers and offices in the Southern Plains.

Recommendation 2:
NOAA needs to consider partnering with the state to broaden outreach efforts. In particular, NOAA should work with the state of Texas to devise plans for sustained outreach efforts. These efforts may include hosting workshops where experiences of reservoir operators can be shared, conducting training on forecast products, software, and methods of FIRO, and field trips. NOAA may collaborate with the state of Texas to sponsor operators of small reservoirs to participate in training activities so that resource limitations do not pose an obstacle to FIRO adoption.

Recommendation 3:
NOAA should consider providing partial financial support through NIDIS to help kick-start a testbed-like FIRO program in the state of Texas. The program will consist of pilot projects thar would help assess various NOAA products and identify their operational paradigms.

Recommendation 4:
Program offices in OAR (CPO and WPO) need to consider placing a priority on supporting research concepts and products that would facilitate FIRO adoption. These include, but are not limited to statistical postprocessing mechanisms to improve accuracy and precision of precipitation, temperature, and streamflow forecasts at medium and S2S ranges, improving dynamic models to extend the lead times for significant storm events, and refinement of methods for conveying uncertainty and forecast confidence. OAR may use its MAPP and Joint Technology Transfer Initiative (JTTI) programs for this purpose.

Recommendation 5:
NWS OWP need to consider expediting the integration of mature, well-proven techniques into HEFS, including enhancements to meteorological processor and streamflow postprocessor, and improving the graphic user interface for dissemination of the forecasts.

Recommendation 6:
NWS STI and OAR offices need to collaborate to offer more opportunities for private-public-academia partnerships. NWS should consider including FIRO-related enhancements of hydrologic products and tools as a key priority in its CSTAR program, and use the program as the vehicle to support FIRO initiatives.