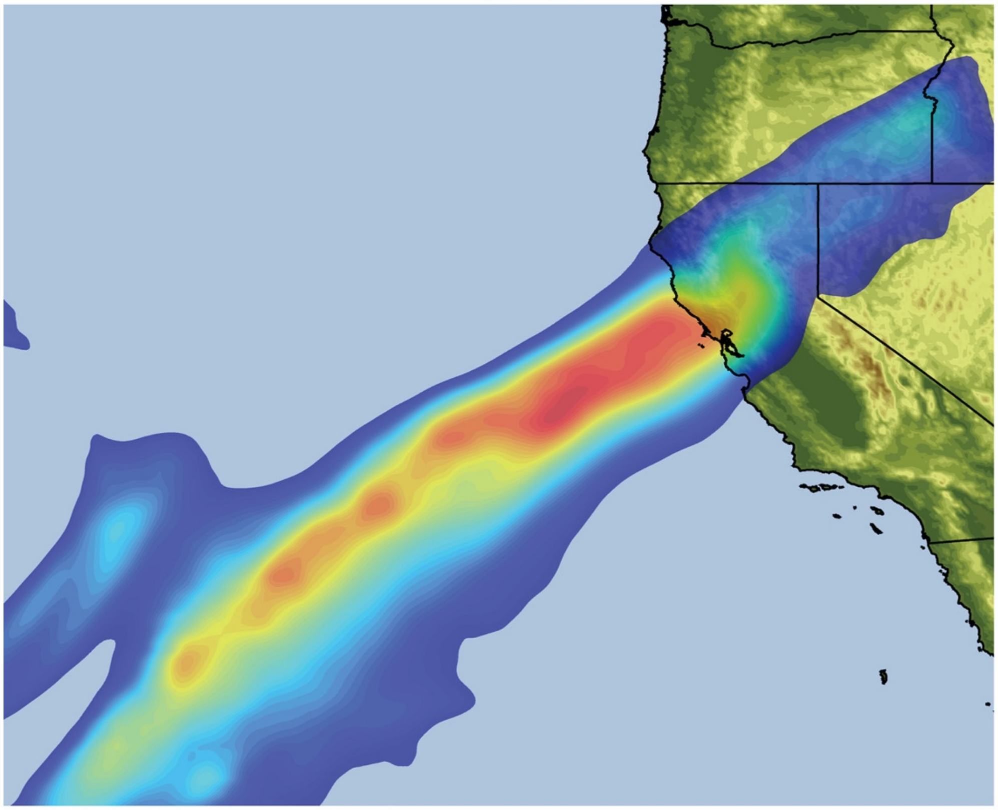
Work Plan for Yuba-Feather

FORECAST INFORMED RESERVOIR OPERATIONS (FIRO)

Work Plan

March 2021



Yuba-Feather FIRO Steering Committee

- **F. Martin Ralph:** CW3E (Co-chair)
- **John James:** Yuba Water Agency (Co-chair)
- **John Leahigh:** California Department of Water Resources (DWR) (Co-chair)
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YUBA WATER AGENCY

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Acronyms

ac-ft	acre-feet
AR Recon	Atmospheric River Reconnaissance
AR	atmospheric river
ASO	Airborne Snow Observatory
BRWC1	Bear River at Wheatland
Bulletin 120	B-120
CAoR	Calibration Analysis of Record
CDEC	California Data Exchange Center
cfs	cubic feet per second
CHPS	Community Hydrologic Prediction System
CNA	Comprehensive Needs Assessment
CNRFC	California Nevada River Forecast Center
CW3E	Center of Western Weather and Water Extremes
CFWC1	Camp Far West Reservoir
CVP	Central Valley Project
DM	Design Memorandum
DSAC	Dam Safety Action Classification
DSS	decision support system
DST	decision support tool
DWR	California Department of Water Resources
ECMWF	European Centre for Medium-Range Weather Forecasts
ECMWF-IFS	European Centre for Medium-Range Weather Forecasts Integrated Forecasting System
EFO	Ensemble Forecast Operations
EIR	Environmental Impact Report
ER	engineering regulation
ERDC	Engineer Research and Development Center
ESRD	emergency spillway release diagram
F-CO	Forecast-Coordinated Operations
FIRO	Forecast Informed Reservoir Operations
FNF	Full Natural Flow
FRM	flood risk management
FY	fiscal year
GDM	General Design Memorandum
GEFS	Global Ensemble Forecast System

GFS	Global Forecast System
GPS	Global Positioning System
GTS	Global Telecommunications System
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HEC	Hydrologic Engineering Center
HEC-FIA	Hydrologic Engineering Center's Flood Impact Analysis
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HEC-ResSim	Hydrologic Engineering Center's Reservoir System Simulation
HEFS	Hydrologic Ensemble Forecast Service
HEMP	Hydrologic Engineering Management Plan
IFS	Integrated Forecast System
IVT	integrated water vapor transport
IWCM	Interim Water Control Manual
IWCP	Interim Water Control Plan
MAP	mean areal precipitation
MEFP	Meteorological Ensemble Forecast Processor
MJO	Madden Julian Oscillation
MOA	Memorandum of Agreement
MODIS	Moderate resolution Imaging Spectroradiometer
MSL	mean sea level
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDSI	Normalized Difference Snow Index
NDVI	normalized difference vegetation index
NOAA	National Oceanic and Atmospheric Administration
NOHRSC	National Operational Hydrologic Remote Sensing Center
NWM	National Water Model
NWP	numerical weather prediction
NWS	National Weather Service
ORD	Oroville Dam
PDT	project delivery team
POR	period of record
PVA	Preliminary Viability Assessment
QPE	quantitative precipitation estimate
QPF	qualitative precipitation forecast
RO	regulating outlet

ROC	Reservoir Operation Center
S2S	sub-seasonal to seasonal
SAC-SMA	Sacramento Soil Moisture Accounting Model
SMAP	Soil Moisture Active Passive
SME	subject matter expert
SNODAS	Snow Data Assimilation System
SNOTEL	snow telemetry
SPF	Standard Project Flood
SWE	snow water equivalent
SWP	State Water Project
TIR	Thermal infrared
UNR	The University of Nevada Reno
USACE	U.S. Army Corps of Engineers
USACE SPD	USACE South Pacific Division
USACE SPK	USACE Sacramento District
USBR	U.S. Bureau of Reclamation
USFWS	U.S. Fish and Wildlife Service
WCM	Water Control Manual
WCP	Water Control Plan
WES	Waterways Experiment Station
West-WRF	West Weather Research and Forecasting
WRF	Weather Research and Forecasting
WRF-Hydro	WRF Hydrological modeling system
WSR	Weather Surveillance Radar
WY	water year
Y-F	Yuba-Feather
Z_{FL}	atmospheric freezing level

Section 1— Introduction

1.1 Project Purpose and Objective

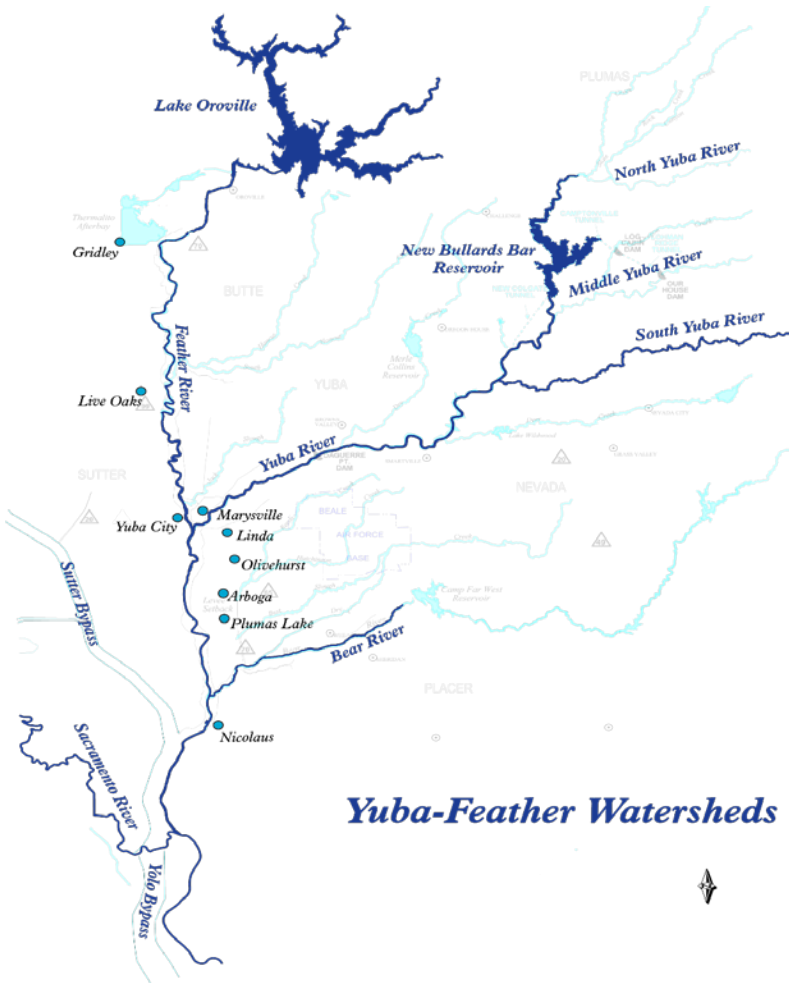

Figure 1-1. Yuba-Feather watersheds.

The Yuba-Feather watersheds (see Figure 1-1) has a long history of catastrophic floods. Since 1950, five major floods have resulted in 41 deaths, significant property damage, and devastating social and economic impacts. In response, Yuba Water Agency, which owns and operates New Bullards Bar Reservoir, and the California Department of Water Resources (DWR), which owns and operates Lake Oroville, are working with the UC San Diego Scripps Institution of Oceanography, Center for Western Weather and Water Extremes (CW3E); the U.S Army Corps of Engineers (USACE); and the National Oceanic and Atmospheric Administration (NOAA) to assess Forecast Informed Reservoir Operations (FIRO). FIRO leverages scientific improvements in forecasting of atmospheric rivers (ARs), which are responsible for more than 90 percent of the flood damages in this region, to anticipate and better manage large storm events. The primary objective of this FIRO project is to reduce flood risk; a secondary objective is to achieve incidental water supply benefits where possible.

This project will assess how improved precipitation and runoff forecasts during large storm events can reduce flood risk by strategically integrating these forecasts into reservoir operations. The primary risk reduction method is potential pre-releases to evacuate water from the conservation pool ahead of large runoff events, which will create additional temporary flood storage capacity to lessen downstream flood impacts.

The Yuba-Feather FIRO project includes the following components:

- Assess the viability of FIRO for both New Bullards Bar Reservoir and Lake Oroville operations.
- Improve precipitation and runoff forecasting for the Yuba River and Feather River watersheds by enhancing understanding of the impact of ARs by utilizing the latest, state-of-the-art technologies and strategies.

- Integrate the advanced flood runoff forecasting into FIRO and the existing Forecast-Coordinated Operations Program for flood operations at both New Bullards Bar Reservoir and Lake Oroville.
- Conduct technical analyses through a multi-agency collaborative process that provides input into and builds support for the USACE update of the Water Control Manuals (WCMs) for Lake Oroville and New Bullards Bar reservoirs.
- Align FIRO and WCM update processes and timelines to ensure communication, information sharing, and coordinated technical analyses to maximize efficiency as these processes occur in parallel.

FIRO is a reservoir operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts.

1.1.1 Project Target Goal

The FIRO operating strategies will consider existing and future reservoir conveyance infrastructure projects and reflect the absence of Marysville Reservoir, which was designed, but never built, to provide 260,000 acre-feet (ac-ft) of flood storage. The Yuba-Feather FIRO target goal is to provide the functional equivalent of 260,000 ac-ft of flood storage space for New Bullards Bar Reservoir and Lake Oroville, combined, to ensure adequate flood storage and protect downstream communities from future flood events.

The Marysville Reservoir was designed to prevent flows from exceeding 300,000 cfs on the Feather River downstream of the Feather-Yuba confluence for the Standard Project Flood (SPF).[1] Based on the 1970 Marysville Reservoir Hydrology Study, the proposed Marysville Reservoir would have 260,000 ac-ft of flood space, so that in combination with the flood space in New Bullards Bar Reservoir and Lake Oroville, the SPF could pass the Feather River communities without exceeding 300,000 cfs. The Yuba-Feather FIRO project will analyze if enhanced observation and forecast information can enable New Bullards Bar Reservoir and Lake Oroville operational strategies to provide a “functional equivalent” of up to 260,000 ac-ft of space without reallocating water supply for flood space. This “functional equivalent” could be feasible through pre-releases of water before major floods.

As an example, existing studies inform how the “functional equivalent” of up to 260,000 ac-ft could potentially be achieved. In April 2020, Yuba Water conducted a reservoir operations study to document the magnitude of potential pre-releases using forecasts to inform the operations with a proposed secondary spillway for an epic flood event, like the 1997 flood. The study indicates that with three days of pre-releases, it is possible to evacuate 87,000 ac-ft of water from New Bullards Bar Reservoir before the storm.

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[1] According to the recent hydrologic hazard report completed for Oroville: The SPF is the water estimated to reach a dam that is reasonably characteristic of the geographic region. The SPF represents reservoir inflow rates that are possible and sometimes have occurred in recent history (e.g., relatively rare events, sometimes estimated to be flood events with 200–500 average recurrence intervals). Engineers design dams with a conservative expectation that during the life of the project, water levels associated with the SPF may occur. Dams are designed so that their reservoirs are able to absorb the inflow while allowing the dam to release the outflow at a lower rate in order to reduce the chances of downstream flooding.

As an alternative to functional flood control space, “functional equivalency” could also be defined in terms of other flood performance metrics, such as downstream flood flow frequency, magnitude, and duration. Yuba-Feather FIRO will assess the viability of using improved inflow forecasts along with pre-releases to regain flood operation performance that would have been achieved with the Marysville Reservoir flood pool. The 260,000 ac-ft “functional equivalent” target value will be a useful goal in analyzing alternatives to support the Yuba-Feather FIRO primary objective of flood risk reduction.

1.2 Forecast Informed Reservoir Operations

California’s water supplies rely on adequate precipitation, which largely depends on ARs. ARs originate in the Pacific Ocean and make landfall along the California coastline. The absence of AR storms often leads to drought in California, whereas strong ARs are often responsible for flooding. In fact, AR storms account for over 90 percent of flood damage claims in the western United States. Figure 1-2 shows an AR that impacted the Yuba-Feather watersheds in 2012.

Figure 1-2. Image of an AR that made landfall on December 2, 2012, and impacted the Yuba-Feather watersheds, courtesy of CW3E.

The main driver in flood forecast improvement is the ability to improve the short- and medium-range meteorological forecasts, particularly for AR events. CW3E has established an advanced AR observational and meteorological research program to assess and improve forecasts for the Yuba-Feather watersheds using state-of-the-art science. CW3E’s work, done in close collaboration with USACE’s Engineer Research and Development Center and Hydrologic Engineering Center (HEC), develops tools and methods that support FIRO objectives. By establishing the AR forecast improvement process, pending favorable results from the FIRO Viability Assessment, WCM updates can confidently operationalize FIRO safely and reliably.

Currently, most reservoirs operate without the benefit of skilled AR forecasts. CW3E has developed significant skill in forecasting ARs. Predicting the timing and intensity of these critical precipitation events is essential to providing water managers and dam operators with the information they need and with enough lead time to operate reservoirs in anticipation of floods and drought. Currently, many dam operators are required to keep reservoirs at a significantly reduced water level during storm seasons to ensure enough space to handle subsequent storms, regardless of the forecast. FIRO uses data from watershed monitoring programs and improved weather and water runoff forecasting to help water managers selectively retain or release water from reservoirs in a flexible manner that reflects prevailing and anticipated conditions. FIRO represents an innovative use of emerging science and technology to optimize limited resources and adapt to changing climate conditions without costly reservoir infrastructure improvements.

1.2.1 History of FIRO

This Yuba-Feather FIRO project builds on FIRO work in other watersheds in California. FIRO was first initiated in 2014 by the creation of the Lake Mendocino FIRO Steering Committee, an interagency collaboration with a self-imposed mission to develop and test FIRO at Lake Mendocino in the Russian River watershed to increase reservoir resiliency to future droughts, after experiencing a major drought in 2013–2014. The Steering Committee determined FIRO to be viable after a Preliminary Viability Assessment (PVA), published in 2017. Following completion of the PVA, FIRO was tested under two consecutive major deviation approvals, which demonstrated significantly improved water supply reliability. For example, for water year 2020, which was the third driest in 127 years, water supply storage in Lake Mendocino with FIRO was about 20 percent greater than without FIRO. The Final Viability Assessment was completed in December 2020 and will inform an update of the WCM.

A second FIRO project for Prado Dam Reservoir in the Santa Ana River watershed in southern California was initiated in late 2017. The Yuba-Feather FIRO project builds on past success and is modeled after the process established by the Lake Mendocino pilot project and refined by the Prado Dam FIRO project.

1.2.2 Yuba-Feather FIRO Steering Committee

The Yuba-Feather Steering Committee first met in June 2019. Meeting quarterly, it is co-chaired by Dr. F. Martin Ralph, Director of CW3E; John James, Water Operations Project Manager of Yuba Water; and John Leahigh, Water Operations Executive Manager, DWR. Members were selected to represent key organizations, and they bring together innovative leaders from those organizations to collaborate and contribute expertise and resources to accomplish common goals. Yuba-Feather Steering Committee membership is listed below. The Steering Committee developed and agreed to its operating principles called the "Terms of Reference," which consist of its mission, vision, goals, and strategies to achieve these goals; processes and procedures; and importantly, the project objective and target goal described above.

1.2.2.1 Steering Committee Membership (see Figure 1-3)

Co-Chairs:

- F. Martin Ralph: Director, CW3E, Scripps Institution of Oceanography, UC San Diego
- John James: Water Operations Project Manager, Yuba Water Agency
- John Leahigh: Water Operations Executive Manager, DWR

Members:

- Jay Jasperse: Chief Engineer, Sonoma Water
- Michael Anderson: State Climatologist, DWR
- Cary Talbot: Division Chief, USACE, Engineering Research and Development Center
- Alan Haynes: Hydrologist-in-Charge, NOAA National Weather Service, California Nevada River Forecast Center

- Joseph Forbis: Chief, Water Management Section, USACE Sacramento District
- Molly White: Chief, State Water Project, Water Operations Office, DWR
- Steven Lindley: Director, Fisheries Ecology Division, Southwest Fisheries Science Center, NOAA Fisheries

Figure 1-3. Photo of Yuba-Feather FIRO Steering Committee meeting.

1.2.2.2 Terms of Reference

The first task of the Steering Committee is to formulate and agree to the "Terms of Reference" for the functioning of the Committee. The Terms serve as a governance agreement and spell out commitments from all members, as well as procedural matters. A summary of the Terms of Reference follows.

1.2.2.3 Vision, Mission, Goal, and Strategies

- **Vision:** Develop robust forecast data and tools that support increased flexibility in reservoir operations to improve water conservation, flood control, and habitat management outcomes.
- **Mission:** Guide a highly collaborative engagement process to ensure that deliverables reflect interdisciplinary perspectives and interagency input.
- **Goal:** Develop clear pathways for assessing the viability of FIRO at New Bullards Bar Reservoir and Lake Oroville.
- **Strategies:** Draft a PVA outlining tasks, roles, schedule, and requirements for assessing FIRO viability; conduct preliminary technical studies; and develop a PVA based on current forecast skill and a Final Viability Assessment based on potential improvements in forecast skill.

1.2.2.4 Process for Achieving Mission

- Hold quarterly Steering Committee meetings, at least two of which are in person each year (except from spring 2020 to spring 2021 when meetings transferred online due to the pandemic).
- Develop meeting agendas, circulate meeting notes, and document and track action items.
- Conduct conference calls, site visits, small working group meetings, and other means of coordination.
- Hold an annual workshop to engage with, coordinate with, and learn from each other.
- Pursue communication and outreach opportunities.
- Develop a strategy for launching the viability assessment, including funding and implementation commitments.
- Coordinate FIRO and the WCM update processes for New Bullards Bar and Lake Oroville (added after Steering Committee formation)

1.3 Yuba-Feather FIRO Process and Timeline

Figure 1-4 shows the evaluation process that is being used to assess FIRO for the Yuba-Feather system. It follows the same procedure used for the Lake Mendocino and Prado Dam viability assessments.

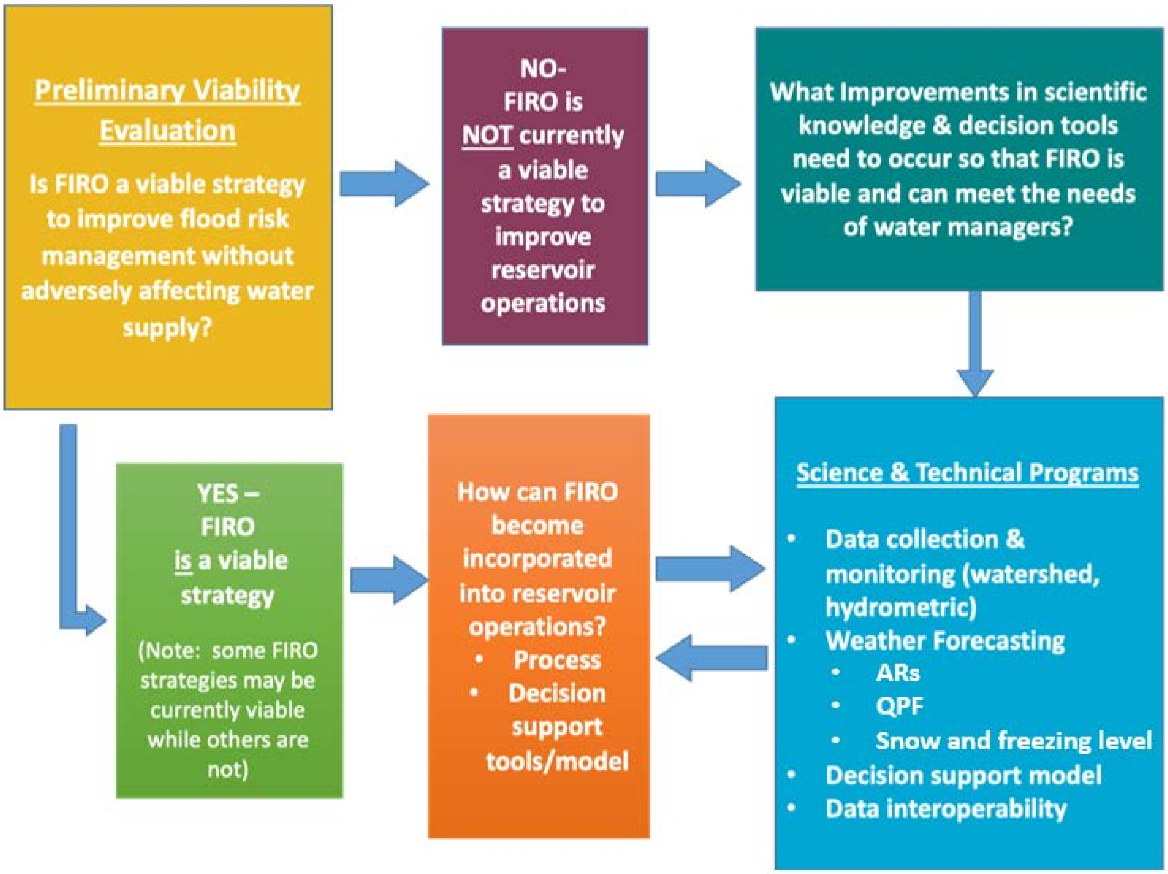

Figure 1-4. Generalized FIRO preliminary viability assessment process.

The Yuba-Feather Project timeline is shown in Figure 1-5. The FIRO viability assessment will contribute to and inform the WCM updates as shown in the aligned schedules. This aligned schedule was developed as part of a three-day workshop that focused on coordination between FIRO and the WCM updates.

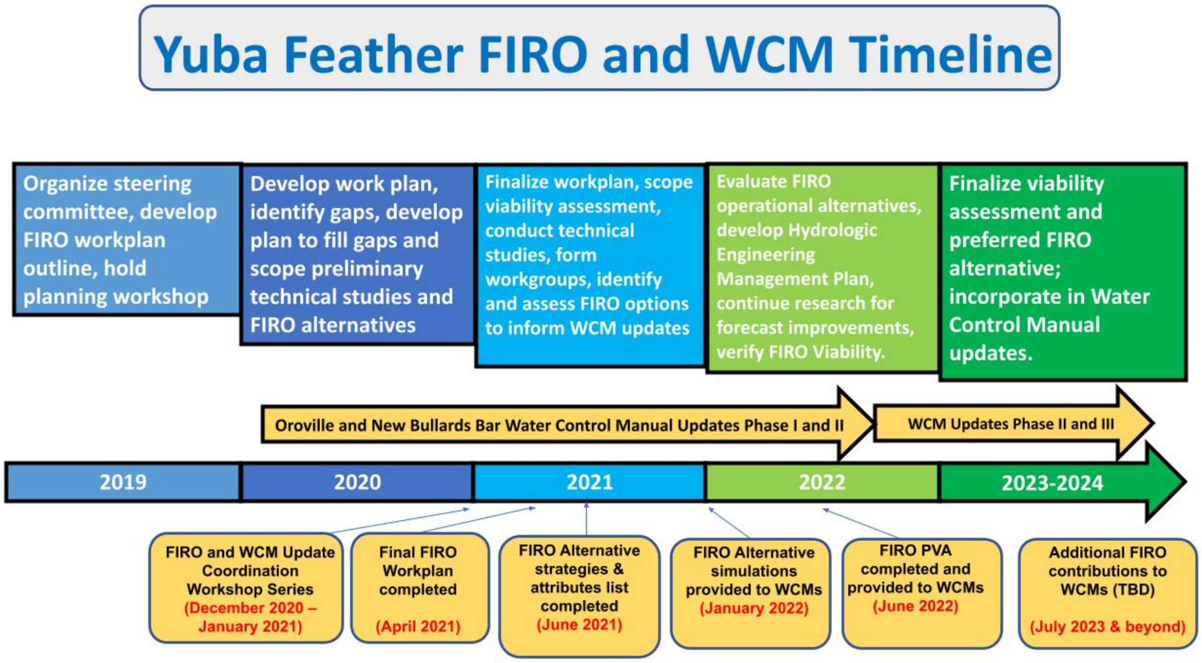

Figure 1-5. Project timeline for Yuba-Feather FIRO and WCM updates.

1.4 Work Plan Contents

This work plan establishes a common understanding of reservoir management in the Yuba-Feather system and identifies further studies that are needed to develop the FIRO viability assessment. The process of creating the work plan is a necessary step in building a cohesive and trusted team to collaboratively pursue a demonstration of FIRO viability and contribute toward the integration of FIRO components and technologies into future WCM updates. This is especially important since the WCM update and FIRO assessment are being conducted concurrently.

The following sections describe the existing system and planned improvements; assessments of current monitoring, modeling, and forecasting components; forecast requirements, frameworks for evaluating FIRO alternatives, and potential socio-economic benefits; and tasks, studies, and research that are needed to support FIRO viability and ultimately operational use through updated WCMs.

Section 2— Watershed Characteristics, Existing Operations, Planned Improvements, and Alignment with New Bullards Bar and Oroville Water Control Manual Updates

2.1 Watershed Characteristics

The Yuba River flows into the Feather River at Yuba City, which in turn flows into the Sacramento River just upstream from Sacramento (see Figure 2-1). The Yuba-Feather River basin gets 80 to 90 percent of its annual rainfall from November through April. Heavy rains and snowfall at higher elevations (usually greater than 5,000 ft) result from large-scale, long-duration (multi-day) storms flowing west to east from the Pacific Ocean. Mean annual precipitation in the watershed ranges from about 15 inches on the eastern slopes of the Sierra Nevada to about 90 inches along the ridges on the western slopes.

Figure 2-1. Yuba-Feather watershed.

New Bullards Bar Reservoir is located on the North Yuba River northeast of the city of Marysville in Northern California. The Yuba River watershed (Figure 2-2) responds quickly to winter storm events, especially when temperatures are higher and snowfall occurs only at the highest elevations. The mountainous terrain is steep, rugged, and sparsely populated. Lakes and reservoirs in the Middle and South Yuba Rivers provide very limited and incidental flood water retention. Retention is more common in the early winter as reservoirs recover from the dry summer months when they provide water supply and hydropower generation.

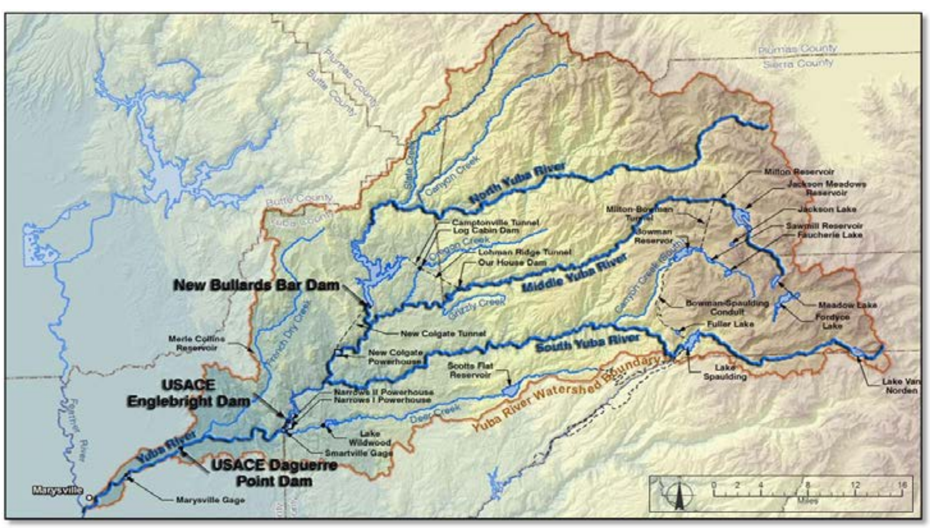

Figure 2-2. Yuba River watershed.

The Yuba River supports populations of several special status fish species, including spring-run Chinook salmon and steelhead trout, which were historically abundant on the Yuba River, as well as green sturgeon. All three species are listed as threatened under the federal Endangered Species Act, and the lower Yuba River has been designated as critical habitat. Yuba Water Agency has worked with local, state, and federal agencies, environmental groups, and tribes to protect the fisheries resources of the lower Yuba River. The Lower Yuba River Accord ensures higher, more protective flows 78 percent of the time to benefit fish and provide one of the most suitable water temperature profiles of any Central Valley river across all water years.

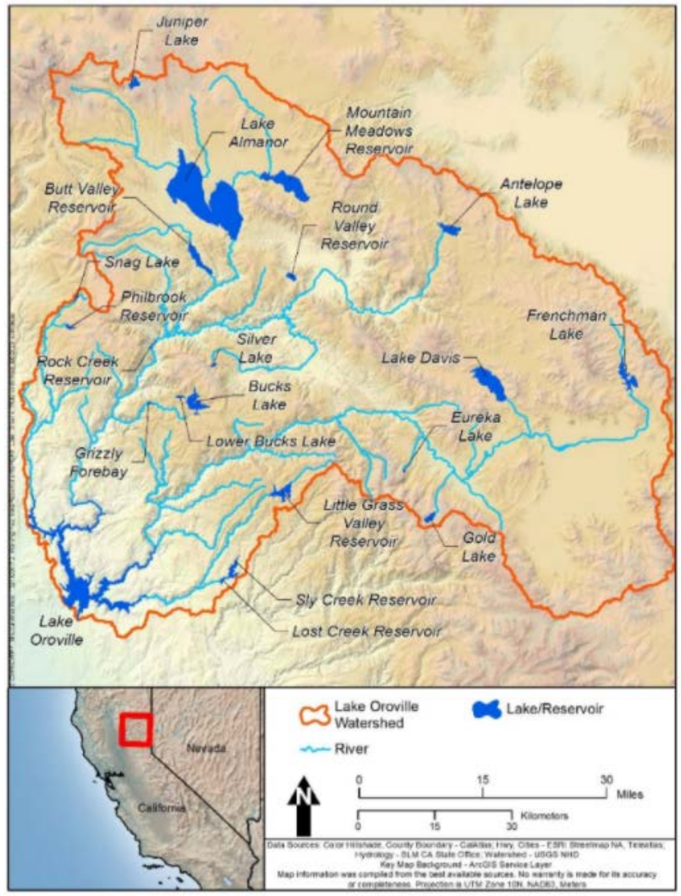

Figure 2-3. Lake Oroville watershed and upstream reservoirs.

Lake Oroville and Oroville Dam are located on the Feather River, a major tributary of the Sacramento River and about 6 miles northeast of Oroville in Butte County, California. The watershed that yields inflow to Lake Oroville is 3,625 square miles in area (Figure 2-3). The reservoir has a capacity of approximately 3.5 million acre-feet (ac-ft). There are nine upstream reservoirs that control inflow to Oroville on the Feather River.

A typical flood-producing storm event lasts multiple days and consists of a rapid succession of several individual storms. During large floods, runoff accumulates rapidly in higher-elevation upstream areas and flooding is intense, but of short duration. In downstream areas, however, the river rises and falls much more gradually. As a result, stream velocities are less, but flood inundation duration may last for days.

2.2 New Bullards Bar Dam and Oroville Dam Existing Operations

The Oroville and New Bullards Bar dams are the primary flood management features on the Feather and Yuba Rivers, respectively. They were completed to reduce flood risk, improve water supply, generate hydroelectricity, provide sources of recreation, and produce environmental benefits. The dams provide water supply to areas adjacent to each of their respective rivers and downstream to the Sacramento River, and eventually to the Sacramento–San Joaquin Delta. Together, Lake Oroville and New Bullards Bar Reservoir provide flood protection for properties and interests downstream of the structures.

Table 2-1. Lake Oroville watershed and upstream reservoirs.

Lake Oroville

Capacity	3,537,600 ac-ft
Flood Pool	750,000 ac-ft
Year Built	1967
Watershed	2,320,000 acres
Owner	DWR
Purpose	Water supply, flood protection, recreation, environmental, hydropower

New Bullards Bar Reservoir

Capacity	970,000 ac-ft
Flood Pool	170,000 ac-ft
Year Built	1969
Watershed	313,000* acres
Owner	Yuba Water Agency
Purpose	Water supply, flood protection, recreation, environmental, hydropower

*The NBB Reservoir is on the North Yuba River; the entire Yuba River watershed is 957,000 acres.

New Bullards Bar Dam was completed in 1969 and is owned and operated by the Yuba Water Agency as the primary feature of the Yuba River Development Project. The dam forms New Bullards Bar Reservoir, which, at a normal maximum water surface elevation (NMWSE) of 1,956 ft, extends about 15.3 river miles upstream on the North Yuba River. The reservoir has an estimated gross storage capacity of 966,103 ac-ft, a surface area of 4,790 acres, a shoreline of about 71.9 miles, and a drainage area of 488.6 square miles. The dam includes an overflow-type spillway with a maximum design capacity of 160,000 cfs. Under the contract between the United States and Yuba Water that was entered into on May 9, 1966, Yuba Water agreed to reserve 170,000 ac-ft of storage space in New Bullards Bar Reservoir for flood control.

Oroville Dam*,* completed in 1970, impounds the 3.54 million ac-ft Oroville Reservoir on the Feather River and is owned by the California Department of Water Resources (DWR) and operated as part of the California State Water Project (SWP). DWR operates Oroville Dam as a key component of the SWP that delivers water to contractors serving both agricultural and municipal interests in Northern California, the Bay Area, the San Joaquin Valley, the Central Coast, and Southern California. In addition to providing water supply benefits to cities and farms throughout the state, the SWP operates Lake Oroville to meet

Delta water quality standards in the Sacramento–San Joaquin River Delta in coordination with the U.S. Bureau of Reclamation's Central Valley Project.

The federal government paid for the top 750,000 ac-ft of seasonal flood pool storage and issued regulations for the Flood Control Manual. After the gated spillway chute failed in February 2017, DWR reconstructed the chute in November 2018.

The U.S. Army Corp of Engineers' (USACE's) Englebright Dam was completed in 1941 on the mainstem of the Yuba River about 17 miles downstream of New Bullards Bar Dam and about 24 miles from the confluence of the Yuba and Feather Rivers. It is a smaller project that was constructed to trap sediment from the historical hydraulic mining operations in the upper Yuba River watershed. Englebright Dam provides some water rights delivery benefits, but it delivers no flood control capacity to the system. Congress authorized a third reservoir called Lake Marysville with 260,000 ac-ft of seasonal flood storage, but it was never constructed. Interestingly, the USACE Water Control Manuals (WCMs) for both New Bullards Bar Reservoir and Lake Oroville reference and rely on this unconstructed dam to help meet Feather River flood control objectives. The absence of the Marysville dam and reservoir heightens the need to employ innovative solutions to improve flood risk management, such as the Yuba-Feather Forecast-Coordinated Operations (F-CO) and Forecast Informed Reservoir Operations (FIRO).

Valley reaches of both the Feather and Yuba Rivers are leveed and were subject to breaches from extreme flood events in both February 1986 and January 1997. These breaches resulted in over $500 million in flood damage payments by the state of California. After the devastating 1997 flood event, Yuba Water initiated a $1 million Supplemental Flood Protection Study that identified numerous actions to improve flood protection of life and property, including the Yuba-Feather F-CO Program.

Both DWR and Yuba Water have agreements with USACE for seasonal flood control space in the Oroville and New Bullards Bar Reservoirs, respectively, to reduce flood risk to downstream communities. The use of the flood control space is specified according to their respective WCMs, which stipulate operational requirements. Each reservoir has a flood reservation space (nominally 750,000 ac-ft for Oroville Reservoir and 170,000 ac-ft for New Bullards Bar Reservoir), along with operable spillways that are designed to safely release flood flows coming into each reservoir. The WCM for each reservoir specifies flood operations, including operations for individual downstream objectives (see Appendix 2).

2.2.1 Forecast-Coordinated Operations Program

FIRO is different from F-CO in that it is a research-based effort to enhance and inform reservoir operation decision-making through improvements in weather and runoff forecasts over it provides a pathway and process for integrating the use of improved forecasts into operating procedures with an explicit goal of codification into the USACE WCMs. F-CO is the real-time coordination of reservoir operations and improved communications among operating entities in a flood emergency response mode. Coordinating releases based on improved information minimizes the chance of exceeding channel capacity and increases warning time to communities in the basin. The WCM notes that "close liaison with other agencies"—including Yuba Water, the National Weather Service, DWR/SWP, State-Federal Flood Operation Center, and USACE—is required on a daily or hourly basis to ensure that the flood control operation will be as effective and reasonable as possible.

In 2005, the DWR Flood Operations Center and Operations Control Office, USACE's Sacramento District, the National Weather Service's California Nevada River Forecast Center (CNRFC), and Yuba Water launched the F-CO Program to coordinate flood operation of the reservoirs in the Yuba and Feather rivers. The program was developed in response to the flood of 1997 to improve forecasts and the communication and coordination of reservoir releases between the two facilities with the goal of improving public safety during flood events.

Specifically, an F-CO Program for the Yuba-Feather Rivers system strengthens operations by:

- Enhancing communications and information exchange among agency operators.
- Improving flood forecasts.
- Closely integrating the flood operations of Lake Oroville and New Bullards Bar Reservoir during major flooding.
- Identifying changes in operational procedures that would improve efficiency.
- Providing operators and downstream emergency managers with frequently updated forecast information, including uncertainty bounds associated with the flows at key locations in the Yuba-Feather Rivers flood system.

Developing and implementing the F-CO Program has been a multi-agency partnership effort. The hydraulic interconnection of the confluence of the Yuba and Feather Rivers and points downstream demands that the systems coordinate their operation decisions to avoid excessive flows, while taking advantage of the full channel capacity. The participants have a history of working together in preparing flood-related information, operating and maintaining the flood control structures, and serving the public during flood emergencies. The F-CO Program has enhanced this working relationship and developed a formal infrastructure for exchanging and sharing flood information.

The goal of the F-CO Program is to better protect life and property for communities along and downstream of Lake Oroville and New Bullards Bar Reservoir without impacting the water supply of the facilities. The objective of the F-CO Program is to reduce peak flood flows through improved river flow forecasting and improved coordination between Lake Oroville and New Bullards Bar Reservoir flood operations.

Water managers at Yuba Water and DWR's Operations Control Office make decisions about operation of New Bullards Bar Reservoir and Lake Oroville. Both operators receive forecasts of inflows and downstream unregulated flows and river conditions from the CNRFC and Flood Operations Center and use this information along with information from other sources to make decisions about reservoir releases. The operating agencies consider their mission, the needs of their customers, downstream constraints, and the current state of their reservoirs when making release decisions. Those decisions include current operation (how much to release immediately) and future operations (how much to release in the future if the forecasts are correct or incorrect).

USACE's Sacramento District plays a major role in the management of the flood pool. Section 7 of the Flood Control Act of 1944 (58 Stat. 890, 33, U.S.C 709) directs USACE "to prescribe regulations for the use of storage allocated for flood control at reservoirs constructed wholly or in part with Federal funds provided based on such purposes," and to ensure "that the operation of any such project shall be in accordance with such regulations." Both New Bullards Bar Reservoir and Lake Oroville facilities received partial federal funds for the reservoirs' flood pool and thus are subject to this regulation.

In addition to providing agency coordination, the F-CO Program has developed a Decision Support System (DSS) as a centralized data and common modeling framework for F-CO during normal conditions and storm events. The F-CO DSS has two general features: entering forecasted reservoir releases, and performing reservoir operation simulations using the Hydrologic Engineering Center's Reservoir System Simulation (HEC-ResSim). The DSS is housed on the DWR California Data Exchange Center (CDEC), which directly receives updated runoff forecasts, the current release schedule, the reservoir's top of conservation level, and supporting data (i.e., precipitation, reservoir elevation).

CNRFC and DWR forecasters regularly issue flow forecasts that are directly ingested into the DSS with a five-day forecast time horizon. Water managers enter reservoir release changes based on the latest forecast as soon as possible. The DWR Reservoir Coordinated Operations Section works with CDEC on any DSS issues.

During flood events, any one of the F-CO Program partners may initiate coordination calls. USACE regularly engages with SWP and Yuba Water managers to ensure compliance with written regulations and approve any deviations from the WCM. If release coordination is needed due to any forecasted control points above the target flows, water managers can run simulations and commit to a flood release schedule in the DSS. Through the DSS, USACE can view and approve the results of the proposed reservoir operation. The DWR Flood Operations Center then makes necessary notifications to local communities for forecast points exceeding stage thresholds. With this greater understanding, and the advancement of runoff forecast information and other supporting technologies and tools, the F-CO Program has identified opportunities to further enhance flood management of this system by using inflow forecast to decide early releases from the reservoir in advance of the large storms. This process is broadly outlined in Figure 2-4 and described in great detail below.

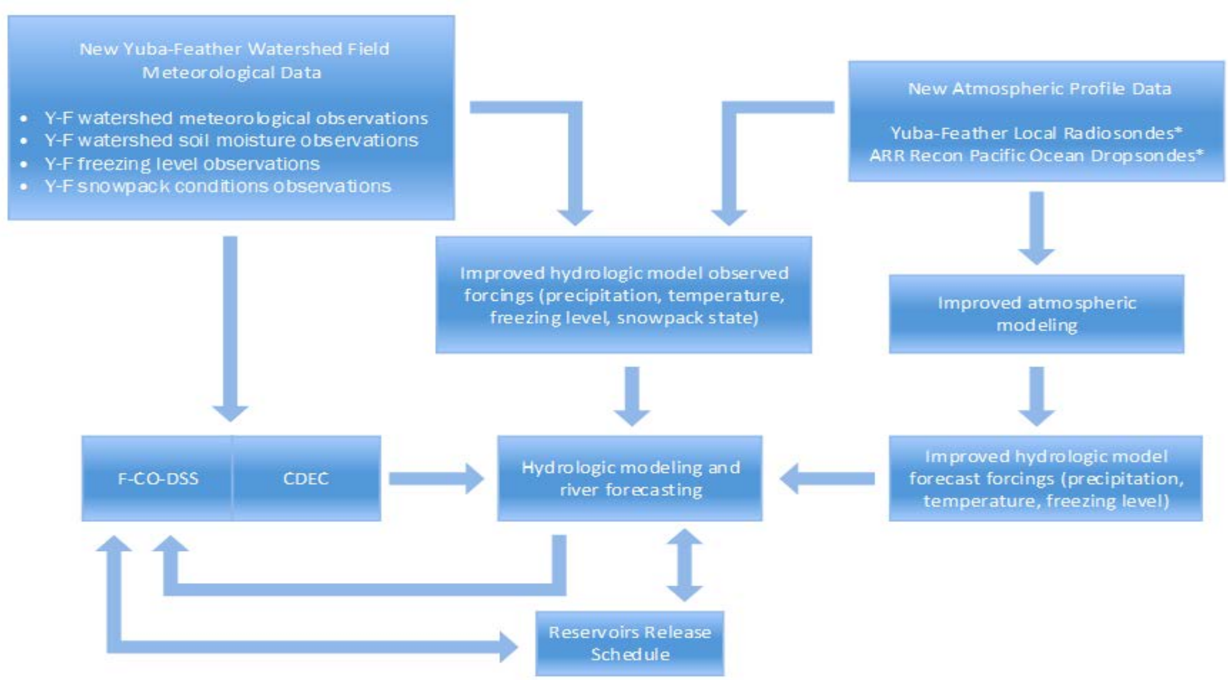

Figure 2-4. Path for incorporating new data and atmospheric river research information into runoff forecasting and enhancing reservoir operations.

2.2.2 Preliminary FIRO Reconnaissance-Level Study

This FIRO initiative follows a preliminary exploration of the potential of FIRO to reduce flood risk. The early successes of the F-CO Program led Yuba Water, DWR and its partners to test FIRO at Lake Oroville and New Bullards Bar Reservoir. They used five-day inflow forecasts to inform decisions about releasing water before a large storm event to create additional flood storage space in the reservoir and reduce peak flood releases later during the flood event.

Yuba Water documented this effort and the findings in a January 2018 summary report titled *Feasibility of Forecast-Informed Operations and Structural Modifications for Yuba-Feather Watersheds*. The report describes the F-CO Program for the Yuba-Feather system, reviews past studies and investigations of flood management improvements with elements of F-CO and FIRO, and summarizes alternatives evaluated for Lake Oroville and New Bullards Bar Reservoir. A project team then tested the FIRO viability of the Yuba-Feather Rivers system using a spreadsheet model followed by HEC-ResSim.

Three alternatives were explored, all of which assumed Oroville FIRO operations with existing facilities:

- FIRO of Lake Oroville and New Bullards Bar Reservoir alternative with existing New Bullards Bar facilities.
- FIRO with New Bullards Bar Dam raise alternative.
- FIRO with New Bullards Bar low-level secondary spillway alternative.

Flood protection benefits were estimated based on reductions in peak stage and flow at critical downstream locations and additional operational redundancy to manage large storm events if existing primary release structures became compromised during flood operations.

The study found that FIRO with existing New Bullards Bar facilities provides minimal additional flood protection benefits for Yuba River. FIRO with the New Bullards Bar Dam raise alternative and FIRO with the low-level secondary spillway alternative provided greater protection against larger flood events. Compared to the dam raise alternative, the low-level secondary spillway alternative provided the greatest reduction in downstream stage during peak flood events, improved operational flexibility and dam safety, had the lowest cost and complexity, and had fewer environmental impacts.

The project team conducted a more detailed reservoir operations analysis using HEC-ResSim and flood damage assessment (FDA) modeling using HEC-FDA to further evaluate implementing FIRO in conjunction with the recommended New Bullards Bar low-level secondary spillway. This analysis indicated that the addition of the secondary spillway at New Bullards Bar Dam, combined with Yuba-Feather FIRO operation, significantly lowered downstream stages compared to existing operations. The spillway reduced downstream peak flow and stages at all critical downstream locations for 1-in-100-year and 1-in-200-year simulated flood events. Peak flood stage was reduced by up to 3 ft for Yuba River near Maysville and up to 2 ft at the Yuba-Feather Rivers confluence as compared to existing operations. In summary, the study recommended:

- Yuba Water should move forward with engineering, design, and environmental documentation of the proposed low-level secondary spillway at New Bullards Bar Dam. This work is underway.
- Yuba Water should work with DWR, USACE, and the Yuba-Feather F-CO Program partners to advance FIRO for enhanced flood operation of Lake Oroville and New Bullards Bar Reservoir.
- The F-CO Program partners should continue to assess the need to modify any facility and/or operational modifications to fully operate Lake Oroville under FIRO.

In 2019, the project team expanded their FIRO precursor study of New Bullards Bar Reservoir and Lake Oroville to demonstrate how the New Bullards Bar Reservoir could operate while receiving high inflows, such as those resulting from the historic storm event that occurred in northern California in February 2017. The analysis verified previous analyses, and formed the basis of the following objectives for a full FIRO assessment:

- The primary objective is to reduce peak flood releases downstream of the reservoirs.
- When feasible, FIRO should reduce flood releases that would stress the levee system (i.e., reduce the time that water will be high and against the levees). This would suggest initiating releases early enough, so that high releases are not necessary before high inflow to the reservoir.
- When feasible, FIRO should avoid the use of a full flood pool or surcharge of the reservoir during major flood events.
- To the degree possible, FIRO should minimize fluctuations in reservoir release rates throughout the storm event.
- FIRO should be designed as simple, practical, flexible, and adaptable to future climate change, changes in hydrology, advances in technology, and improved understanding of storm events.

These preliminary studies of FIRO provided confidence to move forward with a formal FIRO viability assessment, one that would incorporate more robust alternatives analyses, watershed-specific meteorological assessments, and formalized partnerships through a structured process.

2.2.3 F-CO and FIRO

FIRO will build on the existing relationships and tools among the F-CO project partners. F-CO and FIRO share the same goal of reducing flood risk for communities along the Yuba-Feather Rivers system. The F-CO Program provides a pre-existing, coordinated operations framework and decision support system, which is initiated prior to and during major floods events. A key to successful FIRO implementation is improving understanding of the landing, magnitude, and duration of atmospheric rivers (ARs), which results in more accurate precipitation forecasting, runoff forecasting, and forecasting lead time for major storm events. As part of the FIRO implementation strategy, F-CO operations will integrate FIRO's improved precipitation and runoff forecasts to determine pre-release of water in advance of major storms. These early releases will create additional storage in the reservoir to capture peak inflow to the reservoir, thereby reducing peak flood releases downstream. FIRO will also explore when reservoir operations can possibly produce secondary benefits of increased water supply reliability by allowing encroachment into the flood space without impacting flood operations.

2.3 Planned Operational Improvements

2.3.1 New Bullards Bar Secondary Spillway

In 2018, based on the results of a feasibility study, Yuba Water started the process to permit and design a secondary spillway for New Bullards Bar Dam to improve flood management (see Figure 2-5). Construction on the secondary spillway is scheduled to be complete in 2025. This new feature will be added to the new WCM.

Figure 2-5. General alignment of New Bullards Bar Dam with spillway detail.

A prerequisite for FIRO implementation is the ability to release water from lower levels in the reservoirs. The New Bullards Bar Reservoir currently does not have adequate release capacity at the low level. Yuba Water is planning to build a new high-capacity secondary spillway at New Bullards Bar (estimated completion in 2025) that will allow for additional flood control releases to be made at lower lake levels. The New Bullards Bar Secondary Spillway will provide spillway redundancy should the primary spillway overtop or become inoperable. Spillway redundancy analysis illustrated that the secondary spillway could independently pass an event with a frequency of approximately 1-in-275 years, without overtopping the parapet wall. Coupled with FIRO, this new spillway will enable Yuba Water to release water early in anticipation of major flood events while improving conservation storage during dry conditions.

2.3.2 Lake Oroville Comprehensive Needs Assessment

Following the 2017 Oroville Spillway Incident, DWR made a commitment to federal and state dam safety agencies to formally initiate a Comprehensive Needs Assessment (CNA) to identify and prioritize potential dam safety enhancements and improvements to provide increased operational flexibility for the future. It is primarily a dam safety assessment, but it does have flood and water supply operations implications. The CNA lays out, in concept, how FIRO could be implemented for Oroville Dam. FIRO would provide a mechanism for operational flexibility to release more water ahead of a forecast flood event or store more water when no large events are forecast. Operators can implement FIRO by using forecast inflows to determine variable flood storage space and release rules.

DWR created an Independent Review Board of dam safety experts to conduct independent technical reviews of DWR's work products, including the CNA. Six task teams were formed to examine potential vulnerabilities and improvements for the Embankments, Gated Spillway, Emergency Spillway, Outlets, Operations, and Instrumentation associated with the Oroville Dam Complex. Among the many efforts was the completion of one of the most extensive semi-quantitative risk analyses ever performed. Over 300 potential failure modes (PFMs) were initially considered. Following the completion of the semi-quantitative risk analyses for the various facilities under existing conditions, a range of potential improvement measures were developed to reduce estimated risks to even lower levels. In addition, 33 potential improvement measures were developed for inclusion in potential alternative plans for reducing potential risks. In the end, the CNA Initiative recommended consideration of a set of Alternative Plans with different levels of investment and potential residual risk for future consideration by DWR. The CNA is being finalized at the time this work plan is being completed; results will be considered in the FIRO Preliminary Viability Assessment (PVA).

The CNA includes bookend analyses to demonstrate that flood management and water supply benefits are possible with FIRO alternatives. These analyses have considered increasing flood space, releasing more water sooner, delaying releases, and other potential operational scenarios. For more information on the CNA, see Appendix 2.

2.3.3 Climate Change Vulnerability Assessment

DWR has initiated a reservoir vulnerability assessment to demonstrate how increased runoff volume due to climate change impacts the Central Valley streams and floodplains. The assessment considers potential solutions to mitigate additional flood risk. To do this, DWR will assess how 16 selected flood control reservoirs (including Oroville and New Bullards Bar) function as integral parts of the overall flood management system. DWR will also analyze how regulated outflows from reservoirs compare under current and future climate conditions using existing reservoir operation rules. This analysis will help determine how regulated flows will change within the Sacramento–San Joaquin basin with increased runoff volume, following current reservoir operations.

Findings of the DWR reservoir vulnerability assessment will provide runoff volume inputs into flow models of the Yuba-Feather system, advancing our understanding of changing flows with a changing climate. F-CO and FIRO are highly adaptable to a wide range of runoff scenarios today and in the future, allowing operators to plan for these changing conditions.

A recent paper by Corringham et al. (2019)[2] has established that climate change, along with rising population and increased development, are expected to worsen the risk of AR-driven flood damage in future decades. Figure 2-6 compares the differences and ratio of annual flood damages between the 1990s and the 2090s.

[2] Corringham, T. W., Ralph, F. M., Gershunov, A., Cayan, D. R., & Talbot, C. A. (2019). Atmospheric rivers drive flood damages in the western United States. Science advances, 5(12).

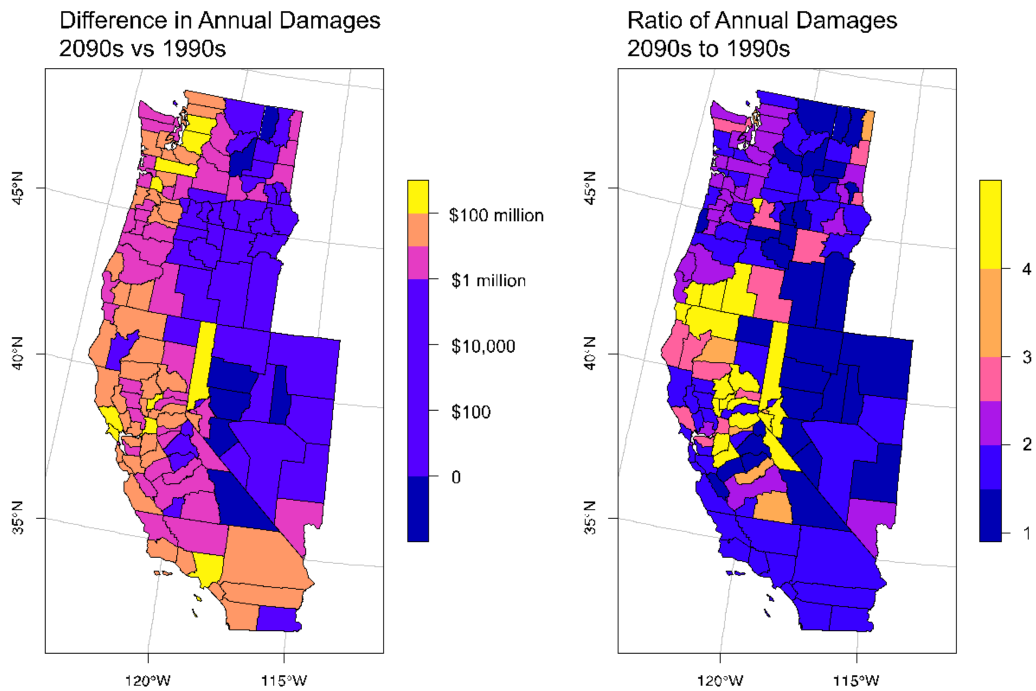

Figure 2-6. Changing flood costs of ARs in the United States.

The study indicates the region surrounding the Yuba-Feather system could have one of the highest ratios of increased flood damaged in the state. This emphasizes the importance of FIRO forecast improvements and subsequent flood risk reduction strategies as an important and ultimately necessary climate resiliency tool for the region.

2.4 Alignment with New Bullards Bar and Oroville WCM Revisions

The WCMs for New Bullards Bar Dam and Oroville Dam have not been updated since the original versions were produced in August 1970 and June 1972, respectively. The WCMs are based on historical hydrology. Hydrologic and meteorological forecast skill that has advanced significantly in the past 50 years and continues to improve. Moreover, the existing manuals assumed the Marysville Dam would be operated to help meet the objective of not exceeding 300,000 cfs flow for the Standard Project Flood downstream of the confluence of the Yuba River. The Marysville Dam was never built and thus must be removed from the WCM assumptions. The WCMs will be modernized to reflect today's flood operation needs, incorporate advanced engineering and new facilities (i.e., secondary spillway at New Bullards Bar Reservoir), acknowledge advancement in ARs and watershed runoff forecasting science, and incorporate FIRO operations, with the objective of reducing the frequency of exceeding the combined downstream flow constraints.

Yuba-Feather FIRO will inform USACE as to whether FIRO is viable and how USACE should incorporate FIRO in the updated WCMs to reduce flood risk for the communities along the Yuba and Feather Rivers. Yuba-Feather FIRO will help inform the USACE WCMs update process to include additional flexibility to

> "The updated manuals, combined with the planned Secondary Spillway at New Bullards Bar, will help Yuba Water maximize the value of that critical infrastructure improvement and enable us to respond to changing climate conditions. This will significantly improve our ability to operate the project in extreme flood events, and help us more efficiently manage water for local farmers, ranchers and fisheries, as well as the 80 percent of Yuba County's population that relies on groundwater for their primary water supply."
> **- Willie Whittlesey, Yuba Water Agency General Manager**

safely encroach into the flood storage space, enabling improved water supply reliability when prolonged dry conditions are forecast.

The USACE's Sacramento District has received partial funding for WCM updates for the two reservoirs and has begun working on them. The timing of the FIRO assessment aligns well with future operational decisions related to the anticipated WCM revisions. The Steering Committee convened a series of WCM-FIRO coordination and alignment workshops with leadership and technical experts from each of the organizations involved with the projects. There were many beneficial outcomes from the workshops, including schedule alignment, creation of WCM-FIRO technical and leadership subgroups, and updates to each of the projects' work plans.

USACE has established a multi-agency, collaborative approach to develop a work plan and execute technical activities needed for the WCM updates. The completion of the new WCM for New Bullards Bar is targeted for 2025, corresponding with planned completion of secondary spillway construction. The completion date for the new WCM for Lake Oroville is also targeted for 2025.

A FIRO-WCM leadership team will meet monthly to ensure communication, coordination, and alignment of scopes and schedules. The goal of the alignment is to streamline processes, minimize redundancies, and leverage the combined knowledge and skills of the groups working on both projects. This will ensure that the analyses undertaken in the FIRO PVA, and the subsequent Final Viability Assessment, can be used to inform the WCM update, and WCM analyses can similarly be used to inform the FIRO assessment. The timing and requirements associated with both studies will need to be crosswalked in detail to determine the extent to which efficiencies can be realized. An initial crosswalk of tasks, and alignment milestones developed at the workshop, are presented below:

- Identify attributes for FIRO alternatives strategies for input into WCM Hydrologic Engineering Management Plans: June 2021
- Continue with forecast improvement field work and develop meteorological/hydrologic forecast skill metrics for operational alternatives and adaptive WCMs: January 2022
- Produce draft FIRO PVA with initial scoping of FIRO alternative strategies and draft metrics: January 2022
- Produce final PVA with initial assessment of FIRO alternatives; identify alternatives for full evaluation in Final Viability Assessment: June 30, 2022

Section 3— Catalog and Assessment of Existing and Planned Monitoring Programs

Sufficient monitoring is crucial for the success of Forecast Informed Reservoir Operations (FIRO), which is predicated on watershed monitoring in order to understand the potential impacts of extreme precipitation events. Antecedent watershed conditions of snowpack, streams, and soils can modulate these impacts significantly. In addition, observations can help models verify that atmospheric and hydrologic processes are being simulated correctly when appropriate metrics are designed (see Section 6 and Section 7). When they are not, observations can help improve process-based understanding and the representation of these processes in models. This section describes the work that needs to be done to catalog and assess existing and planned monitoring programs, and it provides some specific recommendations that should be considered carefully in developing the Preliminary and Final Viability Assessments. Continuous integration with the modeling and forecasting portion of the project is required for success, as has been shown in FIRO projects in other watersheds.

3.1 Existing Surface and Atmospheric Observations

3.1.1 Existing Surface Observations

Geostationary Operational Environmental Satellite (GOES) telemetered gauging is the primary and preferred data delivery system for surface observations in the Yuba and Feather watersheds so that observations can be used in National Weather Service (NWS) forecasts and for other applications and end users. Another important data stream, which includes GOES telemetered gauges, is the California Data Exchange Center (CDEC). A total of 21 cooperators operate 245 stations within the Yuba and Feather watersheds, as shown in Table 3-1. The cooperative agreements include flood management, water and irrigation districts, hydropower generation, local government agencies, federal government agencies (U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and U.S. Geological Survey), forest management, and parks and recreation. South Feather Water and Power, Sutter County, Pacific Gas and Electric, Sierra Pacific Industries, and the Nevada Irrigation District are collecting other data, but the data are not always publicly available. The parameters being measured are not clear, and these agencies could be contacted for potential partnerships as these observations are almost certainly useful for Yuba-Feather FIRO objectives. There are several additional atmospheric observations that are not reported via GOES or to CDEC at this time, but are still usable by NWS through other avenues, such as the National Oceanic and Atmospheric Administration's Hydrometeorology Testbed (NOAA HMT) website and the Global Telecommunications System (GTS). There is an opportunity to improve existing surface observations r as part of the FIRO project.

Table 3-1. Summary of existing surface observations available for the Yuba and Feather watersheds. Station elevation ranges 43-8500 ft; data resolution ranges from 15 minutes to hourly.

Observation	Parameter and number of stations	Data available in near real-time	Notes
Rivers	Stage: 36 Storage (in acre-feet): 24 Discharge: 32	CDEC	

Observation	Parameter and number of stations	Data available in near real-time	Notes
Reservoir	Levels: 17 Storage: 24	CDEC	
Soils	Moisture: 4 node networks, 12 total sensors	Not available	UC Berkeley, working to transfer to CDEC via GOES
Snow	Snow water content: 69 Surveys: 43 Depth: 64	CDEC	
Precipitation	81	CDEC	
Surface Meteorology	Air Temp: 56 Rel. Humidity: 33 Solar Radiation: 19 Wind speed and direction: 25	CDEC	
Upper Atmosphere	temperature, moisture, pressure, winds	GTS	Radiosondes released twice daily; relevant locations are Reno and Oakland
Lower/Upper Atmosphere	winds, total precipitable water	NOAA HMT	Atmospheric River Observatories; in Thermalito and along the California coast
Snow Level	1 radar in watershed; several others nearby	NOAA HMT	

3.1.2 Central Sierra Snow Lab

The UC Berkeley Central Sierra Snow Laboratory (CSSL) is the principal research grade study location, on Forest Service land in the Yuba River basin. It has 70 years of snow depth and snow water content data, daily observations from 1971 to present, and other measurements such as precipitation, soil moisture, lysimeter, and more. In 2019, the CSSL went through a change in staffing that caused interruptions in measurements, but as of early 2021, it has found a solution to restart the manual measurements to keep the period of record to present. The University of Nevada Reno will deploy a disdrometer and continuous snow temperature profiler at the Central Sierra Snow Laboratory for monitoring starting water year (WY) 2021. The CSSL is also an ideal location to test different measurement technologies.

3.1.3 Decision Support

The monitoring described above supports decisions pertaining to flood management, water supply forecasting and planning, hydropower planning, and ecological sustainability, including forest management. Data are used for climate change studies and applied to environmental studies for California Environmental Quality Act Environmental Impact Reports. Water availability and historical reservoir levels are also used in new policy and legislation like the Sustainable Groundwater

Management Act and California Water Fix (now the Delta Conveyance). On a local government level, the data are also used to drive policy decisions such as water pricing changes and water restrictions for citizens.

Research activities range from short-term studies to long-term historical record building. Relevant examples that should be explored for potential FIRO partnerships include the South Yuba River Citizens League, which mainly researches forest health, meadow restoration, salmon restoration, and mine monitoring; Greg Pasternack's research team at UC Davis, which partners with Yuba Water to understand watershed hydrology, geomorphology, and ecohydraulics using stream observations; and the North Yuba Restoration Project. An effort should be made to comprehensively catalog other activities in the watershed for potential collaborations or leveraging opportunities.

3.2 Existing Remote Sensing Available in the Yuba and Feather Watersheds

3.2.1 Existing Remote Sensing

The Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat TM missions (Table 3-2) provide the majority of satellite remote sensing data in the Yuba-Feather watersheds. The MODIS-produced Normalized Difference Snow Index (NDSI) can be used to spatially estimate the fraction of snow-covered watershed and to estimate snow cover anomalies (e.g., Hatchett and McEvoy, 2018) due to the reasonably long period of record of MODIS data, which begins in 2002. The Landsat TM mission produces these data as well, though reduced temporal frequency increases the likelihood of cloud cover obscuring the landscape during an overpass.

A group led by Noah Molotch at the University of Colorado produces bimonthly, spatially distributed MODIS snow water equivalent (SWE) estimates (Schneider and Molotch, 2016; see also examples here). These reports are delivered to the Water Supply Forecasting Staff and State Climatologist in DWR's Hydrology and Flood Operations Office. Two other remote sensing-based experimental/research products exist for the Yuba-Feather watersheds: Xubin Zeng's (University of Arizona) SWE product and Steve Margulis' (UCLA) Landsat-derived SWE. While exceptionally valuable for retrospective research, neither of these are regularly updated, and are therefore of limited use for real-time operations. Other research-level satellite data include passive microwave estimates of snow surface melting and refreezing. Snow surface conditions are important controls on melt and melting events, and can be determined by relating satellite-observed surface brightness changes to air temperature changes and identifying deviations from a linear regression-based relationship between the two (Tuttle and Jacobs, 2019). Microwave instruments can be used to achieve relatively high spatial resolution (~5 km) estimates of melt, as well as to identify and study important hydrologic processes in snow-dominated mountains (Johnson et al., 2020).

The Soil Moisture Active Passive (SMAP) mission uses a radiometer to measure the amount of water in the surface soil every two to three days (Table 3-2). SMAP can also detect the physical state of the land surface as frozen or thawed. Landsat and MODIS retrieve wavelengths that can be used to calculate the normalized difference vegetation index (NDVI), and the U.S. Geological Survey uses MODIS data to calculate evapotranspiration. NDVI can be used as a surrogate for evaporation and many other vegetation properties (some of which require ground-truthed measurements), including leaf area index, biomass, plant productivity, and fractional vegetation cover. NDVI is often used as a metric to monitor plant health, especially in agricultural crops. Other calculations include the burned area index, land surface temperature, and enhanced vegetation index. The long periods of records of MODIS and Landsat allow for the production of climatological calculations and anomalies.

Table 3-2. Remote sensing available in the Yuba and Feather watersheds.

Satellite	Parameter	Resolution	Data Source	Notes
MODIS	SWE (derived), snow cover	every 2 days, 250m, 500m, 1km	climateengine.org; ftp://snowserver.colorado.edu/pub/fromLeanne/forCADWR/Near_Real_Time_Reports/; https://nsidc.org/data/modis/data_summaries#snow	produces NDSI (Riggs and Hall, 2016), and NDVI
Landsat		every 16 days, 30m	climateengine.org	produces NDSI (Riggs and Hall, 2016)
SMAP	soil moisture, temperature (frozen or thawed)	every 2–3 days	https://nsidc.org/data/smap/smap-data.html	

3.2.2 Airborne Observations

There are presently no Airborne Snow Observatory (ASO) flights in the Yuba-Feather watersheds to collect information on snowpack conditions. These observations will possibly begin in the coming years and will take place every month during the late winter and early spring. ASO data are acquired using lidar altimetry and a snow density model, and they provide information on snow depth, SWE, and snow albedo (Painter et al., 2016). Snow-free flights are required first as a baseline. These are currently available for the Feather River but not for the Yuba River. See Section 7.2.2 for more details.

3.2.3 Model Output Using Data Assimilation from Satellites and Airborne Observations

The National Operational Hydrologic Remote Sensing Center (NOHRSC) provides remotely sensed and simulated snow hydrologic products using the physically based, energy and mass balanced, multilayer, 1 km spatial resolution and hourly temporal resolution Snow Data Assimilation System (SNODAS) model. NOHRSC generates these products using all available airborne, satellite, and simulated snow information in the conterminous United States and Alaska. Outputs include a wide range of snow variables, including SWE, snow depth, snowpack temperatures, snow sublimation, snow evaporation, blowing snow estimates, modeled and observed snow information, airborne snow data, satellite snow cover, historic snow data, and time series for selected modeled snow products. SNODAS does have limitations and biases in high-elevation, complex terrain.

3.3 Existing Environmental Sensing

Management actions associated with FIRO on the Yuba and Feather Rivers could potentially impact Endangered Species Act (ESA)-listed fish species by altering the quantity and quality of the existing habitat. Key factors include (but are not limited to) flow, temperature, and turbidity. To effectively, dynamically, and rapidly evaluate the impacts of proposed operations, a series of decision support tools (DSTs) are needed to forecast each of these factors. Fortunately, there has already been an extensive amount of related research and monitoring on both the Yuba and Feather Rivers, including temperature monitoring in support of the Yuba River Development Program relicensing conducted by the River Management Team, which should substantially facilitate the development of useful DSTs (see Appendices 2 and 5). FIRO work should focus on evaluating the change in temperature, flow, and turbidity compared with baseline conditions associated with the preferred FIRO reservoir re-operation plan, computed via modeling studies, and the resultant change in environmental conditions based on the existing environmental monitoring sites and models. All these efforts should be explicitly coordinated with the U.S. Army Corps of Engineers to make sure that work conducted for the Preliminary Viability Assessment (PVA) will help support potential WCM updates.

3.4 FIRO Program Monitoring

This section describes efforts by the Center of Western Weather and Water Extremes (CW3E) scientists to install and operate new hydrometeorological instrumentation within the Yuba and Feather watersheds in the context of previous efforts to enhance monitoring completed by Forecast-Coordinated Operations (F-CO), as shown in Figure 3-1. The scientific goals of the FIRO instrumentation campaign are to observe and monitor the hydrometeorology of the watersheds during cool-season precipitation events, including those associated with atmospheric rivers (ARs). ARs bring large atmospheric moisture fluxes to the watershed and result in heavy precipitation, saturated soils, and high streamflow rates, such that they provide the majority of the annual inflows to the New Bullards Bar and Oroville reservoirs in the Yuba and Feather watersheds. Distributed atmospheric profiles, precipitation and soil moisture observations, and pre-installed streamflow measurements made by Yuba Water, the U.S. Geological Survey, and others (see Section 3.1) will help to quantify magnitudes and spatial variability during AR events. Continuous evaluation is necessary to determine if the additional instrumentation is sufficient to support monitoring needs for forecast improvement, as well as answer the research questions regarding atmospheric and hydrological processes. Due to the size of the Yuba and Feather watersheds and the lack of existing soil moisture measurements, it is anticipated that more stations will be required in order to achieve FIRO goals. Data from the installed sites should inform a future gap assessment and help to guide locations for additional installation requests. Installed sites also provide us with opportunities to educate citizens and build community partnerships in the watersheds. Beyond existing project partners, we have worked with private landowners, the Soper-Wheeler timber company, the U.S. Forest Service, with local universities (Feather River College and San Francisco State University), and with the local K-12 school district. This is an excellent opportunity to provide information on ongoing FIRO work and its benefit to the population in the watersheds.

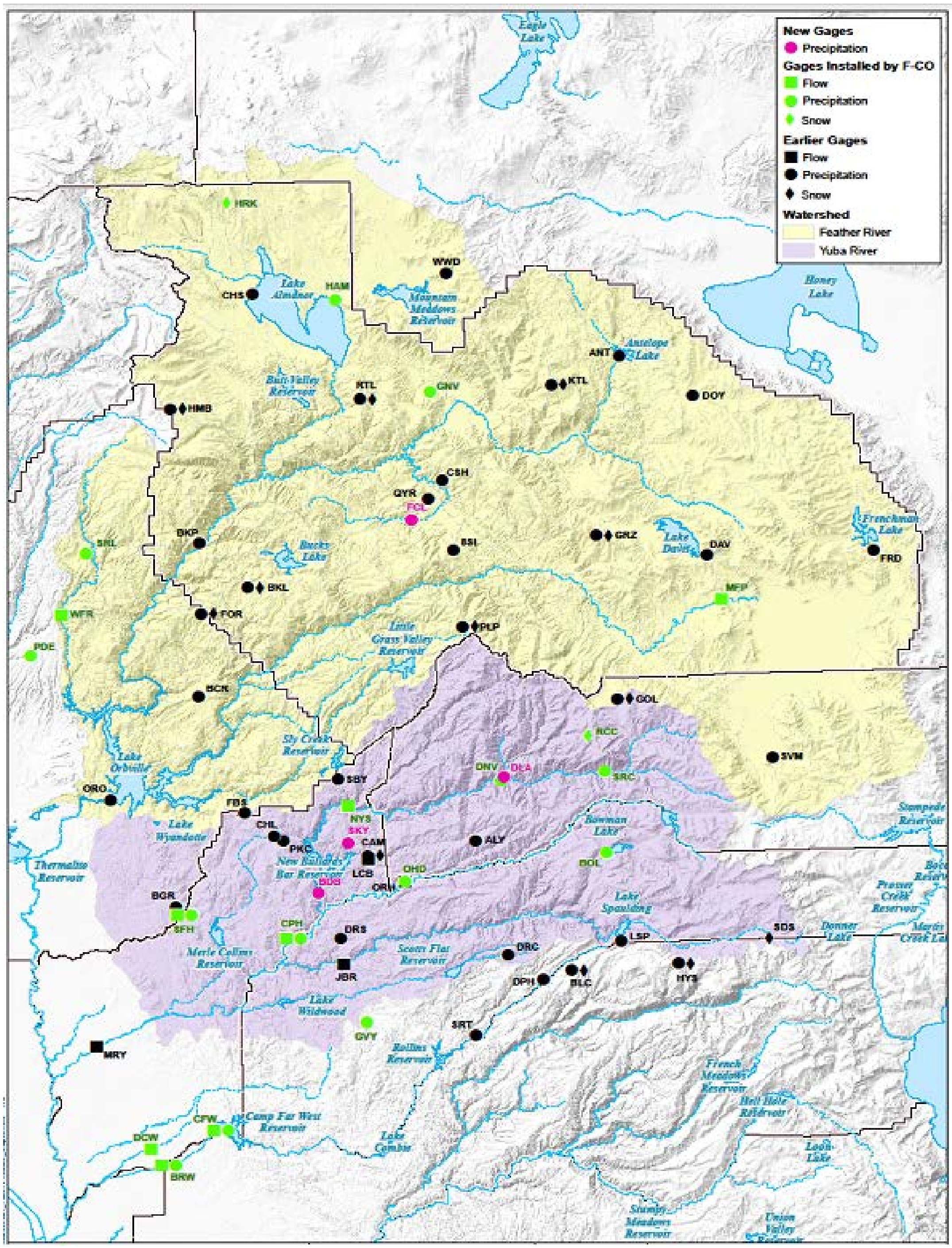

Figure 3-1. Yuba-Feather gaging stations (September 2020). Stations in pink were recently installed under FIRO Program and Stations in green were installed earlier by F-CO Program.

3.4.1 RadMet Sites

Equipment at these sites includes MicroRain Radars, optical PARSIVEL disdrometers, GPS-Met sensors, and a surface meteorology suite—including air temperature, humidity, pressure, winds, solar radiation, and precipitation. These sites provide near real-time data on hydrometeorological conditions within the watershed that will likely be of operational value to partners, including the NWS, that use vertically pointing radar sites extensively throughout California to understand snow levels and the proper partitioning of snow and rain at different locations throughout the watershed (see Section 6 and 7.1.3). These data will help us answer important research questions around physical processes in AR-driven precipitation in complex terrain. In particular, these data will improve understanding of the phenomenon of melting level bending near complex terrain. In the Yuba and Feather watersheds, this phenomenon is an important modulator of rain-snow partitioning. Currently, two RadMet stations observe watershed conditions (see Table 3-3). The data from RadMet stations are available via visualizations in near real-time on the CW3E website. The goal of this project is to make these data available at CDEC and wherever forecasters at the California Nevada River Forecast Center (CNRFC) and other weather service offices can most readily and easily access them. In addition, the products on the CW3E website will be modified in accordance with feedback from stakeholders. It will be essential to carefully analyze the data from this WY to determine if the additions are sufficient to support monitoring needs for forecast improvement, as well as answer the research questions regarding melting level bending. Moving this research forward is essential to accurately representing this process in numerical weather prediction models, thus also supporting forecast improvement.

3.4.2 Surface Meteorology and Soil Moisture Sites

Equipment at surface meteorology and soil moisture sites (dubbed “SMOIL” sites) contains a surface meteorology suite, including air temperature, humidity, pressure, winds, solar radiation, and precipitation, along with soil moisture and temperature at six depths beneath the ground (5, 10, 15, 20, 50, and 100 cm). SMOIL sites are used for several purposes. They provide near real-time, two-minute resolution data on hydrometeorological conditions (in particular, antecedent soil moisture conditions) within the watershed that will likely be of operational value to partners, including the NWS and Yuba Water. In addition, these data will help us answer important research questions around physical processes that modify runoff efficiency during heavy precipitation (see Section 6.5). Currently, four SMOIL stations observe watershed conditions (see Table 3-3). Four other stations are planned at this time, with finalized site locations for one station. The data from two of the SMOIL stations are available via visualizations in near real-time on the CW3E website, on the NOAA Earth System Research Laboratories Physical Sciences Division website, and at CDEC. The other two stations will have communication set up this WY. The goal of this project is to always make these data available at CDEC so forecasters at CNRFC and other weather service offices can readily and easily access them. In addition, the products on the CW3E website will be modified in accordance with feedback from stakeholders.

3.4.3 Radiosonde Site

Equipment at the radiosonde launch site (Table 3-3) includes a system to launch sensors measuring air temperature, moisture, pressure, and winds from the surface upwards into the atmosphere until signal is lost. This most frequently happens after the balloon pops and the sensor descends. These sites are used to collect high temporal resolution samples of the vertical profile of the atmosphere during ARs. They provide near real-time data of operational value and will help us answer important research questions around physical processes in AR-driven precipitation in complex terrain (see Section 6). In particular, these data will improve understanding of the phenomenon of melting level bending near complex terrain—in conjunction with the RADMet sites described in Section 3.4.1—by providing valuable data on the thermodynamic environment.

Currently, one available radiosonde launch location is set up in the Yuba River watershed (see Section 7) on Yuba Water Agency property in Marysville, California. When storms are sampled, data from the radiosonde launches are available via visualizations in near real-time on the CW3E website. Data are also sent directly to both a shared Google Drive folder that NWS Western Region Weather Forecast Offices can access and to the GTS. Providing the data via the GTS allows the radiosondes to be available for ingest into global numerical weather prediction models such as the GFS, the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Navy Global Environmental Model.

Permissions for a second site at a higher altitude above the New Bullards Bar Dam were also granted at the fire department in Camptonville, California. During the next WY, this site may be used for simultaneous releases along with the Marysville, California, site if storm conditions and uncertainties warrant two sites. The purpose for having two sites is to understand how the near-surface thermodynamics of storm systems evolve as they interact with complex terrain.

Table 3-3. FIRO observations.

Site Name (Code)	Site Type (Section)	Latitude (°)	Longitude (°)	Elevation (m)	Install Status
Skyline Harvest (SKY)	SMOIL (4.4.2)	39.47	-121.09	829	Installed, data available in near real-time
North Star Meadow (NSM)	SMOIL (4.4.2)	39.61	-121.07	1235	Installed, GOES communications to be set up
SFSU Sierra Nevada Field Campus Lower Bathhouse (LBH)	SMOIL (4.4.2)	39.62	-120.58	1680	Installed, communications to be set up, disdrometer to be added for precipitation phase since site has power
Browns Valley Elementary	SMOIL (4.4.2)	39.24	-121.41	70	Site agreement underway
Downieville (DLA)	RADMet (4.4.1)	39.56	-120.82	910	Installed, data available in near real-time
New Bullards Bar Dam (NBB)	RADMet (4.4.1)	39.40	-121.14	650	Installed, data available in near real-time
Feather River College (FRC)	SMOIL (4.4.2)	39.95	-120.97	1048	Installed, data available in near real-time
Graeagle	SMOIL (4.4.2)				Exact location TBD
Four Trees	SMOIL (4.4.2)				Likely install in Feather along with DWR instruments

Site Name (Code)	Site Type (Section)	Latitude (°)	Longitude (°)	Elevation (m)	Install Status
Kettle Rock	SMOIL (4.4.2)				Possible install in Feather along with DWR instruments
Marysville (YUB)	Radiosonde (4.4.3)	39.22	-121.48	34	No storms sampled WY 2020

3.5 Recommendations for Enhancements and Supplementation

The recommendations in this section are categorized as follows: 1) data access, 2) enhancement or maintenance of existing sensors, and 3) new stations or sensor networks. It will be essential to integrate with the other work groups, including meteorology, hydrology, and streamflow forecast requirements, as their work is being conducted in support of the Preliminary and Final Viability Assessments. Observations should continually be evaluated to ensure they are sufficient to support modeling and forecasting, and space should be left to add new observations as the modeling and forecasting groups identify gaps.

3.5.1 Data Access

To meet FIRO objectives, all data should be available via GOES and/or on CDEC in near real-time, including data from long-term sites such as Cooperative Observers. The minimum requirement is to have data available on some platforms in near real-time. One key component of FIRO is using state-of-the-art weather forecasting and watershed monitoring. Forecasters at CNRFC will have ready access to collected data if they are available via GOES and/or at CDEC. A high time resolution (e.g., 15-minute, or as needed by models and forecasters) is preferred. Also, access to data on groundwater should be assessed for potential gaps and areas for improvement. This should be done in collaboration with CNRFC, as it is performing upgrades in this area. During the effort to add monitoring sites for Yuba-Feather FIRO, CW3E connected with the Plumas Corporation through partners at the Feather River College site; this consulting firm has extensive experience in the Feather River, and this project could leverage their expertise on groundwater data during meadow restoration projects—perhaps by seeking their recommendations. Other existing partnerships made during the F-CO project and by Yuba Water Agency and other project participants should be explored for coordination prospects as well.

3.5.1.1 Data Reliability

The PVA should include an assessment of the reliability of the data transmission network, particularly to assess whether there is a potential to lose near real-time data transmission or collection during large storms or other conditions. If this is a possibility, backups should be explored.

3.5.2 Enhancement or Maintenance of Existing Sensors

A wide variety of sensor networks have been installed in the Yuba and Feather River basins. We recommend continuing to maintain these sensors as the longer-term a record is, the more valuable it is for climate studies and other applications. We also recommend thoroughly evaluating large shifts in pool elevation at some reservoirs within the Feather River basin and taking steps necessary to ensure the accuracy of inflow calculations. We have also developed recommendations for enhancing existing sites by adding instrumentation. Soil moisture should be added to all snow sites, including snow pillows and snow courses. Snow depth sensors should be installed over the snow pillows. All-weather precipitation gauges should be added to all sites in the basin; currently, many sites can only handle liquid precipitation. These measurements are crucial to understanding the onset and evolution of the snowpack, answering the FIRO research questions outlined in Section 6 and Section 7, and supporting the forecasts described in Section 5.

3.5.3 New Stations or Sensor Networks

Recommendations on new observations include adding more soil moisture stations throughout the basins, including areas without a high density of observations (e.g., in the western portion of the Middle Fork of the Feather River), to provide valuable information on antecedent soil conditions.

Additional stream gauges are also recommended, with sites selected in collaboration with Yuba Water and other partners. Dry Creek in the Yuba basin has already been identified as an information gap, and the only flow measured is that released from the dam (see Section 5). This location is important as it adds unregulated flow to that observed at Marysville, which is a control point for reservoir operations.

We strongly recommend that the ASO flights described in Sections 3.2.3 and 7.2.2 be carried out as soon as feasible; specifically, this will allow for the understanding of SWE at higher resolution throughout the watersheds. One exercise that could be beneficial for the PVA is to quantify the potential benefits of ASO flights as a part of a comprehensive observing strategy for SWE and snowpack generally.

Other options should be explored in conjunction with ASO efforts. These may include assessing the representativeness of nearby snow telemetry (SNOTEL), using SWE reanalysis from UCLA or the University of Arizona, developing strategies to better use information from monthly snow courses, or upgrading existing snow sites. The PVA should explore the capability of soil moisture and temperature observations to provide binary information on whether there is snow cover (e.g., Flint et al., 2008; ongoing projects led by researchers at Scripps Institution of Oceanography, University of Nevada Reno, and others). In addition, support should continue for extracting information from microwave sensors. Integrating remote and in situ measurements is essential to understanding the snowpack at the watershed scale.

In addition, we recommend developing methodologies for sensing snow wetness. Much of the existing instrumentation measures snow in storage and as snow cover, which addresses how much snow water is currently at high elevations. FIRO, with its underlying flood hazard concerns, needs to understand the potential for snowmelt, which heavily depends on snow wetness in the context of rain-on-snow, readiness to rapid-melt, and capacity to absorb rain where it falls. Storm-time melt (e.g., rain-on-snow, non-rain heat deposition that melts) is of considerable concern, and existing networks need to be reinterpreted and eventually augmented in that context.

Options that should be further researched to observe snow wetness include satellite-based microwave sensing options (e.g., Naderpour and Schwank, 2018). A non-satellite option may include new applications of the GPS receivers (e.g., as discussed by Koch et al., 2014). Eddy covariance towers should also be considered and designed specifically to estimate net turbulent heat transfers to/from the snow surface, therefore monitoring potential storm-time melt events in real time. These can be run during long snowy winters, and a few should be carefully sited above the seasonal snowline. Additionally, in order to monitor where and when storms either rain or melt snow at high altitudes—and specifically which areas contribute to flooding downstream—we recommend deploying a fleet of low-cost, stream-stage loggers and nearby air temperature and humidity loggers in and near large and most medium-small streams in the high country. Actual discharge measurements only need to be made at a subset of these locations to allow for the eventual development of rating curves.

For water balance purposes, most of the loggers will provide indirect information (e.g., when the melt starts and when snowmelt contributions effectively cease). During warm storms, they can inform reservoir operators of which high-altitude streams are experiencing rising waters during the storms, and which are not. The air temperature and humidity loggers can help determine where rain fell and where the streams received rainfall runoff. A similar setup of low-cost loggers should be considered for snowpack. An evaluation of different options should be conducted in collaboration with modeling and forecasting work groups. In our recommendation, the most effective monitoring to support FIRO goals in the Yuba and Feather watersheds' highly variable mountain settings will include network building that is structured with a core of a few high-end monitoring stations, surrounded by an order-of-magnitude cheaper, less precise monitors to provide information about spatial variability that the high-end network cannot (e.g., Bales et al., 2006).

Last, the PVA should also provide an explicit assessment of the efficacy of current monitoring and strive to fill gaps.

3.6 References

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Section 4— Catalog and Review of Existing Models

This section presents an overview of the models used in the Yuba-Feather watersheds that may be applied in the Primary Viability Assessment. Table 4-1 provides an overview of these models and their anticipated application in the process. More detailed descriptions of the models can be found in Appendix 4. Additionally, related models that could be useful in National Environmental Policy Act and California Environmental Quality Act reviews associated with the Water Control Manual update are also included in Appendix 4. The Forecast Informed Reservoir Operations team will consider and leverage available models while exploring and resolving this study's questions.

Table 4-1. Hydrologic and hydraulic models used in the Yuba-Feather watersheds.

Model (Source)	Purpose	Location	Agency	Model Category	Application to FIRO/PVA
Yuba River Development Project Daily Operations Model	Planning and decision support operational model	Lower Yuba River	Yuba Water	Hydrologic / Power generation	Evaluation of Water Control Plan (WCP) alternatives impacts
Yuba River HEC-RAS 2D	2D fixed grid flood inundation mapping model	Lower Yuba River	Yuba Water	Hydraulic	May or may not need depending on level of discrimination determined later
Yuba River 2D Hydrodynamic Model (TUFLOW HPC)	2D fixed grid model that simulates hydraulic conditions over a broad range of flows	Lower Yuba River	Yuba Water	Hydraulic	May or may not need depending on level of discrimination determined later
Feather River HEC-RAS 2D	2D fixed grid flood inundation mapping model	Lower Feather River	DWR	Hydraulic	May or may not need depending on level of discrimination determined later
F-CO ResSim	F-CO of Oroville and New Bullards Bar reservoirs	Yuba River, Feather River	DWR and Yuba Water	Hydrologic	Provides all the operational constraints and physical constraints for boundary conditions for alternatives

Model (Source)	Purpose	Location	Agency	Model Category	Application to FIRO/PVA
CalSim II	CVP/SWP planning model	Lower Feather River, Sacramento River, San Joaquin River Delta, south of Delta	USBR/DWR	Hydrologic	Impacts analysis; assesses whether WCP alternative has a negative impact on Sacramento–San Joaquin system
LTGEN and SWP Power (companion to CalSim II)	CVP and SWP power generation and pumping models	CVP/SWP system	USBR/DWR	Power generation	Secondar Impacts analysis
CHPS: Community Hydrologic Prediction System	NOAA's CNRFC model	California, Nevada	NOAA/NWS/ CNRFC	Hydrologic	Generates streamflow hindcasts for analysis that are consistent with operational streamflow
CWMS: Corps Water Management System	Interface that allows the use of multiple USACE models (e.g., HEC-RAS, HEC-ResSim)	USACE (SPK) reservoirs and flood control space in non-USACE reservoirs	USACE	Hydrologic	Components used
CalSim II	CVP/SWP planning model	Lower Feather River, Sacramento River, San Joaquin River Delta, south of Delta	USBR/DWR	Hydrologic	Impacts analysis; assesses whether WCP alternative has a negative impact on Sacramento–San Joaquin system

Table 4-2. Numerical Weather Prediction Models

Model	Location	Agency	Application to FIRO/F-CO	For details on model, see:
ECMWF-IFS	Global	ECMWF	Major global NWP model used by weather forecasters to produce QPF	https://www.ecmwf.int/en/publications/ifs-documentation
GEFS	Global	NOAA NCEP	Major global NWP model used by weather forecasters to produce QPF	https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php
WWRF	Western U.S. and Northeast Pacific	CW3E	High resolution research model tailored for ARs to support improved western weather prediction	https://cw3e.ucsd.edu/west-wrf/
HRRR	Continental U.S.	NOAA NCEP	Major high resolution continental US model used by weather forecasters	https://rapidrefresh.noaa.gov/hrrr/

Section 5— Current Streamflow Forecasts and Anticipated Requirements

This section addresses the assessment of streamflow forecasts needed to manage Forecast Informed Reservoir Operations (FIRO) at New Bullards Bar and Oroville Reservoirs primarily during large flood events in winter, while considering reservoir refill operations related to seasonal background watershed conditions.

This section will investigate supporting questions to inform FIRO alternatives, including:

- What streamflow forecasts are currently available for reservoir operations decision support?
- What are the flood risk management objectives for the basin and how are they currently managed?
- What are the potential areas of improvements in both forecasts and decision support tools?

5.1 Current Streamflow Forecasts

5.1.1 CNRFC's Community Hydrologic Forecasting System

The California Nevada River Forecast Center (CNRFC) uses a suite of state-of-the-art programs to compute current and future streamflows for the Yuba and Feather River watersheds shown in Figure 5-1. The CNRFC utilizes the National Weather Service (NWS) Sacramento Soil Moisture Accounting Model (SAC-SMA) coupled with a snow model (SNOW-17) to compute streamflows at various locations within the Yuba-Feather system. To properly represent the entire system, the CNRFC model also includes existing release decisions by the responsible agencies.

Figure 5-1. Forecast-Coordinated Operations Decision Support System model input and output schematic.

The Community Hydrologic Prediction System (CHPS) provides the framework for running these rainfall-runoff models. Operationally, each sub-basin is forced with unique precipitation, temperature, and freezing level information, resulting in continual tracking of current soil moisture, snow water equivalent (SWE), runoff, and other watershed states for every sub-basin. Runoff from upstream basins is routed downstream and added to runoff from sub-basins farther downstream using a variable LAG/K hydrologic routing routine. The CHPS also uses the NWS RES-SNGL (Single Reservoir Regulation) reservoir routing program to account for regulation by upstream reservoirs. The single value forecasts (deterministic) are forced with 10 days of observed and six days of future precipitation, temperature, and freezing levels.

The CHPS also produces hourly ensemble streamflow forecasts (39 ensemble members) using the Hydrologic Ensemble Forecast Service (HEFS). HEFS forecasts extend out a full year and include short-term weather model uncertainty within the first 15 days, and long-range climatological uncertainty extending from day 16 out to day 365. The short-term precipitation uncertainty is based on two different sources. The first three days are based on uncertainty from the CNRFC Quantitative Precipitation Forecast (QPF), and days four through 15 from the mean of the GEFS. The short-term temperature uncertainty is based solely on the GEFS for the first 15 days. The long-range climatology uncertainty extending from day 16 through day 365 is currently represented by historical precipitation and temperature from 1980–2019. Long-range products going out a full year are available on a daily time step and are issued every morning. Fifteen-day hourly time step HEFS streamflow products are available every time a single value forecast is issued. During the wet season, this is at least twice a day—once in the morning and afternoon. During flood events, hourly HEFS forecasts can be produced as often as every six hours. The HEFS streamflow forecasts are initiated with the same model antecedent conditions as the single value forecasts.

5.1.2 Streamflow Forecasts for Oroville Dam and the Feather River

Lake Oroville captures all branches of the Feather River and its tributaries and has 750,000 acre-feet (ac-ft) of flood control space. Lake Oroville's Water Control Manual (WCM) provides a set of guiding criteria for how the reservoir is operated to balance its congressionally authorized purposes. The WCM details the reservoir's upstream watershed conditions, downstream conditions and capacities, general operation, stakeholder coordination, flood control design, flood operation, and operational instructions to follow during emergency situations. Figure 5-2 provides a schematic of the Feather River system.

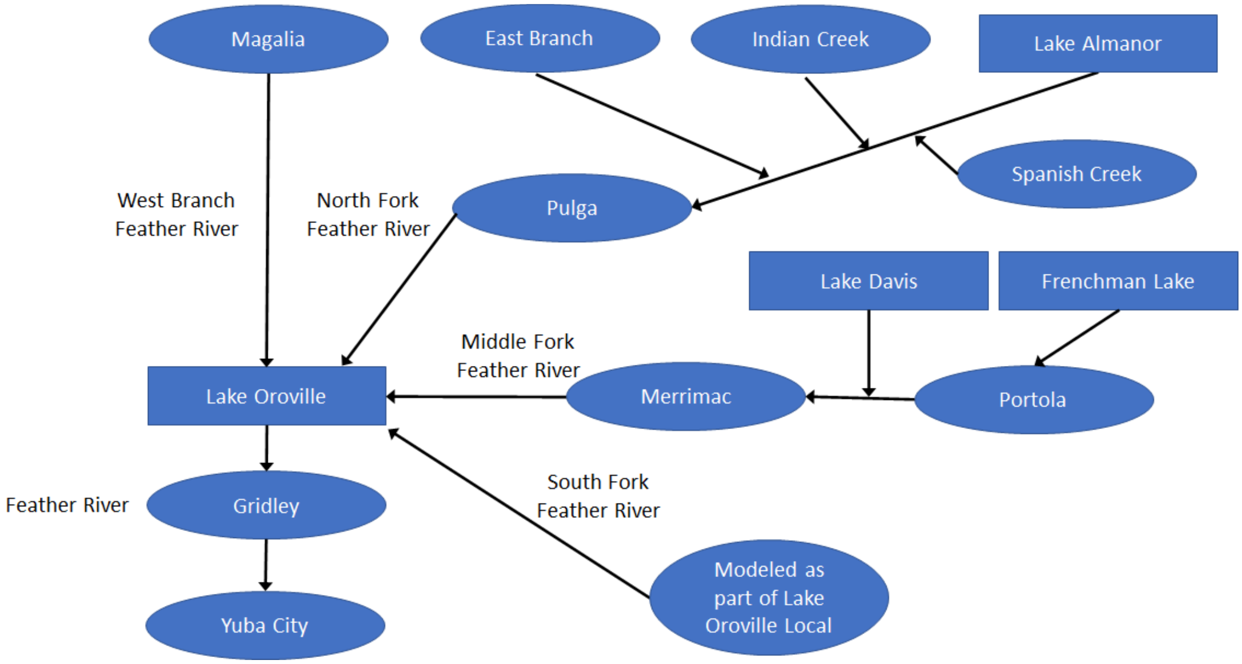

Figure 5-2. CNRFC CHPS model schematic of Feather River.

5.1.3 Streamflow Forecasts for New Bullards Bar Dam and the Yuba River

New Bullards Bar Reservoir is located on the North Yuba River and has 170,000 ac-ft of dedicated flood control space. The Middle and South Yuba Rivers downstream of the dam are essentially unregulated and can contribute to a large percentage (~50 percent) of the flood flows measured at Smartsville below Englebright Lake. In addition, smaller tributaries of Deer Creek and Dry Creek add to the percentage of unregulated flow (10 to 15 percent of total flood flows) observed at Marysville near the confluence of the Yuba and Feather Rivers.

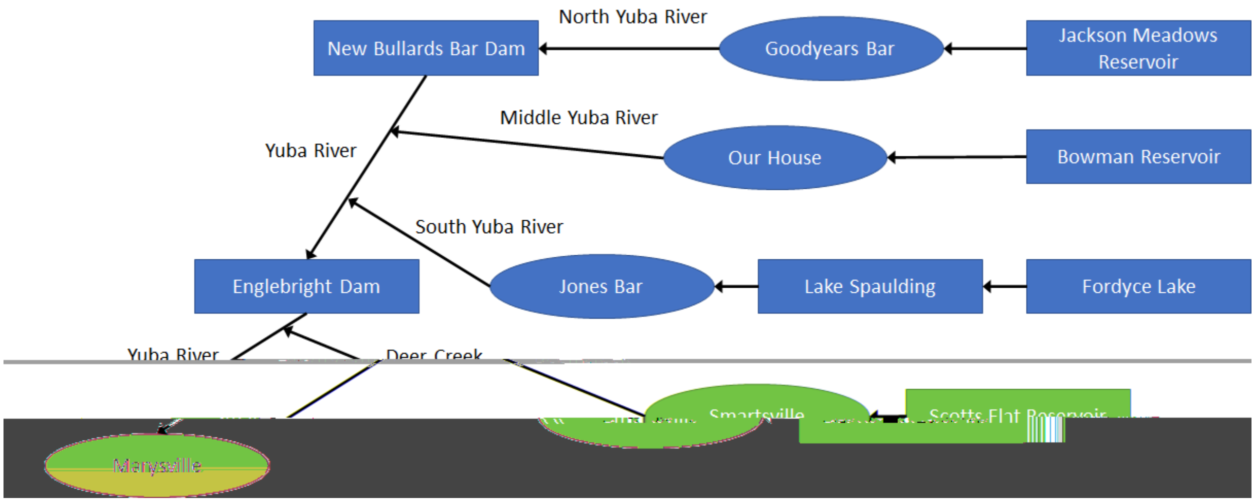

Figure 5-3. CNRFC CHPS model schematic of Yuba River.

5.1.4 Streamflow Forecasts Below the Confluence of the Feather and Yuba Rivers

Additional modeling and forecasting is needed to project the impacts of the Oroville and New Bullards Bar reservoir releases on stages below the confluence of the Feather and Yuba rivers. This includes more complex routing that considers the effects of backwater, as well as the introduction of flows from the Bear River system. Figure 5-4 shows the model topology supported in the CNRFC's CHPS model.

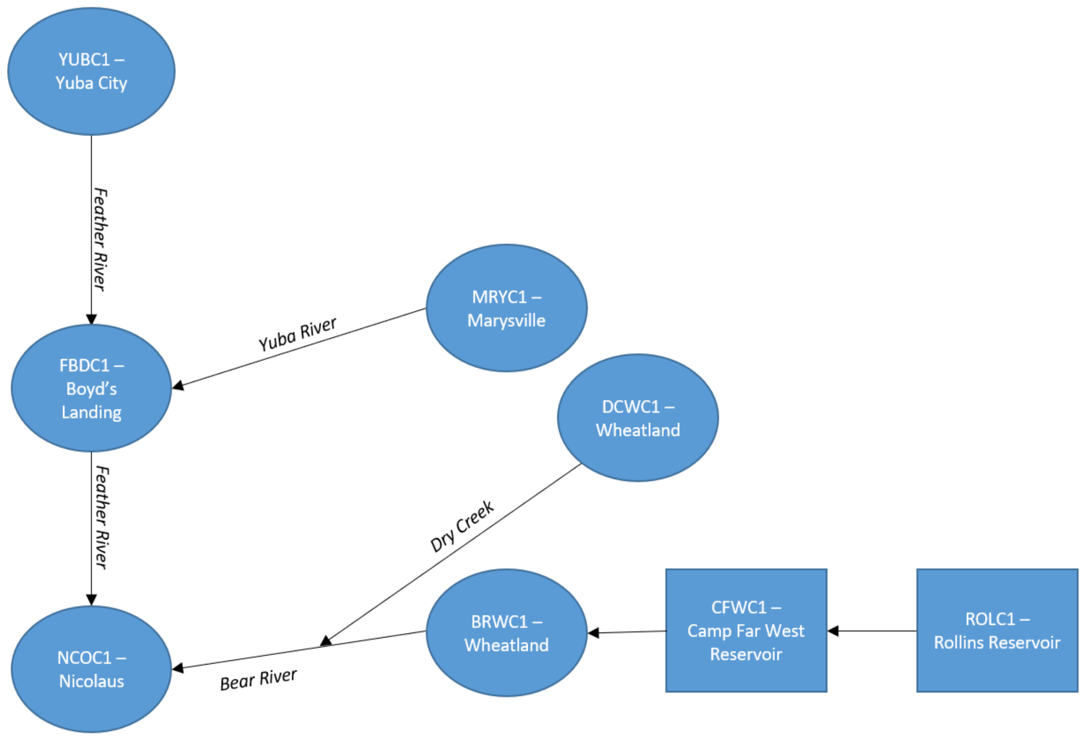

Figure 5-4 CNRFC CHIPS model schematic of the Feather River System below the confluence with the Yuba River.

5.2 Flood Risk Management Objectives

5.2.1 Objective Flows

Water managers at the Sacramento District of the U.S. Army Corps of Engineers (USACE), Yuba Water, and the California Department of Water Resources (DWR) State Water Project (SWP) make decisions about the operation of New Bullards Bar Reservoir and Lake Oroville. Water managers receive forecasts of inflows and downstream flows from the CNRFC and DWR and use this information along with information from other sources to make decisions about releases. The operating agencies consider their mission, public safety, customer needs, upper watershed conditions, downstream conditions, and the current state of their reservoirs when making release decisions. Those decisions include current operation (how much to release immediately) and future operations (how much to release in the future if the forecasts are correct or incorrect).

Objective flows for the Yuba-Feather system have been established in consideration of downstream channel capacities and levee safety guidelines. The Oroville and New Bullards Bar WCMs specify the following streamflow targets:

- 180,000 cfs for Feather River at Yuba City with 120,000 cfs for Yuba River at Marysville. Corps approval is needed to exceed these limits.
- 300,000 cfs for Feather River downstream of the confluence with Yuba River.
- 320,000 cfs on the main stem of Feather River downstream of Bear River (i.e., the Feather River near Nicolaus).

5.2.2 The unconstructed Marysville Reservoir

The proposed Marysville Reservoir was designed to operate in coordination with New Bullards Bar Reservoir and Lake Oroville and, if constructed, would have 260,000 ac-ft of flood control space (determined to be required for adequate flood control in the region during the 1960s). This flood storage would have regulated roughly 64 percent of the region for the Yuba River basin, and the lack of the reservoir has strained the Yuba-Feather Rivers system ability to maintain system flow constraints during flood events.

5.2.3 Forecast-Coordinated Operations

To ensure coordination between reservoir water managers and minimize downstream risk in the Yuba-Feather region during large events, a partnership project called Forecast-Coordinated Operations (F-CO) was initiated in 2005. The F-CO Program involves real-time coordination of reservoir operations and improved communications among operating entities in a flood emergency response for the Yuba and Feather Rivers. Mitigating flood potential involves a common operating environment for the coordination of releases based on enhanced observations and improved streamflow forecasts to minimize the chance of exceeding channel capacity and increase warning time to pertinent communities.

For the F-CO Program, several key agencies have imperative roles when anticipating a high-water event (i.e., AR4 or higher). In addition to providing agency coordination, the program has developed a Decision Support System (DSS) as a centralized data and common modeling framework for F-CO during normal conditions and storm events. The DSS is housed on DWR's California Data Exchange Center (CDEC) and has two general features for reservoir water managers, forecasters, and regulatory agencies:

1) Entering release changes that are transmitted to CNRFC operations.
2) Performing reservoir simulations using HEC-ResSim to aid in decision-making.

HEC-ResSim model inputs include inflow into two reservoirs (Oroville and New Bullards Bar), local flow contributions for three locations (Feather River at Yuba City, Yuba River at Englebright, and Yuba River at Marysville), and flow contributions from Bear River (Dry Creek near Wheatland and the Camp Far West outflow). The F-CO DSS reservoir model directly ingests the seven input files for forecasted flow from the CNRFC, while the CNRFC CHPS model considers forecasts of headwater influence and sums them specifically for the boundary conditions in the F-CO DSS (Figure 5-5).

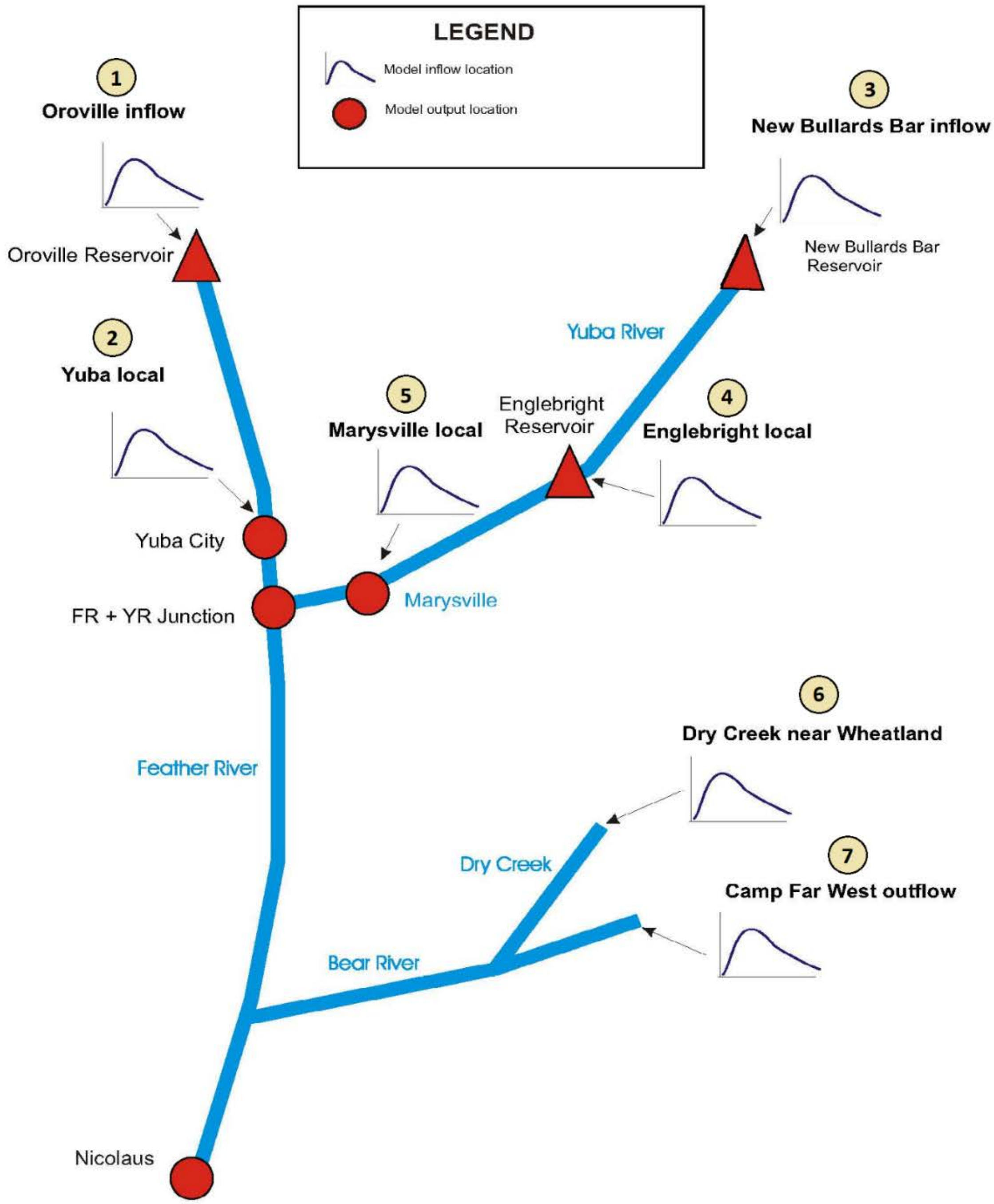

Figure 5-5. HEC-ResSim boundary conditions and topology used in F-CO DSS.

Table 5-1 summarizes the differences in the CNRFC CHPS and F-CO DSS topology. The upstream forecast points that are modeled in CNRFC CHPS are aggregated together and directly ingested into the HEC-ResSim model for the F-CO DSS. Within the F-CO DSS, local flows are an aggregate of contributing flows between two control points. For example, the Yuba Local point accounts for the additional flows between Oroville and Feather River at Yuba City. Likewise, Marysville Local accounts for the additional flows between Englebright and Yuba River at Marysville. Englebright Local represents the flows from the Middle and South Forks of the Yuba River.

Table 5-1. Summary of differences in CNRFC CHPS and F-CO DSS topology.

F-CO DSS Boundary Conditions*	CNRFC CHPS Upstream Forecast Points	CNRFC Aggregated Forecast Ingested into F-CO DSS
1 **Oroville Inflow**	1. PLGC1: North Fork Feather River at Pulga 2. WBGC1: West Branch Feather River at Magalia 3. MRMC1: Middle Fork Feather River at Merrimac	**PLGC1 + MRMC1 + WBGC1 + ORDC1 Local Flow**
2 **Yuba City Local Flow**	1. GRIC1: Feather River at Gridley	**GRIC1 Local Flow + YUBC1 Local Flow** Note: Oroville outflow is simulated with HEC-ResSim (therefore not included in the provided Yuba City Local)
3 **New Bullards Bar Inflow**	1. GYRC1: North Fork Yuba River at Goodyears Bar	**GYRC1 + Modeled Contributing Creeks**
4 **Englebright** **Local Flow**	1. NBBC1: Outflow from New Bullards Bar 2. OURC1: Middle Fork Yuba River at Our House 3. JNSC1: South Fork Yuba River at Jones Bar 4. HLEC1 Local: Englebright ungauged local flow downstream of NBBC1, JNSC1, and OURC1	**OURC1 + JNSC1 + HLEC1 Local Flow** Note: New Bullards Bar outflow is simulated with HEC-ResSim (therefore not included in Englebright Local)
5 **Marysville** **Local Flow**	1. HLEC1: Outflow from Englebright 2. DMCC1: Dry Creek at Merle Collins 3. DCSC1: Deer Creek at Smartsville	**DMCC1 + DCSC1 + MRYC1 Local Flow** Note: Englebright outflow is simulated with HEC-ResSim (therefore not included in the provided Marysville Local)
6 **Dry Creek Near Wheatland**	1. DCWC1: Modeled forecasted flow for Dry Creek near Wheatland	**DCWC1**
7 **Camp Far West Outflow**	1. CFWC1: CNRFC modeled outflow for Camp Far West on Bear River	**CFWC1 Outflow**

* Numbered based on Figure 5-5.

During high-water events, CNRFC and DWR forecasters issue streamflow forecasts (if on 24-hour shifts, they issue forecasts every six hours starting at 3 a.m.), which are directly ingested into the DSS with a five-day forecast time horizon. Water managers are advised to enter release changes as soon as possible, because they are ingested into the forecast itself. Any one of the F-CO Program partners may initiate coordination calls. The DWR Reservoir Coordinated Operations Section works with CDEC on any DSS issues and helps facilitate operator coordination calls. USACE regularly engages with SWP and Yuba Water managers during this time to ensure compliance with written regulations. If release coordination is needed due to any forecasted control points above the target flows, water managers can run simulations and commit to a flood release schedule in the DSS. USACE can then view the results of the proposed operation and approve a deviation from the Water Control Plan if needed. The DWR Flood Operations Center makes necessary notifications to local communities for forecast points exceeding stage thresholds.

In addition, reservoir water managers can "pressure test" their proposed release strategy using the ensemble forecast. These simulation results give the operator an estimate of the probability of exceeding critical storage thresholds and downstream flow targets given their release selection and the forecast watershed response. As shown in Figure 5-6, the DSS presents the results in box and whisker plots and in tabular form, showing the number of ensemble traces exceeding any critical thresholds at the reservoir or target flows downstream.

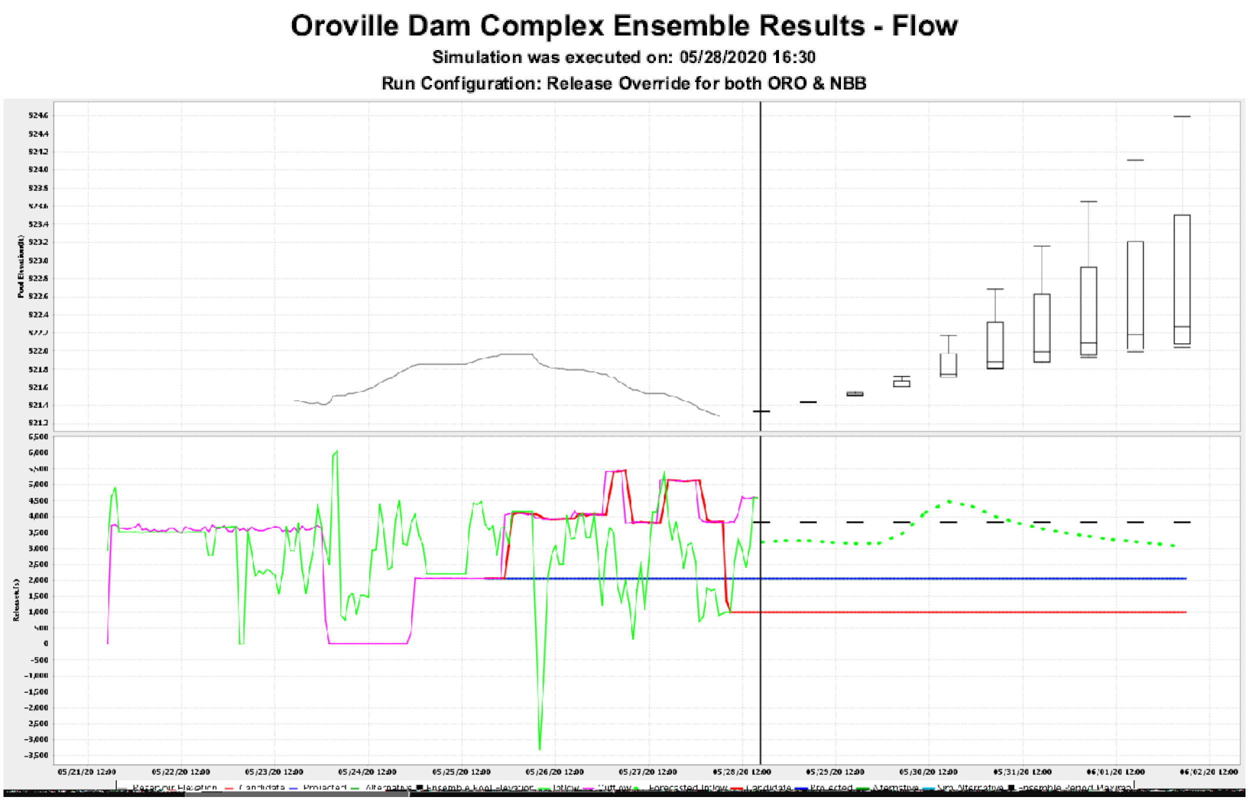

Figure 5-6. F-CO DSS results from an ensemble simulation displaying box plots to represent the ensemble traces.

5.3 Spring Reservoir Refill Operations

Improved quality, timing, and coordination of seasonal runoff forecasts will support flood management decision-making for water supply considerations after events. Proposed analyses are intended to support the spring refill analysis of flood control diagram updates as part of the WCM update process at Oroville and New Bullards Bar.

Yuba-Feather FIRO intends to investigate how improved seasonal forecasts can provide additional insight into information that helps water managers make better pre-release decisions before a forecasted flood event and in response to the subsequent water supply impacts in the spring. Existing background watershed conditions such as snowpack, soil moisture, and upper reservoir storage conditions can influence decisions on water management after flood events.

The DWR publishes Bulletin 120 (B-120) four times a year in the second week of February, March, April, and May. B-120 contains forecasts of the volume of seasonal runoff from California's major watersheds and summaries of precipitation, snowpack, reservoir storage, and runoff in various regions of the state. The CNRFC issues April–July runoff forecasts that are updated daily through the CHPS model. Figure 5-7 shows an example CNRFC runoff forecast product.

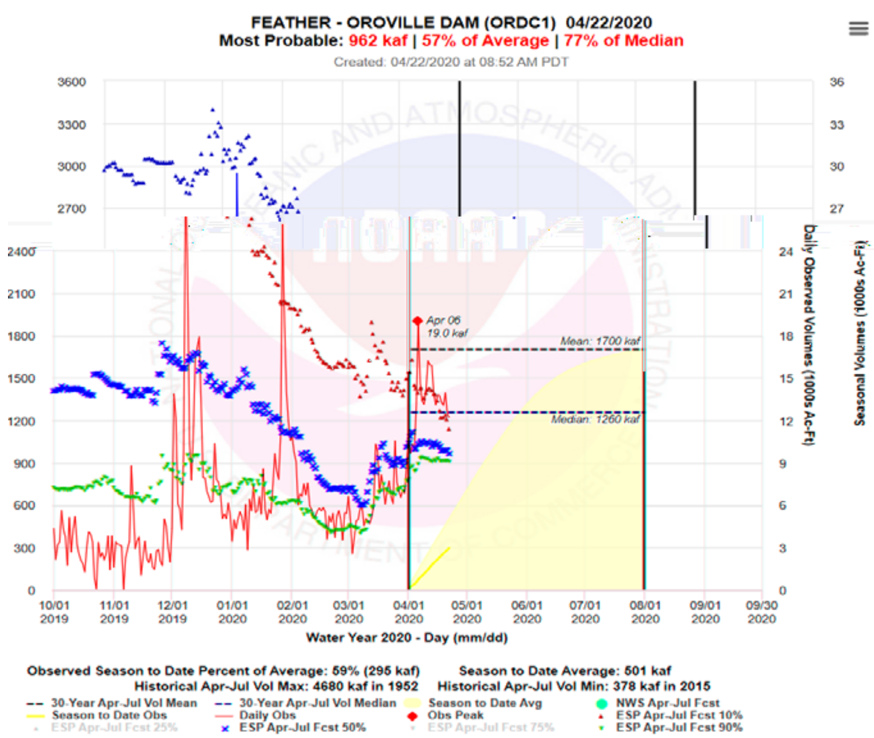

Figure 5-7. CNRFC Lake Oroville April–July seasonal observed and ensemble forecast runoff.

The CNRFC and DWR B-120 forecasts have direct operational impacts on water manager decision-making. Seasonal runoff forecasts support various project operations for each water manager, including snowmelt and reservoir management, water supply deliveries, environmental compliance, and hydroelectric generation.

As part of Revised Decision 1644, the Yuba Accord established fisheries seasonal flow requirements based on the DWR B-120 Yuba River watershed runoff forecasts, mandating the calculation of North Yuba Index minimum instream flow requirements at Marysville and Smartsville gaging stations on the lower Yuba River. Additionally, at the SWP, the ability to meet water demands depends in part on the operation of Lake Oroville. The balance between flood protection, water supply, and downstream flow and water quality requirements are key aspects of release decisions in the spring.

5.4 Potential for Streamflow Forecast and Decision Support Tool Improvements

5.4.1 Streamflow Forecast Skill and Reliability Improvements

5.4.1.1 Establishing Metrics and Baseline Forecast Streamflow Skill

The first step toward improving streamflow forecasts involves establishing the baseline. To establish baseline forecast skill and evaluate improvements over time, we recommend establishing key metrics and assessing the forecast inflows to Lake Oroville and New Bullards Bar Reservoir, as well as all downstream locals needed for reservoir release decision-making. Specific forecasts would include five-day single value and 15-day ensemble products. Ensemble streamflow verification should be based on the newer GEFSv12 forcings. In addition to informing FIRO alternatives, this information will directly support baseline assessments within the Oroville and New Bullards Bar WCM update process.

5.4.1.2 Opportunities for Streamflow Forecast Skill Improvement

While the modeling system that generates operational forecasts is well established, well supported, and reliable, several important opportunities for improvement remain, including:

- Better leveraging of observational investments,
- Explicit modeling of freezing level uncertainty
- Explicit modeling of hydrologic model uncertainty
- Improved snowmelt modeling under extreme atmospheric river (AR) conditions
- Improved recession limb forecasts.

In addition, more general improvements in the methods used to generate the ensemble meteorologic forcings for HEFS have the potential to improve the skill and sharpness of the ensemble streamflow forecasts.

Improved leveraging of observational investments includes assimilating soil moisture observations into hydrologic forecast models to better assess the readiness of the watershed to respond to forecast storm events. This is particularly important when conditions “dry out” for a multi-week period in the middle of the winter flood season. For those observations that the forecast modeling process cannot directly include, ancillary decision support materials can be developed to aid forecasters and improve situational awareness.

The Yuba-Feather watersheds drainage area has an elevation range from the Central Valley (near sea level) to the Sierra crest (8,000+ ft). During storm events, it is critical to have precipitation and freezing level profile inputs into the CNRFC models that produce streamflow forecast hydrographs at various geographic locations for the Yuba-Feather watersheds to inform release decisions. Understanding the uncertainty in runoff forecasts associated with the freezing elevation transitions during the storm event can help inform release decisions that mitigate downstream fluctuations and associated damage. Freezing level uncertainty is currently not a part of the HEFS streamflow products. We recommend that the NWS engage in a collaborative process to add freezing level to the functionality of the Meteorological Ensemble Forecast Processor (MEFP). Additionally, a shift should be made from the traditional maximum/minimum temperature observations to six-hour values, as assumptions about the diurnal pattern of problematic temperature during storm events are no longer necessary.

Considering hydrologic model uncertainty, while relatively small during extreme AR events, is important to accurately represent total uncertainty. This source of uncertainty, however, becomes dominant during spring refill when snowmelt drives the runoff process.

Improvements in snowmelt modeling processes under extreme AR conditions are also important. Improvements are possible through better estimation of the snowpack energy budget and the vulnerability to rain-on-snow runoff enhancement during extreme AR events. Improved modeling of snowpack during extreme AR events has the potential to also improve the recession limb forecasts that proved troublesome during the February 2017 Oroville spillway failure event.

5.4.1.3 Opportunities for Seasonal Streamflow Volume Forecast Skill Improvement

Seasonal water supply volume forecasts issued by both DWR and the CNRFC are used to guide spring refill decisions, establish environmental releases, plan hydroelectric power generation, and can inform mid-winter flood control release decisions before and after runoff events. A rigorous review of each may yield significant opportunities for improvement.

5.4.2 Forecast System Configuration Enhancements

Investigate additional model topology granularity for diversions along the Middle Yuba at Our House Dam and Oregon Creek upstream of Log Cabin Diversion and Deer Creek. Additionally, investigate the installation of new streamflow gaging sites along Dry Creek and at Collins Lake in Browns Valley to support improved streamflow forecasts for Marysville.

Better model and anticipate the release and spills from smaller, higher-elevation reservoirs in theSouth and Middle Yuba through improved communication of releases and streamflow observations from the reservoir operating agencies. These reservoirs capture approximately 250 of the 1,300 square miles of the upper watershed (generally above 5,000 ft to the Sierra Crest) and include some of the highest mean annual precipitation sub-basins in the Yuba watershed. The reservoirs noted are Jackson Meadows Reservoir, Milton Reservoir, and Bowman Reservoir (owned and operated by Nevada Irrigation District) for the middle Yuba; Spaulding and Lake Fordyce (owned and operated by PG&E) for the South Yuba; and Scotts Flat Reservoir (owned and operated by Nevada Irrigation District) along Deer Creek.

5.4.3 F-CO Refinements

The Yuba-Feather F-CO DSS does not model Bear River at Wheatland (BRWC1) as a boundary condition with uncertainty; instead, it uses the observed and specified future outflow from Camp Far West Reservoir (CFWC1). We suggest updating the boundary condition to CNRFC forecast point BRWC1, which would include upstream routed flow from CFWC1. CFWC1 operations are not modeled or updated in coordination with Yuba-Feather F-CO Program partners and are therefore not modeled in HEC-ResSim. The Yuba Water Agency supports U.S. Geological Survey stream gaging at BRWC1.

The Oroville and New Bullards Bar WCMs specify control points in the F-CO DSS as target flow locations. HEC-ResSim lumps local contributions for headwaters because they are not explicitly used for hydrologic modeling (i.e., HEC-HMS would be linked with HEC-ResSim for this purpose). For continuity, the CNRFC forecasts are used as input with reservoir modeling from HEC-ResSim downstream of Oroville and New Bullards Bar. We advise updating the Yuba-Feather F-CO DSS topology boundary conditions to align with the target locations identified in the current WCM and consider additional locations identified through the WCM update project. Extending the hydrologic forecast time horizon in the F-CO DSS would enable water managers to fully utilize the proposed reservoir infrastructure improvements during large flood events and allow time to operationally regulate and ramp spills proactively. We propose investigating extending the forecast time horizon on the F-CO DSS ResSim Model streamflow volume forecasts beyond the current five days.

In addition to river monitor, alert, and warning stage communications from NWS Sacramento, downstream evacuation triggers (based on elevation of the water surface) are an important operational decision point that arises from F-CO DSS model forecasts. These include stages at Lake Oroville and New Bullards Bar Reservoir WCM control points—Yuba City (Feather), Marysville (Yuba), Boyds Landing (Feather), and Nicolaus (Feather)—in addition to F-CO model output forecast locations at Dry Creek and the Bear River in Wheatland. Yuba-Feather FIRO should consider validating these elevations, rating curve conversions, and datums and including them in F-CO output communication and coordination with emergency managers. Improved forecast time horizon and accuracy of downstream flow/stage outputs from the F-CO model will give emergency managers advanced notice and time to implement evacuations and other safety measures.

5.4.4 Streamflow Forecast Applications for Release Decisions

The HEFS exceedance probability percentage used for a threshold basis for Oroville and New Bullards Bar forecast inflow volumes needs to be assessed (i.e., 25 percent exceedance). The appropriate exceedance probability can shift over time depending on forecast skill. As forecast skill evolves, adaptive management should be considered when specifying FIRO trigger volumes, forecast time horizon, and exceedance probability levels. This assessment should also extend to forecasts lead times between 5 and 10 days as they are considered for the F-CO application.

5.5 Recommendations

- Establish metrics and baseline for streamflow forecast skill as described in Section 5.4.1.1.
- Develop and pursue a Research and Operations effort to improve streamflow forecast attributes and components as identified above in Section 5.4.1.2.
- In collaboration with the CNRFC and DWR, investigate pathways to improve seasonal water supply forecasts issued for the Yuba-Feather basin as identified in Section 5.4.1.3.
- In collaboration with the CNRFC and DWR, pursue forecast system configuration enhancements and refinements as identified in Section 5.4.2.
- In collaboration with F-CO partners, pursue F-CO enhancements and refinements as identified in Section 5.4.3.
- Assess HEFS exceedance probability levels and thresholds used for decision-making as identified in Section 5.4.4.

modifies precipitation generation in ARs, including synoptic-scale forcing (Hecht et al., 2017), thermodynamic stability, mesoscale mountain circulations (e.g., the Sierra Barrier Jet; Nieman et al., 2013), and microphysical processes (e.g., cloud physics; Minder et al., 2014). A FIRO preliminary viability assessment (PVA) requires a thorough treatment of the contributions of these individual mechanisms to event-total precipitation. Such an effort to quantify the importance of these features will provide guidance on the most important focus areas for precipitation forecast skill assessment and ongoing numerical weather prediction (NWP) developments.

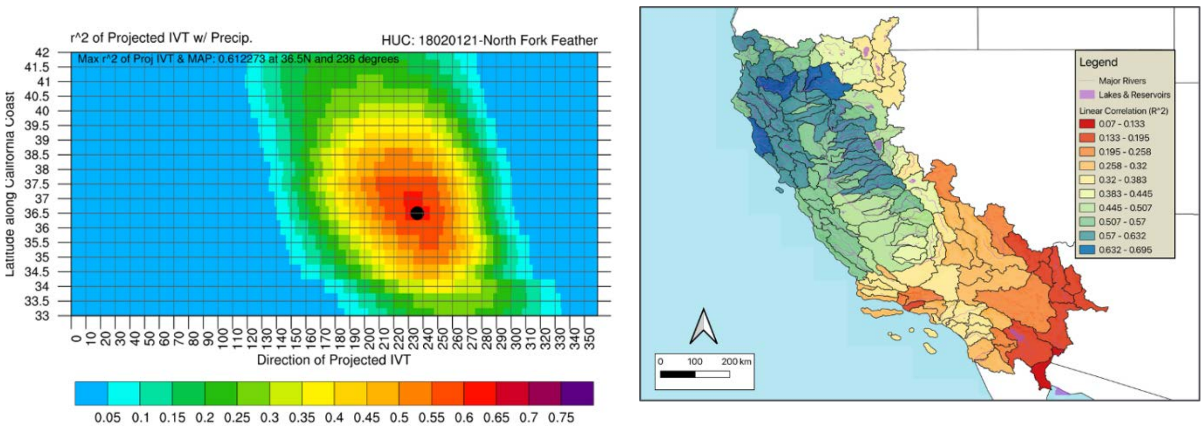

Figure 6-2. North Fork Feather River watershed daily map variance explained by IVT according to direction and coastal latitude (left). The maximum of 61 percent for IVT from 236 degrees (WSW) at a latitude of 36.5N appears to be related to a gap in coastal topography along the San Francisco Bay and Sacramento River, which serves as a conduit for AR moisture into the northern Sierra. The maximum MAP variance explained by directional IVT into each watershed in California is shown on the right (Ricotti and Cordeira, 2020).

6.1.3 Melting-Level Variability in Extreme Events

The above research tasks focus on improving understanding of spatiotemporal precipitation distributions in AR events, but the importance of snow in the northern Sierra to reservoir inflow also necessitates advancements in understanding and predicting the phase of precipitation. The atmospheric freezing level (Z_{FL}) determines the rain-snow transition zone at the surface, how much rainfall is available for runoff, and the flood risk during a precipitation event. An accurate Z_{FL} forecast is thus critical for reservoir operation, especially in mountain watersheds with large fractions of the watershed area within narrow elevation bands—for example, the Feather and North Fork Yuba watersheds in California, where a 500 m elevation gain can amount to >50 percent of the watershed area (Figure 6-3). Notably, the freezing level in individual ARs varies dramatically both during individual events, as demonstrated by the Day -1 through Day +1 variability in Figure 6-4, as well as from event to event.

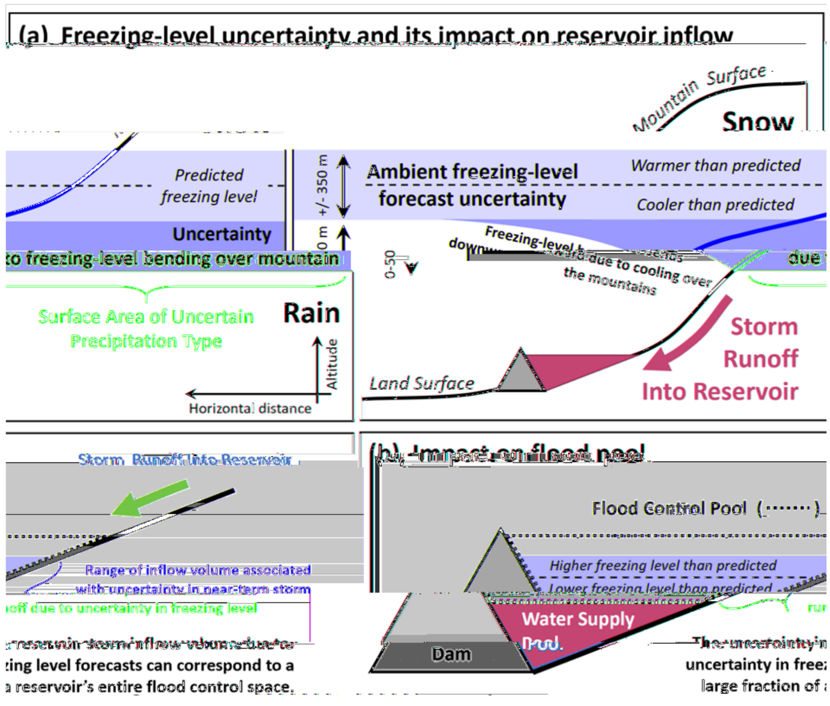

Figure 6-3. Schematic description of the impact of Z_{FL} forecast uncertainty on (a) storm runoff from the watershed and (b) the associated inflow to the reservoir flood pool. The ±350 m average Z_{FL} forecast uncertainty in (a) is based on Henn et al. (2020) and valid up to a 72-hour forecast lead time. The 0–500 m downward bending of Z_{FL} over the mountain topography in (a) is based on the results of Minder and Kingsmill (2013). (Figure from Sumargo et al., 2020.)

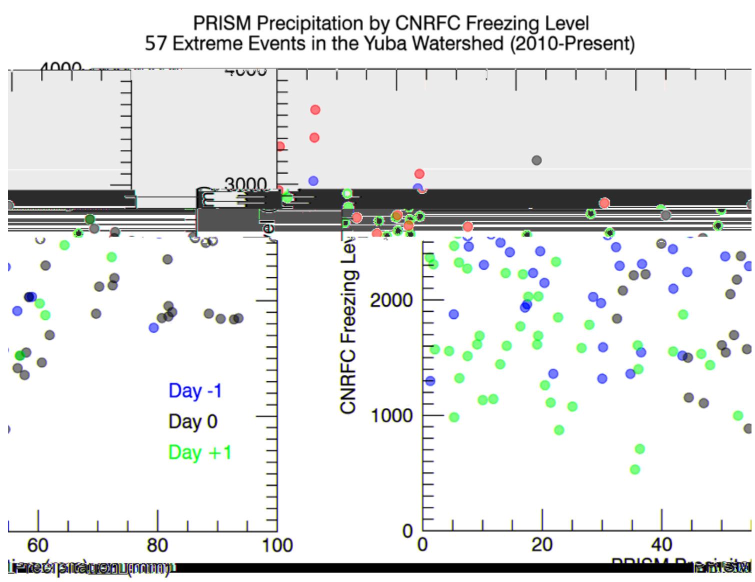

Figure 6-4. Scatter plots of daily PRISM precipitation vs. daily averages of six-hour California Nevada River Forecast Center (CNRFC) Z_{FL} for the three-day periods of the 57 "extreme" (90th percentile) PRISM precipitation events since 2010 in the Yuba watershed. (Figure from Sumargo et al., 2020.)

6.2 Predictability of Extreme Events

6.2.1 Development of Tailored Forecast Skill Metrics for Yuba-Feather Decision Support

6.2.1.1 Current Decision Support System

While formal metrics exist to assess precipitation forecast skill, similar metrics for AR forecast skill are in their infancy. Continued development at the Center for Western Weather and Water Extremes (CW3E) will support the Primary Viability Assessment (PVA) by assessing the skill of AR-related variables across forecast systems, including the GFS, ECMWF-IFS, and West Weather Research and Forecasting (West-WRF) model (Section 6.3). To date, efforts to quantify AR forecast performance have focused on landfall error and intensity across operational and research models. Quantitative metrics to assess current skill and forecast improvements through time will be essential to the possibility of an adaptive FIRO strategy.

6.2.1.2 Precipitation Forecast Metrics

Yuba-Feather FIRO PVA development will include an assessment of operational precipitation and freezing level forecast skill relative to the baseline reservoir inflow forecast skill in extreme events. These variables serve as key inputs to the Community Hydrologic Prediction System (CHPS) and determining their performance in previous extremes is a fundamental step toward understanding current forecast limits and identifying areas for improvement.

A preliminary assessment of California Nevada River Forecast Center (CNRFC) 24-hour Yuba River watershed average precipitation accumulations across 57 extreme (90th percentile) precipitation events demonstrates a negative bias that increases with lead time and event magnitude (Figure 6-5). The 24-hour period facilitates assessment of the meteorological conditions responsible for generating the most extreme portion of the precipitation event, which would otherwise be difficult to assess over the event's full duration. PVA research will require applying formal skill metrics, similar to those employed by the National Weather Service (NWS), to the full record of events.

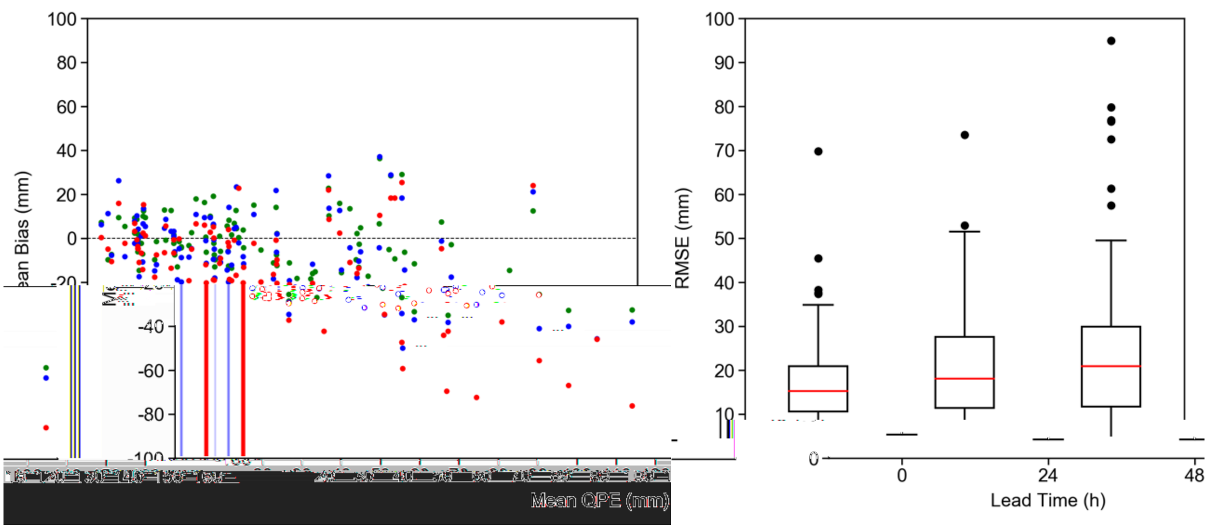

Figure 6-5. Scatter plots of 24-hour CNRFC watershed average precipitation accumulation forecasts for the Yuba River at lead times of 2 (red), 1 (blue), and 0 (green) days for 57 extreme precipitation events (a). Root mean square error statistics for the set of precipitation forecasts according to lead time (b).

Case studies in the preliminary FIRO scoping study investigated AR events with good forecast skill, including an impactful event in December 2012. The CNRFC quantitative precipitation forecast (QPF) for over 9 inches in two days showed an error of less than 10 percent 24 hours before the event. Forecast guidance in that event benefited from a high degree of global forecast model agreement in AR position, timing, and intensity that led to increased forecaster confidence in orographic precipitation location and duration. While the December 2012 event illustrated a promising forecast example, it is necessary to also evaluate events with poor short-range forecast skill. Table 6-1 introduces nine AR-driven, two-day precipitation events in which the CNRFC issued 24-hour precipitation forecasts that were more than 2 inches below the observed amount. Apparent differences in the large-scale conditions associated with well-predicted and poorly predicted categories of AR events will be investigated in detail as independent case studies and via composite analyses to identify sources of forecast error and potential areas for improvement (e.g., forecast diagnostics, model development, understanding flow-dependent predictability).

*Table 6-1. Two-day extreme precipitation events with >2 inches of forecast bias.**

Mean Bias < -50 mm (24-h Lead Time)

pt Error (%)		Valid Date (12Z)	Mean QPE (mm)	Mean QPF (mm)	Mean Bias (mm) / Perce
	-61.00	20050324	81.99	31.98	-50.01
	-57.42	20051202	141.20	60.12	-81.08
	-78.53	20051219	94.95	20.39	-74.56
	-38.93	20060101	217.81	133.01	-84.80
	-58.98	20070211	122.75	50.35	-72.40
	-46.88	20101025	188.07	99.91	-88.16
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	-51.82	-39.88	20141204	129.94	78.12
	-60.73	-42.97	20161211	141.32	80.59

* Table 6.1 shows the dates of two-day extreme precipitation events that had a watershed average forecast bias of more than 2 inches in the North Fork of the Yuba River watershed. The table provides quantitative precipitation estimates and forecasts in addition to the bias and percent error. The period of record is 2004–2020.

6.2.1.3 Freezing Level Forecasts

In addition to better understanding the physical processes that define melting-level elevation variability and their impact on reservoir inflow (Section 6.1.3), it is desirable to establish model skill in representing melting-level as a baseline for future forecast improvement. Using an average ±350 m Z_{FL} forecast error at a one- to three-day lead time for the Sierras (Henn et al., 2020), Sumargo et al. (2020) developed a simplified approach that found inflow volume uncertainties of <10 percent to >50 percent of the flood pool storages at the Lake Oroville and New Bullards Bar reservoirs, depending on the Z_{FL}, antecedent moisture condition, and precipitation event magnitude. This result emphasizes the significant impact of Z_{FL} forecast error and the critical need for Z_{FL} forecast accuracy for reservoir and flood control operations in the two watersheds. The FIRO PVA for Oroville and New Bullards Bar will evaluate this concept using real forecasts of recent extreme events to identify the sources of Z_{FL} forecast error and will leverage field campaign observations (e.g., Micro Rain Radars) and West-WRF to pursue future reductions in these errors.

The proposed evaluation of melting-level forecast skill for the Yuba and Feather watersheds benefits from the recently installed National Oceanic and Atmospheric Administration 915-megahertz wind profiler (snow-level radar) at Lake Oroville Dam, as well as two "RadMet" sites that were installed in the North Fork of the Yuba River watershed during Year 1 of the FIRO scoping study. RadMet sites include a Micro Rain Radar that provides snow level, optical PARSIVEL disdrometer, GPS-Met sensor, and surface meteorology suite—including air temperature, humidity, pressure, winds, solar radiation, and precipitation (described in detail in Section 3). These sites provide near real-time observations of hydrometeorological conditions within the watershed that are of operational value to partners, including the NWS. The observational snow-level radar data are publicly available through CW3E's website, www.cw3e.ucsd.edu, under the Observations tab. In addition, these observations support the evaluation of physical processes that cause AR-driven precipitation in complex terrain, as well as the development of forecast models to represent those processes.

6.2.2 Identification of Predictability Limits Across Relevant Processes and Lead Times

AR forecast tools developed at CW3E will be leveraged to understand the condition-dependent predictability of precipitation. This task arises from differences in the skill of global NWP across different circulation patterns. Thus, different AR large-scale evolutions and mesoscale meteorological processes in individual events have different predictability limits and different forecast skill. The condition-dependent predictability should be quantified to better inform uncertainty around precipitation and hydrologic forecasts. Evaluation of forecast skill across lead times in collaboration with the U.S. Army Corps of Engineers (USACE), the California Department of Water Resources (DWR), and Yuba Water Agency will ensure that scientific effort is specific to current operational needs.

6.2.3 Use of Machine Learning to Address Forecast Deficiencies (Suggested Additional Topic Area)

Broad goals from the AR program include developing and testing state-of-the-science machine learning algorithms to improve predictions of extreme weather events over the western United States, with an emphasis on predicting the IVT and precipitation associated with extreme events. This task is suited to address biases in forecast systems and to bridge an existing gap between atmospheric conditional probability and hydrologic forecast uncertainty.

6.3 West-WRF Transferability

West-WRF (Martin et al., 2018) is a version of the WRF model (Skamarock et al., 2008; Powers et al., 2017) that CW3E developed to run operationally during the winter season and to use for research purposes. West-WRF is configured toward optimal forecasting of extreme precipitation events (especially those associated with ARs) that are key to water supply and flooding in California and the western United States in general (Dettinger et al., 2011; Ralph and Dettinger, 2012; Ralph et al., 2013; Ralph et al., 2016; Cordeira et al., 2017; Martin et al., 2018).

The transferability of West-WRF to the northern Sierra for accuracy during ARs is crucial to improved QPF skill and water supply prediction in mountain environments, where global model resolution poorly represents orographic precipitation and the relevant physical processes that modify its spatiotemporal distribution. West-WRF's 3 km resolution is a significant improvement over GFS and ECMWF; moreover, relative to other mesoscale models, such as the operational High-Resolution Rapid Refresh (HRRR), West-WRF's domain and physics are tailored to AR prediction. The proposed work plan includes using West-WRF modeling capabilities to benefit meteorological understanding and improved forecast skill in the Yuba and Feather watersheds. A key step will be identifying the primary sources of West-WRF QPF errors in the northern Sierra via an assessment of the recently completed reforecast (1986–2019) and targeting those physical mechanisms for continued development.

6.3.1 Mesoscale Precipitation Mechanisms

Research thus far has defined the dominant role of ARs in regional hydroclimate, and the efforts proposed here will further address challenges in predicting ARs and related precipitation. This section outlines research that focuses on an ingredients-based approach to identify and understand a range of meteorological processes that modify AR evolution, predictability, and precipitation impacts. While previous case studies have performed similar investigations, no one has systematically evaluated AR forecast skill or the predictability of the individual forcing mechanisms that modify precipitation and freezing level—including synoptic-scale dynamics, frontal processes, and thermodynamics—for a large record of events in the northern Sierra. The relative lack of emphasis on these complex and compounding meteorological mechanisms suggests a knowledge gap that is potentially problematic for forecasting hydrologic extremes in the Yuba and Feather River watersheds. Such an effort to quantify the impact and predictability of AR meteorology will provide guidance on the most important focus areas for precipitation forecast skill assessment, ongoing NWP developments, and observational campaign needs.

Research to identify the physical processes controlling the spatiotemporal distribution of precipitation in extreme events that impact the Yuba and Feather River watersheds will utilize observations of AR conditions from the existing network of vertically profiling radars, reanalysis data, CW3E observing systems (Section 3), and high-resolution West-WRF mesoscale model simulations. The processes to be investigated include, but are not limited to:

- The Sierra Barrier Jet (Cordeira et al., 2012)
- Mesoscale frontal waves (Martin et al., 2018)
- Synoptic-scale forcing for ascent (Hecht et al., 2017)
- Cold-frontal rainbands (Cannon et al., 2018)
- Cut-off low pressure systems (Oakley et al., 2017)

As the relevant CW3E citations for each of the above topics suggest, the processes have been investigated previously and are relatively well defined. What this future research specifically seeks to address is their collective impact on the northern Sierra precipitation distributions across the record of extreme events and if/how they modify precipitation forecast skill.

The continual improvement of precipitation predictability by better understanding and simulating the mechanisms that modify AR characteristics is a CW3E long-term objective that extends beyond this study. Thus, the proposed research task aligns with, and benefits from, broader CW3E efforts to advance NWP—including creating community-standard AR forecast metrics, developing Atmospheric River Reconnaissance (AR Recon) (Ralph et al., 2020), and continually improving West-WRF (Martin et al., 2018). Here, CW3E will systematically evaluate the representation of the above physical processes across the suite of operational and experimental weather models, including GFS, ECMWF-IFS, HRRR, and West-WRF. This evaluation will focus on their influence over precipitation generation and forecast skill in the northern Sierra. The research will also re-evaluate CNRFC precipitation forecast skill (Figure 7.5) relative to the presence/absence of meteorological features that modify AR characteristics to understand their relationship with baseline streamflow forecasts.

6.3.2 WRF Freezing Level

The proposed research will assess WRF high-resolution freezing level characteristics in the northern Sierra during AR events. This analysis will leverage the West-WRF reforecast (available for 1986–2020) to establish climatological behavior. Additionally, alongside a skill evaluation of CNRFC forecasts, the analysis will be conditioned upon large-scale to mesoscale meteorological processes to understand event-to-event variability in freezing-level characteristics and their predictability. The analysis will further apply diagnostics to evaluate the reforecast to the near-real-time forecasting system and will inform the development of web-based decision support products. A key component of this research will be comparing WRF forecasts and profiling radar observations of bright-band height. Figure 6-6 provides a preliminary example of using the augmented observation network to model freezing-level validation—the Micro Rain Radar data from New Bullards Bar and Downieville on May 18, 2020, and the 12- to 24-hour forecasts of simulated observations are useful at first order to identify some of the challenges in comparing observations and model data that will be targeted in the following year. Notably, the model vertical resolution will need to be improved to better resolve the hypsometry of northern Sierra watersheds. Both the Yuba and Feather River watersheds have considerable watershed area in a narrow elevation band at 1,500 to 2,000 m.

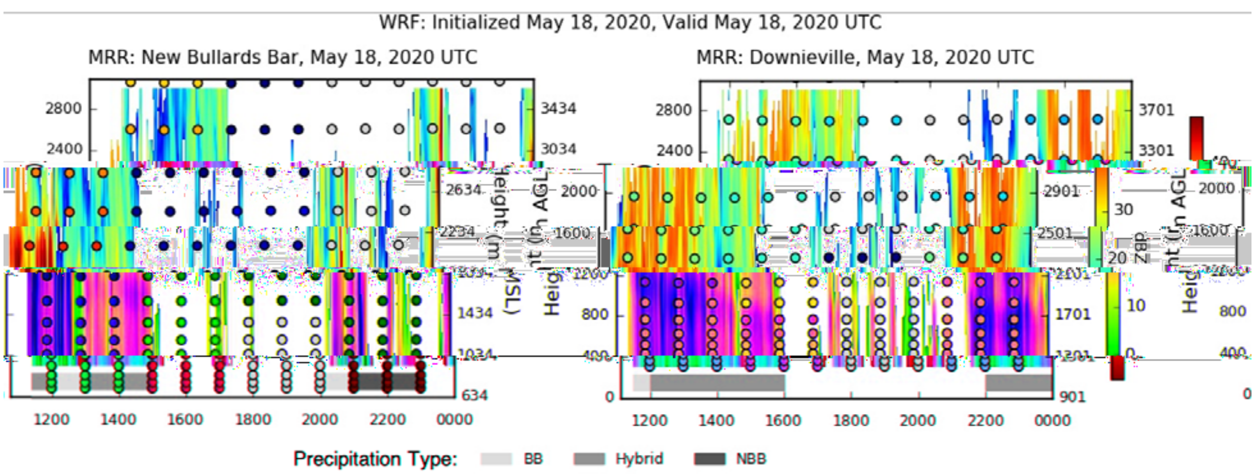

Figure 6-6. Reflectivity time/height cross-sections from the New Bullards Bar (left) and Downieville (right) Micro Rain Radar sites (color fill) that were installed in Year 1 of the FIRO scoping study. The colored dots (same scale as color fill) depict WRF-simulated reflectivity profiles at model vertical resolution and one-hour time resolution for the grid point corresponding to the RadMet sites.

6.3.3 Reforecast-Based Skill Assessment

CW3E generated a 34-year reforecast of West-WRF to assess the model's performance throughout the climatological record of extreme events. The goals of a West-WRF reforecast assessment in the Yuba-Feather watersheds are to 1) assess the benefits of a West-WRF high-resolution reforecast to CNRFC operations; 2) enhance CW3E predictive capabilities by exploring post-processing techniques and machine learning to reduce raw model output biases; and 3) perform in-depth, process-based studies of predictability over a climatological record.

6.3.4 WRF Development Considering Yuba-Feather Meteorology and Uncertainty Estimates

An important focus of understanding the sources of West-WRF QPF error during ARs (Martin et al., 2018) will be developing ensemble simulations to account for uncertainty in the model's initial state, unresolved physical processes, and parameterization errors (Berner et al., 2014). Ensemble generation in West-WRF represents a significant advancement toward quantifying and understanding individual sources of uncertainty and mitigating initial condition errors in forecasts of western United States weather for water resource conservation and hazard mitigation. These efforts will potentially improve the forecasts associated with the full range of storm magnitudes and provide crucial information about forecast uncertainty for decision support.

In addition, West-WRF is now being forced by ECMWF forecast data, and a 9 km WRF ensemble that uses the ensemble members from GFS and ECMWF is under development. A preliminary evaluation of West-WRF 24-hour precipitation forecasts over the Russian River watershed in California's coast range demonstrated a significantly improved centralized root mean square error using ECMWF boundary conditions to force West-WRF.

Ensemble sensitivity testing will further benefit from an enhanced observation network that measures relevant meteorological parameters within AR events. The observation network that CW3E developed for FIRO at Lake Mendocino is an example of an augmented observation system that supports understanding and simulation of key precipitation processes during ARs impacting the Russian River watershed. Development of an observation network for the Yuba-Feather watersheds (described in Section 3) focuses on precipitation and freezing level at high spatiotemporal resolution in the complex environment. Measurements of precipitation, atmospheric temperature, humidity, and winds via in situ measurement (e.g., met stations and radiosondes), as well as their proxies via remote sensing, will yield necessary ground truth for forecast model assessment and development.

6.3.5 Development of Supplemental High-Resolution Forecast Products

Efforts to diagnose regionally important precipitation processes in Section 6.1.2 will be translated into near real-time mesoscale forecast products that are available for decision support. These products will provide supplemental information on physical processes that modify precipitation generation and forecast skill at scales that global forecasting systems have not adequately resolved.

Additionally, several automated and post-season verification tools have been developed that run in parallel with the West-WRF near real-time forecasting system. These verification analyses include a measurement of forecast accuracy for AR landfalls, precipitation amounts and spatial extent, and freezing-level altitude. The former two analyses are scientifically innovative in that they apply object detection algorithms to both forecasts and environmental analyses to estimate the forecast error. In addition to benefiting the development of West-WRF forecast skill, these verification analyses measure the forecast accuracy of daily forecast information throughout the winter season.

6.4 Assessment of AR Recon Benefit to Yuba-Feather Forecast Skill

The AR Recon project is exploring the use of dropsonde measurements in and around ARs over the northeast Pacific Ocean to improve the prediction of landfalling ARs on the U.S. West Coast, including their associated precipitation and streamflow. Previous research has shown that AR forecasting is more skillful at long lead times than precipitation forecasts alone (Lavers et al., 2016) and can be leveraged to increase forecast lead time of high-impact AR events. However, it is also understood that initial condition errors in and around ARs offshore at one to three days lead time are the leading source of model error. To provide increasingly skillful forecasts of ARs and their associated impacts, improved observations ahead of landfall are required, including through airborne observation campaigns (Doyle et al., 2014; Ralph et al., 2014; Neiman et al., 2016; Cordeira et al., 2017).

Stone et al. (2019) have shown that the challenge associated with AR forecasting is attributed, at least in part, to the scarcity of Eastern Pacific in situ observations. They determined the forecast sensitivity observation impact for each dropsonde variable from AR Recon missions in 2018 and compared them to similar measurements made by the North American radiosonde network. Their study found that the reconnaissance soundings have significant benefits, with a per-observation impact more than double that of the North American radiosonde network. The reconnaissance soundings reduced the 24-hour global forecast error 33 percent to 75 percent compared to the North American radiosonde network. The FIRO viability assessment will assess the impact of dropsonde observations on precipitation and hydrologic forecasts for sampled events that affected the northern Sierra. While the work will primarily be executed under the AR Program, the PVA will evaluate the results as a possible means of improving the accuracy of decision support information in the northern Sierra.

6.5 Assessment of Contributing Factors to Runoff Variability Among Extreme Events

Antecedent soil moisture and snowpack conditions significantly influence runoff generation and reservoir inflow during extreme precipitation events impacting the Yuba and Feather River watersheds. This work plan task will quantify the relative importance of these conditions and consider the range of influence in evaluating potential impacts of AR events. The hazards associated with antecedent conditions may manifest more regularly in ARs that occur in rapid succession and/or those that occur later in the winter season. Proposed analyses will assess the seasonality of AR extremes, AR families (Fish et al., 2019), and event-to-event variability in AR temperature (Hatchett et al., 2019).

6.5.1 Impacts of Advected Latent Heat on Snowmelt During AR Conditions

The influence of latent heat advection on snowpack melting during AR conditions is potentially impactful, but not straightforward to observe. Preliminary analysis of snow measurements (e.g., pillows and snow water equivalent) in nearby Sierra basins in February 2017 demonstrated melting via observed rain-on-snow and possible periods of latent heat advection—identified as periods when snow water equivalent increased, snow density increased, and snow depth decreased. However, the sensitivity of the instruments to these processes appears smaller than their uncertainty/errors at relevant time scales. Additional attempts to evaluate these processes via the National Water Model were confounded by errors in that model’s forcing. Ongoing work to quantify the role of latent heat advection on the snowpack will necessitate sensitivity experiments using a snow model.

6.5.2 Impacts of Antecedent Soil Moisture Conditions on Runoff Efficiency

The results of Sumargo et al.’s (2020) study of reservoir inflow as a function of forecast precipitation event magnitude, freezing level, and soil moisture clearly demonstrate the importance of antecedent conditions on extreme precipitation event runoff generation. For the largest precipitation events occurring with freezing levels near most sensitive rain-snow transition zones, runoff uncertainty due to antecedent soil moisture can exceed 50 percent of reservoir flood pool volume at both Lake Oroville and New Bullards Bar Reservoir (Figure 6-7). The results of the Sumargo et al. (2020) idealized study motivate analyses on real events, hydrologic model development, and augmentation of the existing observation network.

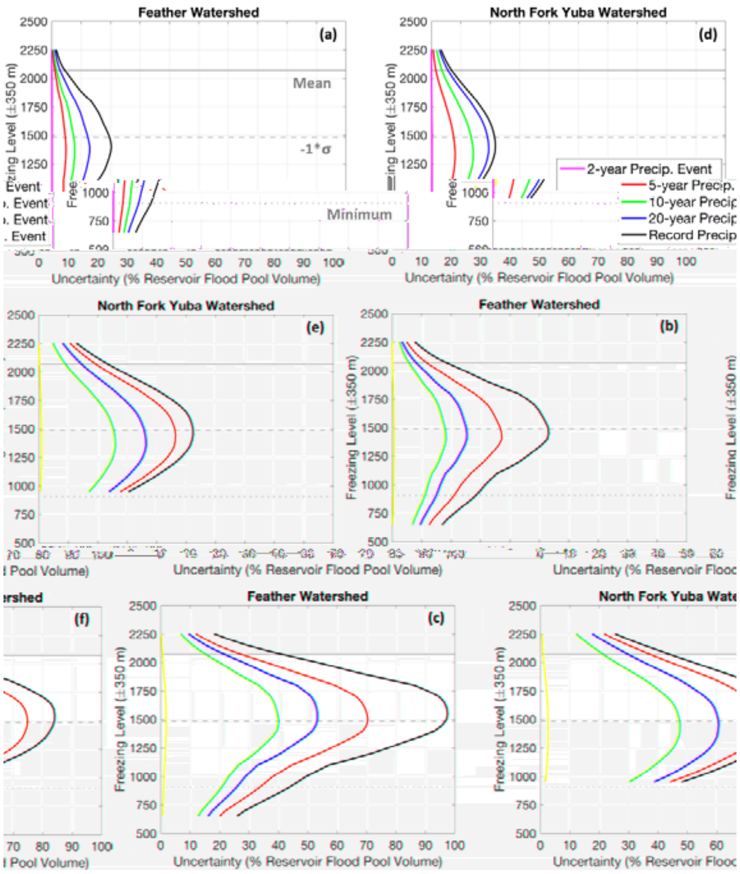

*Figure 6-7. Feather River (a–c) and North Fork Yuba River (d–f) watersheds runoff associated with a Z_{FL} forecast error of ±350 m in percent of the reservoir flood pool capacities as functions of Z_{FL} and event return periods based on the 1981–2018 daily PRISM precipitation (colors). The top-to-bottom panels represent the runoff corresponding to (a and d) dry, (b and e) average, and (c and f) wet antecedent moisture conditions. The gray horizontal lines denote the mean, the -1*standard deviation (σ) from the mean, and the minimum CNRFC Z_{FL} averaged over the three-day periods of top 10th percentile precipitation events since 2010 (Sumargo et al., 2020).*

6.6 Transferability of Scientific Research to Forecast Operations

6.6.1 CW3E Product Development

CW3E maintains a considerable number of forecast diagnostics and decision support tools on its website, including a landfall tool, AR plume diagram, AR scale, and watershed precipitation and freezing-level forecasts (Figure 6-8 provides an example of the AR plume diagram). Existing tools will be evaluated specific to the Yuba-Feather FIRO project for the record of available extreme events to determine the benefits and limitations of individual tools in high reservoir inflow scenarios. Quantification of a forecast product's performance through time is necessary for any future event for which those same tools will be used for decision support. Ongoing research will also target the creation of diagnostic tools that provide guidance on different precipitation mechanisms within ARs that modify their rainfall/snowfall distributions and forecast confidence. This effort will include assessing the performance of new forecast products over an extended historical record to determine their predictive skill for a large number of observed extremes, as well as their false alarm rate.

Research toward the development of the Yuba-Feather FIRO PVA will also seek to identify and capitalize upon opportunities for significant forecast improvements. One such example is a partnership between CW3E and ECMWF that provides access to the 51-member IFS ensemble and the possibility of drastically augmenting probabilistic AR, precipitation, and freezing-level forecast skill. In such a case, as well as for any other significant advancements to CW3E forecast tools, it will be necessary to recreate forecast diagnostics of recent extreme events to compare with the operational information used at that time and to do so in the context of forecaster and water management information needs in the northern Sierra.

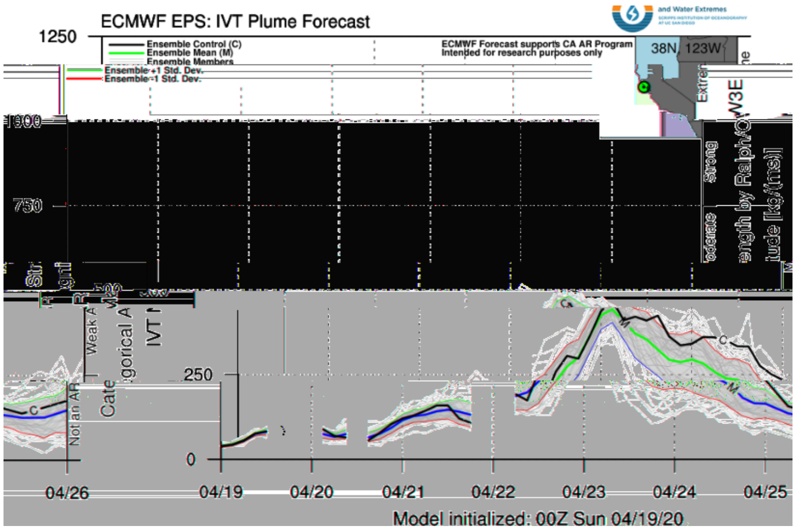

Figure 6-8. An example of the CW3E AR landfall plume from water year 2020 using ECMWF forecast data. Current development toward merging forecast information from the GEFS and ECMWF ensemble systems could considerably improve regional extreme event prediction but requires significant retrospective testing and diagnostic development.

6.6.2 Cross-Agency Research to Operations Initiatives

In developing FIRO at Lake Mendocino, CW3E has worked with reservoir managers and USACE to ensure detailed understanding of the forecast information and decision support tools that are produced and to allow opportunities for feedback, especially regarding ensemble-based uncertainty products. Interaction between the forecast information source (CW3E, NWS) and the end user (DWR, Yuba Water) will be essential as the FIRO Yuba-Feather PVA ventures to develop enhanced decision support tools that end users can readily understand and easily employ. Previous discussions in a similar context have highlighted that this information is not translated among atmospheric scientists, hydrologists, reservoir operators, and stakeholders with perfect fidelity, and that assuming perfect fidelity can have consequences. An iterative approach to developing forecast diagnostics and decision support tools that simply and effectively meet end-user needs via constant interaction (e.g., technical workshops) is essential to FIRO success.

Section 7— Identification, Review, and Assessment (Comparison with Operational Baseline) of Contemporary Hydrologic Forecast Modeling

7.1 Snow Modeling Assessment

7.1.1 Introduction to Snow Hydrology in the Yuba-Feather

The Yuba and Feather watersheds have complex hydrology and runoff generation processes, driven by mixed-phase precipitation events, rain-on-snow events, and steep topography that can funnel winter storms (Koczot et al., 2004). Due to the importance of snowmelt for flood control and reservoir operations in these watersheds, multiple previous studies have described observational and modeling programs. For example, Avanzi et al. (2018) describe a wireless snow sensor network to support Precipitation-Runoff Modeling System (PRMS) modeling for the Feather River, while Tang et al. (2010) evaluate Moderate Resolution Imaging Spectroradiometer (MODIS) snow-cover data for inclusion in the Variable Infiltration Capacity model. The PRMS model has been further used to understand the impact of temperature changes on the watershed's hydrology (Huang et al., 2012).

This project will build on those previous studies to bring together existing and new hydrology observations in the Yuba and Feather watersheds, with the Forecast Informed Reservoir Operations (FIRO) team applying and comparing multiple hydrologic modeling frameworks. We will conduct new research to quantify the uncertainty and skill level of existing snow and hydrology forecasts for the Yuba-Feather to provide baseline information and comparison to observations. Further detailed research will investigate how snow accumulation and melt processes contribute to high-impact events in the Yuba-Feather, including processes such as freezing-level changes, dew-on-snow processes, and the impact of warm atmospheric river (AR) events. We will use this knowledge to benchmark snow models against observations, to analyze the performance of seasonal forecasting in the watersheds, and to recommend future improvements in the use of forecasting for the Yuba-Feather area.

7.1.2 Geographic and Timescale Scoping

The Yuba-Feather Hydrology Working Group will determine which locations and time periods are most suitable for snow hydrology analysis and model evaluation. We envision that snow volume assessments and seasonal forecasting will include the entire watershed area above the Oroville and New Bullards Bar Reservoirs, while detailed analysis of existing forecast skill and comparisons of snow models will select sub-watershed areas based on the availability of observational data (i.e., precipitation and snow water equivalent [SWE]) that spans climatic and topographic gradients.

Further, model evaluations require the selection of events, time periods, and lead times to ensure a fair comparison between models. We will identify a set of AR events in the recent record for model evaluation, including events with varying temperature and meteorological characteristics.

7.1.3 Data for Snow Models

We will collaborate with the Monitoring Working Group, which is cataloging and assessing existing and planned monitoring programs. This task aims to 1) provide a consistent database of observed snow and hydrology data for our modeling efforts, 2) provide information to the Monitoring Working Group on requirements and limitations in data availability to support modeling efforts, and 3) develop expanded observations of snowpack antecedent conditions (i.e., cold content). These efforts will improve the usability of existing observations and guide new installations and new data streams in the watersheds. New and improved observations can both be used to benchmark our snow hydrology models. Regular feedback and discussion among field staff, data management staff, and data users/modelers are essential to ensure consistent understanding of data quality.

The snow and hydrology database will include observations from precipitation gauges, snow depth sensors, snow pillows, the Airborne Snow Observatory (ASO) (if available), and stream gauges to evaluate model skill in simulating snowpack dynamics and runoff generation in the Yuba-Feather.

Specific activities include collating data requirements for each snow model included in the study, creating an overview document describing current and planned observations in the watersheds based on Monitoring Working Group information, and videoconferencing with Monitoring and Hydrology staff to share information.

7.1.4 Quantify Current Forecast Skill

We will quantify the skill of current snow hydrology forecasts in the Yuba-Feather to provide a baseline against which to compare proposed model improvements and alternative models. Following the concept found in Henn et al. (2020), to compare the skill of California Nevada River Forecast Center (CNRFC) operational meteorological forecasts, West-WRF forecasts, and GEFS forecasts under AR conditions, we will compare operational forecast predictions (and alternative meteorological inputs) to observations and assess the role of meteorological forecast products in controlling hydrological skill. Skill assessment tasks cut across multiple working groups: hydrology skill assessment dovetails with skill assessment of precipitation depth and precipitation phase forecasts from Working Group 7, as well as skill assessment of reservoir inflow forecasts from Working Group 6.

We anticipate that multiple forecast products will be available from Working Group 7, "Assessment of Watershed Meteorology, Forecast Skill, and Potential Improvements." These include GFS and European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble forecast systems; West-WRF reforecasts; and high-resolution West-WRF ensembles for the 2017, 2019, and 2020 seasons. National Water Model Calibration Analysis of Record forcings are expected to be available from the University of California, Los Angeles (UCLA). Each of these forecasts can be used to drive the CNRFC SAC-SMA SNOW-17 hydrology model and predict snowpack accumulation, depth, and melt.

The FIRO Steering Committee will collaborate with all FIRO members to develop skill metrics for Yuba-Feather meteorological-hydrological forecasts under AR conditions to ensure their relevance for operational use. We will use these metrics to quantify skill and uncertainty in hydrologic forecasts, as well as their dependence on meteorological drivers.

7.1.4.1 Data Collection, Pre-Processing, and Model Readiness

Several pre-processing steps are necessary. A tool must be created to convert grid-based meteorological model outputs to the sub-watershed and elevation band averages that SAC-SMA SNOW-17 requires. The operational setup of SAC-SMA SNOW-17 must be reproduced offline to allow for experiments with alternative forecasts. Snow hydrology data (Section 7.1.3) must be processed to create sub-watershed and elevation band averages for comparison with model outputs.

7.1.4.2 Model Runs and Skill Analysis

The FIRO team will use each meteorological model or ensemble member to force the SAC-SMA SNOW-17 hydrology model (and alternative snow hydrology models if available) in forecast mode. We will apply skill metrics to estimate skill and uncertainty for lead times of one to six days for the events identified in Section 7.1.2. We will use these model runs to estimate typical snowmelt errors from differences in snowmelt predictions between models and between ensemble members, as well as from comparisons with observations where available. Using this range of expected snowmelt errors, we will apply a method similar to that of Sumargo et al. (submitted) to transform watershed input (here snowmelt) into a runoff estimate using the Soil Conservation Service curve number technique. This will provide an estimate of the impact of modeled snowmelt error and uncertainty bounds on downstream reservoir inflow volumes.

7.1.5 Snow Model Evaluation

7.1.5.1 Model Selection and Setup

Institutions involved in this working group run several snow or snow-hydrology models suitable for predicting snow and water resources in the Yuba-Feather basins. These include WRF-Hydro (Center of Western Weather and Water Extremes), SAC-SMA SNOW-17 (CNRFC, University of Nevada, Reno [UNR]), the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Engineer Research and Development Center [ERDC]), HEC-HMS (ERDC), and the Distributed Snow Model (DSM) (UCLA). Each institution will be responsible for setting up and running their respective model(s), as well as storing outputs that may include fractional snow cover area, snow depth, SWE, and radiative and turbulent energy fluxes. We can use these outputs to evaluate different model snow processes. The outputs may also include volumetric soil moisture and streamflow, which will allow us to evaluate surface runoff responses during rainfall and snowmelt events.

7.1.5.2 Evaluation Framework

We will develop mutually agreed-upon model benchmarking evaluation tests for the snow models in the study. The aim is to test all models against the same data, processes, lead times, etc. The framework will evaluate the current capabilities for snow modeling among participating groups, how well the snow components of these models meet operational flow forecasting needs, and how well the models capture snow hydrology processes. Many factors impact a model's capability to capture snow and runoff processes in a snow-dominated watershed, including the model physics, the quality of its meteorological forcings, and the time and space scale of the model. These factors all include uncertainties that are difficult to disentangle, even with very high-quality observational data. In the Yuba-Feather, the lack of co-located SWE, precipitation, and energy budget data precludes verification of snow models at all but a few observation sites. We therefore plan to build an evaluation framework that spans highly detailed analysis at selected sites to whole-watershed synthesis evaluations, with the overall aim to help pinpoint where the model needs improvement.

Specifically, we will propose a candidate set of processes for evaluating each modeling system (although this may change during the project if agreed upon by all modeling groups). For example, the processes may include the system's ability to model accurate seasonal snowpack, snow accumulation and melt for specific elevation bands or time periods (e.g., high-elevation melt, early season March–May melt), rain on snow, and sublimation. We may also evaluate performance at different lead times, performance based on the scale of ARs, and performance for high-impact events and water resources forecasting. We will draw on Section 7.1.1 to determine the scope of lead times and AR events.

7.1.5.3 Model Tests

Model Timestep

We will conduct tests to determine the impact of changes in model output timestep, as well as the timestep required to make accurate forecasts on timescales from sub-daily to seasonal forecasts. For example, sub-daily output availability is hypothesized to be essential during a warm AR passage, when snow accumulation, ablation, and liquid water drainage can change rapidly within hours after the fluctuations of atmospheric freezing level.

Model Resolution of Watershed Elevation

We will investigate the improvements to model skill metrics and evaluate model simulations against observations such as snow courses when using finer-resolution elevation bands. For example, we will break up a SNOW-17 basin from 5,000 ft to the maximum elevation (about 9,000 ft) into 1,000 ft bands. This would yield four SNOW-17 models in place of the single "above 5,000 ft" SNOW-17 that the CNRFC currently uses. We would then calibrate the models to historical data and compare the results, including an evaluation of operational feasibility when considering the additional overhead costs for managing run-time modifications.

Impact of Data Assimilation

We will conduct tests to investigate the impact of bringing in the model(s) observations of areal extent of snow cover (both historical and real-time) on runoff. We will evaluate different potential sources of snow cover data (e.g., SNODAS, MODIS SWE from the Institute of Arctic and Alpine Research, and ASO if available) and their known biases/uncertainties. For example, SNODAS can add excessive low-elevation snow when the SWE is updated.

7.1.5.4 Model Development

We are planning several longer-term model development activities that will benefit the ability to forecast snow and hydrology in the Yuba-Feather. UNR plans to develop an open-source R version of SNOW-17 and validate it against field observations during rain-on-snow events focused on the Truckee and Yuba basins.

UNR also plans to modify SNOW-17 to include an internal parameter that accounts for antecedent cold content, density, liquid water conditions, etc. The university will calibrate the updated model against existing and newly collected field observations and link SNOW-17 to SAC-SMA to evaluate potential improvements in streamflow forecasts during rain-on-snow events in several basins where observations are available.

7.2 Seasonal Water Supply Forecasts

7.2.1 Comparison of Forecasts

7.2.1.1 Background

The California Department of Water Resources (DWR) Snow Surveys and Water Supply Forecasting Section publish Bulletin 120 (B-120) on the 1st of the month from February to June—for high snowpack water years (WYs), DWR will publish B-120 until July/August. B-120 provides seasonal runoff forecasts for April–July full natural flow (A-J FNF), water year full natural flow (WY FNF), and individual monthly FNF volumes (for February to September) for major upper Sierra River basins in thousand ac-ft. DWR develops the water supply forecasts using multiple linear regression equations, and historical B-120 publications have 10 percent, 50 percent, and 90 percent exceedance volume forecasts. The B-120 forecasts rely heavily on manual snow survey measurements taken at snow courses. DWR makes weekly updates to the B-120 forecast between the official publication on the 1st of each month. These B-120 update reports use automated snow pillow data.

The CNRFC, in conjunction with DWR forecasters, produces ensemble streamflow traces using HEFS. These ensemble streamflow forecasts are produced from continuous simulation hydrology models (using SAC-SMA and SNOW-17) that track current watershed states (soil and snow). They are forced with short-term weather information (precipitation and temperature) for the first two weeks and climatology after that going out a full year. Because all the streamflow traces are equally likely, statistical summary products can be derived for both short-term flood situations and long-range products like A-J FNF, WY FNF, and individual monthly FNF volume probabilities, similar to B-120. The CNRFC began HEFS operations in 2011 and has archived all issued products and the underlying ensembles. Using a hindcasting procedure, HEFS ensembles for WYs 1985–2010 were generated for selected key water supply locations. These forecasts used current operations models, historical data, and the 1985–2010 GEVSv10 reforecasts for the first two weeks of future weather and climatology thereafter. He et al. (2016) describe the hindcasting procedure and the results of the forecast verification.

Table 7-1 lists the number of ensemble members, climatology, and source of forcing members used for hindcast and operational HEFS.

Figure 7-1 shows an example of a current DWR dashboard tool available for comparing CNRFC and DWR April–July runoff forecasts for the current year. The proposed work will analyze similar comparisons for multiple forecast dates, forecast years, and runoff target periods to provide statistical comparisons.

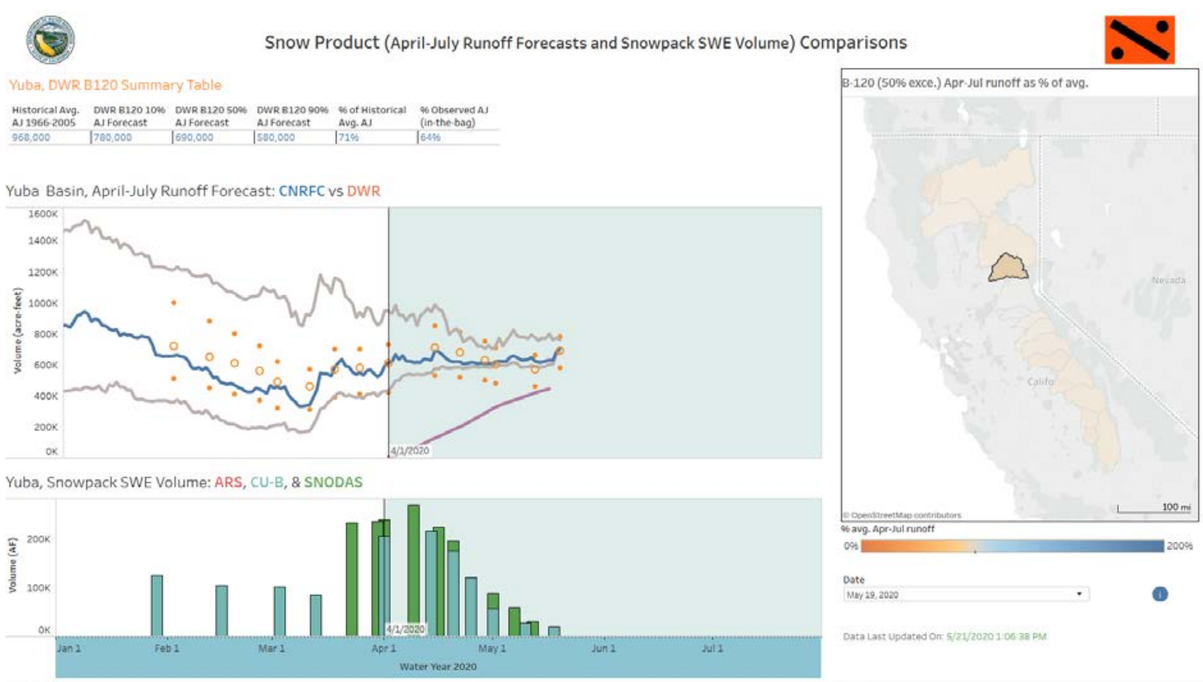

Figure 7-1. Example of current DWR dashboard tool available for comparing CNRFC and DWR April–July runoff forecasts.

Table 7-1. HEFS source and products used for the hindcast and operational streamflow forecasts.

	Hindcast HEFS	Operational HEFS	Operational HEFS
Water Years	1985–2010	2011–2017	2018–Present
Number of Ensemble Members	59	59	68
Climatology-Associated Water Years	1950–2008	1950–2008	1950–2017
MEFP Source **Days 1–3**	Mean GEFS	NWS Hydrometeorological Analysis and Support (HAS) Forecast	NWS HAS Forecast
MEFP Source **Days 4–15**	Mean GEFS	Mean GEFS	Mean GEFS
MEFP Source **Days 16–365**	Climatology	Climatology	Climatology

7.2.1.2 Procedure

The B-120 publication provides water supply volume forecasts for the following locations in the Feather and Yuba watersheds: Feather River inflow to Oroville Dam and Yuba River at Smartsville.

The CNRFC issues HEFS water supply volume forecasts for 11 locations in the Feather River, including the inflow to Oroville Dam, and 14 locations in the Yuba, including the inflow to New Bullards Bar and Englebright Dam. The hindcast effort described above included the inflow to Oroville Dam and the inflow to Englebright Dam. However, it did not include Deer Creek near Smartsville, which joins the Yuba River below Englebright Dam and above the Yuba-Smartsville stream gage. Direct comparison of B-120 and HEFS volume forecasts in the Yuba River therefore requires the generation of hindcasts (1985–2010) for Deer Creek at Smartsville or the assumption that Deer Creek does not substantially add to the Yuba volume.

Comparing B-120 and HEFS forecasts involves the following general steps:

1. Retrieve February 1, March 1, April 1, and May 1 B-120 forecasts for A-J FNF and WY FNF, as well as February–July monthly FNF volumes.
    a. B-120 publishes forecasts for Feather River at Oroville and Yuba River at Smartsville (including Deer Creek FNF).

   b. This includes gathering the 10 percent, 50 percent, and 90 percent exceedance forecasts for the A-J and WY FNFs. The 50 percent exceedance forecast is only available for monthly FNF volumes.
   c. See Table 8.3 regarding data collected and where data are missing.

2. Retrieve February 1, March 1, April 1, and May 1 HEFS forecasts for A-J FNF and WY FNF, as well as February–July monthly FNF volumes.
   a. Hindcasts would need to be used for WYs 1985–2010 and operational forecasts from 2011 to 2018.
   b. Information is missing for seasonal runoff forecasts issued on February 1 and March 1, 2011 (this includes A-J FNF, WY FNF, and monthly FNF volumes for ORDC1 and HLEC1). The HEFS operational runs are available for February 1 and March 1, 2011, and would need to be aggregated for the A-J and WY FNFs to retrieve the 10 percent, 50 percent, and 90 percent exceedance volumes. The same would need to be done for the monthly FNF volumes, but only for the 50 percent exceedance forecast. Operational HEFS runs are in units of thousand ac-ft.
   c. This includes gathering the 10 percent, 50 percent, and 90 percent exceedance forecasts for the A-J and WY FNFs. The 50 percent exceedance forecast is only needed for monthly FNF volume.
   d. See Table 7-3 regarding data collected and where data are missing.

3. Review previous similar research/verifications completed on B-120 and HEFS.
   a. Verification products produced for B-120 and HEFS are worth noting. Sturtevant et al. (near submission) undertook a similar effort for the western United States using SAC-SMA and the Natural Resources Conservation Service principal component regressions that can serve as a model for this work.
   b. Direct comparison between HEFS and B-120 forecasts have not been completed for Oroville and Englebright, but there has been previous, separate verification work on HEFS and B-120 forecasts (see “Statistics: Seasonal Forecast Volume to Observed Volume” in Table 7-2).
   c. A study on HEFS forecasts for major reservoirs in Sierra Nevada has evaluated most of the metrics proposed in this section for Oroville (using hindcast HEFS forecasts from 1985 to 2010), but this work was not completed for Englebright (see “Statistics: Seasonal Forecast Volume to Observed Volume” in Table 7-2).

4. Use the following statistics to compare seasonal forecasts of B-120 and HEFS to observed volumes: percent bias, root mean square error, correlation, Nash-Sutcliffe efficiency, and containing ratio (see “Statistics: Seasonal Forecast Volume to Observed Volume” in Table 7-2).
   a. Once data are retrieved in steps 1 and 2, step 4 will best be illustrated with box plots, summary tables, and additional overlaying plots.

Table 7-2 summarizes the metrics to review the B-120 and HEFS forecasts and Table 7-3 summarizes currently collected data (along with missing information).

Table 7-2. Proposed characteristics for comparing B-120 and HEFS forecasts.

Comparison Information	Details
Period of record	1985 – 2018
Exceedance volumes to review	10%, 50%, and 90%
Forecast issuance date	February 1, March 1, April 1, and May 1
Seasonal forecast volumes	1. A-J FNF 2. WY FNF 3. Monthly FNF volumes (February to July)* * Only have 50% exceedance for entire period of record (10% and 90% exceedance forecasts started in WY 1995 for B-120 and were therefore excluded)
Statistics: seasonal forecast volume to observed volume	1. Percent bias 2. Root mean square error 3. Correlation 4. Nash-Sutcliffe efficiency 5. Containing ratio

Table 7-3. Summary of data retrieved and currently needed for February 1-, March 1-, April 1-, and May 1-Issued Seasonal Forecasts (10%, 50%, and 90% exceedance).

	B-120 ORO	HEFS ORDC1	B120 YRS	HEFS HLEC1
	Feather River at Oroville Dam	Feather River at Oroville Dam	Yuba River near Smartsville (includes Deer Creek)	Yuba River at Englebright
A-J FNF				
Water years available	1966–2018	Hindcasts: 1985–2010 Operational: 2011–2019	1966–2018	Hindcasts: 1985–2010 Operational: 2011–2019
Units	1,000 ac-ft	1,000 ac-ft	1,000 ac-ft	1,000 ac-ft
Missing information	None	A-J FNF forecasts on February 1 and March 1, 2011	None	A-J FNF forecast for February 1 and March 1, 2011
To mitigate missing information	N/A	Aggregate A-J FNF forecasts for February 1 and March 1, 2011, from operational HEFS	N/A	Aggregate A-J FNF forecasts for February 1 and March 1, 2011, from operational HEFS

	B-120 ORO	HEFS ORDC1	B120 YRS	HEFS HLEC1
WY FNF				
Water years available	1979–2018	Hindcasts: 1985–2010 Operational: 2011–2019	1979–2018	Hindcasts: 1985–2010 Operational: 2011–2019
Units	1,000 ac-ft	1,000 ac-ft	1,000 ac-ft	1,000 ac-ft
Missing Information	None	WY FNF forecasts for 2011 to 2013	None	WY FNF forecasts for 2011 to 2013
To mitigate missing information	N/A	Need to confirm with CNRFC if there are archived WY FNF forecasts for 2011 to 2013, otherwise would need to aggregate from operational HEFS	N/A	Need to confirm with CNRFC if there are archived WY FNF forecasts for 2011 to 2013, otherwise would need to aggregate from operational HEFS
Monthly FNF Volume (February to July)				
Water years available	50% Exceedance: 1969–2018 10% & 90% Exceedance: 1995–2018	Hindcasts: 1985–2010 Operational: 2011–2019	50% Exceedance: 1969–2018 10% & 90% Exceedance: 1995–2018	Hindcasts: 1985–2010 Operational: 2011–2019
Units	1,000 ac-ft	1,000 ac-ft	1,000 ac-ft	1,000 ac-ft
Missing Information	There are monthly FNF volume forecasts back to 1969 for 50% exceedance forecasts, but only back to 1995 for 10% and 90% exceedance forecasts	**1.** February, March, and April FNF volume forecasts issued on 2/1, 3/1, and 4/1 WY 2011 **2.** February and March FNF volume forecasts for WY 2012	There are monthly FNF volume forecasts back to 1969 for 50% exceedance forecasts, but only back to 1995 for 10% and 90% exceedance forecasts	**1.** February, March, and April FNF volume forecasts issued on 2/1, 3/1, and 4/1 WY 2011 **2.** February and March FNF volume forecasts for WY 2012
To mitigate missing information	Monthly FNF volume forecasts can be completed for 50% exceedance for period of record, excluding 10% and 90% exceedance forecast	The missing monthly FNF volumes can be aggregated from operational HEFS for the missing date of issuance	Monthly FNF volume forecasts can be completed for 50% exceedance for period of record, excluding 10% and 90% exceedance forecast	The missing monthly FNF volumes can be aggregated from operational HEFS for the missing date of issuance

7.2.2 Airborne Snow Observatory Application

7.2.2.1 Background

ASO snow mapping presently uses two remote sensing instruments: 1) a Riegl Q1560 airborne laser scanner and 2) an ITRES CASI 1500 imaging spectrometer (Painter et al., 2016). The airborne laser scanner is a dual scanning lidar that measures the snow depth at a 3 m spatial resolution by differencing winter snow-on from summer snow-free elevations. The spectrometer measures the reflected radiance across wavelengths from 380 to 1,050 nanometers (nm) at 10 nm nominal spectral resolution to estimate the snow-covered area, spectral albedo, snow grain size, and radiative forcing by light-absorbing particles. Both the lidar and spectrometer are "fused" within the ASO processing pipeline to improve the accuracy and precision of both the ASO-generated snow depth and spectrometer products.

ASO's primary goal is obtaining the basin distribution of SWE (SWE = depth × density). However, because no sensor can yet directly measure SWE in the mountains (Dozier et al., 2016), ASO combines lidar-derived snow depths, coarsened from 3 m to 50 m spatial resolution, with modeled bulk snow density estimates to calculate SWE (Deems et al., 2013; Painter et al., 2016; Tedesco et al., 2014). The bulk snow density is spatially modeled using the iSnobal model (Marks et al., 1999; Painter et al., 2016), which is updated in near real-time with ASO depths (Hedrick et al., 2018). iSnobal represents the snowpack as a two-layered system, rather than a single layer, which allows the model to use a time-sensitive algorithm to account for new snow deposition, snow aging, mechanical compaction, and liquid water. The model has been tested across different landscapes and for various snow research applications, consistently producing reliable results (Garen & Marks, 2005; Link & Marks, 1999; Marks et al., 2002; Nayak et al., 2012).

Errors in ASO's SWE estimate are due to either errors in the snow depth or to modeling errors in the snow density fields. The accuracy and precision of the lidar-measured snow depth are significant, because for SWE, snow depth rather than density is the main source of variability throughout the season (Painter et al., 2016). Painter et al. (2016) reported the root mean square error of the 3 m snow depth product in the upper Tuolumne to be 0.08 m with a bias of less than 0.01 m when compared to manual measurements in 15 x 15 m study plots. This uncertainty decreased for the coarsened 50 m snow depth product to < 0.02 m, which is a much higher vertical accuracy than previously reported in the literature (i.e., DeBeer and Pomeroy [2010]). Of course, the ASO snow depth uncertainty will likely increase within dense forest canopies—some of which cover the Yuba and Feather watersheds. Nonetheless, over time, these types of errors will likely decrease due to both improvements in the technology (i.e., updates to both the lidar and the inertial measurement unit) and improvements in the point-to-grid snow depth algorithm. ASO estimates of density error are valued between 12 and 30 kg m-3—about 3 to 8 percent (Painter et al., 2016). However, for basin-scale total water estimates—a key requirement for FIRO—these errors seem to be somewhat irrelevant (see Painter et al. [2016]).

7.2.2.2 ASO in the Yuba-Feather

During the FIRO Yuba-Feather project, we hope that ASO will make flights for the Yuba-Feather, and our team will be ready to leverage the information that ASO generates, if available, in FIRO work. We will also provide input into data collection, flight paths, and processing if requested. ASO currently has a snow-free digital elevation model of the Feather watershed, so winter 2021 snow-on acquisitions could begin later this year. Moving forward, ASO, Inc. (earlier this year, ASO went through a tech transfer from

NASA's Jet Propulsion Laboratory to a private company) will provide daily streamflow forecasts using WRF-Hydro, in addition to its standard snow products.

ASO flights over the Yuba-Feather watersheds will be instrumental in reducing the uncertainty in the distribution of SWE, as well as for streamflow forecasts. Knowing the distribution of the snow and its albedo in snow-dominated basins reduces the uncertainty in the precipitation forcing, which ultimately improves the accuracy of the melt modeling in both the short and long term (Hedrick et al., 2018). High-resolution estimates of the snow depth, snow-covered area, and grain size before and after a storm can also help improve WRF forecast representation of the spatial distribution of precipitation and the rain-snow transition in hindcasts. While ASO estimates of snow distribution will undoubtedly improve the science, ASO can also directly help water management in real time. Snow measurements reduce the uncertainty in the decision to spill. For example, knowing how much SWE is available for runoff reduces the uncertainty in how much to spill to avoid complications from a large, warm AR. Another example is the potential for ASO to supplement existing water supply forecasts based on snow courses and pillows, which shows promise for mitigating skill loss over the middle of the 21st century (Sturtevant et al., near submission). The wealth of information ASO, Inc., will provide in conjunction with FIRO activities will significantly improve the information accessible to managers and, more importantly, reduce the uncertainty in the decision-making process.

7.2.3 Spring Volume Forecast Uncertainty

Based on the modeling efforts and seasonal forecasting described above, we plan to conduct a preliminary investigation of how snowpack amount and uncertainty in that estimate translates into uncertainty in the spring volume forecast. We will select a model from the participating models described above (candidates include SNOW-17, SAC-SMA, and WRF-Hydro) and a source of seasonal-scale forecasts (candidates include B-120 and HEFS). We will need to identify dominant sources of uncertainty, such as uncertainty in the predicted frequency, duration, or intensities of snowfall events; uncertainty in the impact of rain-on-snow events (Harpold & Kohler, 2017); and uncertainties in melt elevations and melt rates. These will be used to develop an ensemble of possible snowpack amount maps, which will be translated into spring volume forecasts via the B-120 and/or HEFS methods.

Results from this task may be used to help inform a reservoir operator's tolerance for precipitation forecast uncertainty, because a reservoir operator would be more willing to use a meteorological forecast with high uncertainty (e.g., at a five-day lead time) to make pre-releases ahead of a large storm (even into the conservation pool) if they are certain that snowpack is sufficient to refill the reservoir—even without additional precipitation through the rest of the season. Alternatively, meteorological forecast uncertainty tolerance may be lower in a year with little snowpack.

7.2.4 Recommendations

At the conclusion of the research tasks described above, we will recommend how/if seasonal forecasting can be improved in the Yuba-Feather watersheds. These recommendations could include improvements in establishing a current snow state, expanding the data collection network to improve distribution estimates, or changing modeling practices.

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Section 8— Assessment of Potential Socio-Economic Benefits

8.1 Introduction

New Bullards Bar Reservoir and Lake Oroville provide significant socio-economic benefits in the form of flood risk management, municipal and industrial water supply, agricultural water supply, groundwater recharge through agricultural irrigation, hydropower generation, environmental services, and recreation. To quantify the socio-economic benefits of FIRO, we will draw on past benefit assessments for the Lake Mendocino Final Viability Assessment, Prado Dam Preliminary Viability Assessment, and the U.S. Bureau of Reclamation (USBR) (WaterSMART)-funded study commissioned by Sonoma Water and conducted by Eastern Research Group (ERG). Our methodology is based on the following steps:

- Identify benefits.
- Prioritize as needed (some benefits may be minor, extremely difficult to monetize, etc.).
- Choose best methods to estimate benefits (candidate methods described below).
- Collect data.
- Estimate benefits for FIRO scenarios under consideration compared to baseline operations.
- Solicit input from selected individuals with subject matter and/or economic expertise.
- Finalize estimates and present them to reflect seasonal and climate variability.

For each benefit category, we provide background information and an overview of the methods. Each benefit estimate is an average annual estimate based on information about FIRO’s impact on water supply, availability, and dependability. The analysis will also account for the benefits that occur in “wet” years compared to “dry” years. We will compute the annualized value over a timeframe of 20 years using a discount rate of 2.75 percent.

To develop these methods, the FIRO team reviewed the USBR’s prior work on these benefit categories, researched potential methods and data sources, and convened a meeting with economists on March 11, 2020. The National Economic Development (NED) procedures from the 1983 guidelines (U.S. Water Resources, 1983) provide useful parameters for our methodologies. These procedures outline steps to estimate various benefits, using a variety of techniques such as benefit transfer, demand curve estimates, and least cost alternatives.

The main objective of FIRO at New Bullards Bar and Lake Oroville is flood risk reduction. Much of this analysis has been conducted in a feasibility study (Yuba Water, 2018) for Yuba-Feather Forecast-Informed Operations (F-IO), described below. Additional socio-economic benefits to municipal and industrial water supply, agricultural water supply, groundwater recharge, hydropower generation, environmental services, and recreation are secondary to flood risk reduction but may still be significant.

8.2 Flood Risk Reduction

8.2.1 Background

Without more advanced forecasts and lead time, communities on the Yuba and Feather Rivers can suffer from flood damages due to severe water flows during heavy storms. If FIRO allows for more time to prepare for events, as well as better storage metrics so that more water is released before major events, the region will benefit from fewer flood damages, improved water quality from reduced sewer overflow events, and less wear on flood infrastructure.

The most destructive recorded floods on the Yuba and Feather Rivers occurred in 1950, 1955, 1986, 1997, and 2017. Major storms resulted in record flows, which eroded levee embankments and exceeded design levels downstream of New Bullards Bar Dam and Oroville Dam. The 1986 and 1997 flood events caused levee breaches in Yuba County that resulted in loss of life, major property damage, and long-term socio-economic impacts. The state of California paid out $500 million in damage claims associated with the 1986 event. In 2017, the spillways at Lake Oroville were damaged, leading to the evacuation of more than 180,000 people. Reconstruction of the spillways cost over $1 billion.

A feasibility study conducted a flood safety analysis for Yuba-Feather F-IO, combined with structural modifications at New Bullards Bar—namely, raising New Bullards Bar Dam—and the addition of low-level spillway capacity referred to as a secondary spillway (Yuba Water, 2018). Each option has the potential to increase water supply reliability while also increasing flood protection. The cornerstone of these objectives is achieving a high level of flood protection and reliability equivalent to protection against a 1-in-500-year flood event.

Three alternatives were evaluated and compared to existing facility and operational conditions:

- F-IO of Lake Oroville and New Bullards Bar Reservoir (F-IO only)
- F-IO with New Bullards Bar Dam raise
- F-IO with New Bullards Bar secondary spillway

One of the three options, F-IO, is an extension of the earlier F-CO Program. It was recognized that to effectively implement F-IO, the reservoirs must have additional dedicated flood storage capacity or sufficient low-level spillway capacity to evacuate water before major flood flows.

Flood protection benefits had to meet two principal objectives: 1) reduce peak stage at downstream locations, and 2) add redundancy to manage large storm events if existing structures become compromised. F-IO alone was found to provide minimal benefits. The best alternative was the F-IO with secondary spillway, which provided improvements over F-IO with dam raise.

Benefit/cost (B/C) ratios for a secondary spillway with 35 kcfs capacity were found to be on the order of 1.76 to 2.25 depending on the project condition (27 kcfs highest ratio, 35 kcfs, and 46 kcfs lowest ratio; California discount rate 3.5 percent over 50 years with lower ratios and a federal discount rate of 2.75 percent over 50 years with higher ratios).

8.2.2 Methods and Data

Decreasing the number of floods over time could have significant economic consequences for the region. In the 2020 New Bullards Update (hereafter, the 2020 update) of the 2017 David Ford Consulting Engineers study (hereafter, the 2017 study), expected annual damage (EAD) and expected annual benefit computations were calculated using new stage-frequency functions. The 2020 update computed EAD and expected annual project benefits for the existing condition and three secondary spillway designs.

EAD is defined as the integral of the damage-probability function, which weights damage per event by the probability of the event in any given year and sums across all possible events. The damage-probability function is a function of 1) the hazard (e.g., a flood), that is the frequency and magnitude of flows; 2) the performance of flood risk reduction measures; 3) the exposure of people and property in the floodplain; and 4) the vulnerability of people and property in the floodplain. Consequence is the harm that results from a single occurrence of the hazard.

The 2020 update integrated this task using the U.S. Army Corps of Engineers' (USACE's) HEC-FDA, examining 11 impact areas and 19 index points along the Yuba, Feather, and Bear Rivers; Upper Intercept; and Dry Creek. Levee conditions were held constant across scenarios. MBK Engineers provided stage-frequency functions, including events ranging from p = 2/3 to p = 1/5,000. Algorithms in HEC-FDA describe the uncertainty of a stage-frequency function with a statistical model.

The 2020 update used the same exterior-interior functions—defining the relationship between the stage on the river or exterior of the levee and the stage in the floodplain or interior of the levee—as the 2017 study. Levee performance functions were also consistent with the 2017 study, which AECOM developed for the California Department of Water Resources' (DWR's) (2017) Central Valley Flood Protection Plan Update, with additional data from DWR's urban levee evaluations (DWR, 2012) and non-urban levee evaluation projects (DWR, 2011), as well as performance functions from the DWR (2014) performance curve development.

The 2020 update used a structure inventory from DWR (2015) covering single- and multi-family residences; commercial, industrial, and public structures; crops; highways and streets; vehicles; business losses; emergency costs; displacement and temporary housing; and statistical lives lost. Population-at-risk estimates in the 2020 update were consistent with the 2017 study. Residential depth-consequence functions were consistent with depth-damage functions from a USACE economic guidance memorandum (USACE, 2003); non-residential depth-damage functions were derived from the American River watershed project, Folsom Dam modifications, and Folsom Dam raise project final economic re-evaluation report (USACE, 2008).

The 2020 update provides detailed analysis results. In summary, direct EAD was found to be on the order of $20 million for the without-project scenario, $14 million with 27 kcfs, and $13.2 million with 46 kcfs. The 2020 update breaks down costs and benefits by direct damage category and impact area. In addition, indirect damages are estimated at $5 million without project to $3.1 million with 46 kcfs. While the 46 kcfs project provides the greatest estimated benefits, it is also more expensive than the 27 kcfs scenario. Taking costs into account, the lower kcfs scenario yields higher B/C ratios. Computations of the value of statistical life indicated improvements from 2 statistical lives lost without project to 1 statistical life lost with project at Marysville. The value of a statistical life is on the order of $6.9 million to $9.6 million according to different federal agencies.

Summing all benefits yields estimates of annual benefits on the order of $14.6 million for the 27 kcfs option to $15.7 million for the 46 kcfs option (or $394 million to $424 million in present value over 50 years using a federal standard 2.75 percent discount rate). Project costs are estimated at $175 million (27 kcfs) to $210 million (46 kcfs). Hence, B/C ratios range from 2 (27 kcfs) to 2.25 (46 kcfs) using the federal 2.75 percent discount rate. Using the higher 3.5 percent California discount rate, the B/C ratios range from 1.76 to 1.96. These are significant B/C ratios for public water storage reliability and dam safety projects.

8.3 Municipal and Industrial Water Supply

8.3.1 Background

A household's ability to store and use water has significant use-value benefits. Storing more water during wet periods enables households to release more water during dry periods. Therefore, FIRO's improved forecasts will allow households that rely on Lake Oroville for water to benefit from having an increased water supply, especially in times of drought. New Bullards Bar does not directly provide a municipal and industrial (M&I) water supply. M&I water in Yuba County is sourced from groundwater. However, the New Bullards Bar water supply to agriculture has restored the groundwater aquifer to provide a reliable source of water for M&I providers. Note that Yuba Water Agency water transfers to DWR through the Yuba Accord provide water for agriculture and M&I uses. This increased reliability can be analyzed.

Increased consumer water supply reliability would benefit all residents that rely on water from Lake Oroville for many purposes, including but not limited to drinking water. Lake Oroville is a keystone facility within the California State Water Project (SWP) and plays a significant role in providing drinking water to millions of California residents.

Businesses, including agriculture and municipal projects, also depend on water from New Bullards Bar Reservoir and Lake Oroville. Increased water supply for local businesses and the government will lead to more production in general, as well as greater productivity from the production that already occurs. If FIRO allows for additional water availability for businesses and municipalities, the region will realize economic benefits from increased production.

Production for local businesses depends on water supply reliability. Through improved reliability, FIRO could impact economic output, gross state product, and jobs. An example of the potential impact can be seen from a study conducted for the Colorado River. James et al. (2014) estimated the economic impact of the Colorado River's water supply, finding that it led to a gross state product of $657 billion in 2014 and contributed to more than 7 million jobs in just seven counties in Southern California. While increasing water supply reliability at New Bullards Bar and Lake Oroville may not have an impact of this scale, even a small change in water supply reliability could have large economic consequences.

8.3.2 Methods and Data

To measure the benefit of increased water supply for M&I purposes, we will model the expansion of water supply using the cost of water from publicly available data in the 2019 Water and Wastewater Rate Survey Book (American Water Works Association, 2019), water demand, and an estimate of the increase in water supply. This model will allow us to derive a demand equation that results in a new price for water. Furthermore, the new price can be applied to the amount of water that M&I sources use to calculate an economic benefit.

We can use several methods to estimate the value of water for M&I users. One method estimates demand curves for water usage and uses the inferred price elasticities of demand to quantify changes in consumer and producer surplus due to an increase in water reliability. The price elasticity of demand is a measure of the change in the quantity of a good or service demanded based on a change in the price of that good or service, in this case water. The elasticity is then used to generate a demand curve and calculate how price may change due to a change in water reliability. The old and new prices and quantities are then used to calculate the change in consumer and producer surplus.

The first step in this analysis is to estimate the elasticity with a regression model using either 1) time series data on water prices and usage in the Yuba-Feather watersheds and surrounding region, or 2) cross-sectional data on water prices and usage across a variety of locations. Time series data are not readily available in California, so we will use cross-sectional data. A log-log regression model allows the coefficient on price to be interpreted as demand elasticity.

We will draw the sample from the American Water Works Association's (AWWA's) 2019 Water and Wastewater Rate Survey, which collects data on consumer water prices and quantities—the two primary variables necessary for the analysis. Quantity data are available for residential and non-residential users. However, for each of these users, several prices are available. The selection of prices from the complex rate schedules will follow the method outlined in the Lake Mendocino Final Viability Assessment.

To isolate the impact of price on quantity demand, we will use control variables that are expected to influence demand, including temperature and precipitation, median household income, household and population density, and population in the water district.

Next, we will apply estimates of the increase in water supply reliability from this to the demand curve estimated from the AWWA data. Finally, we will estimate the change in consumer and producer surplus. Consumer surplus is the benefit that consumers receive when they value a good or service more than the market price. In a supply and demand model, consumer surplus is represented as the area under the demand curve and above market price. Similarly, producer surplus is the benefit that producers receive from selling a good or service above the cost of production. The increase in producer surplus can be represented by the area above the supply curve and below market price. The shift in the supply curve from FIRO creates an increase in consumer surplus. We will calculate changes in consumer and producer surplus associated with FIRO separately for the residential market and the commercial and industrial market.

8.4 Agricultural Water Supply

8.4.1 Background

Better crop irrigation can improve the quality and quantity of agricultural goods, leading to an economic benefit. FIRO could help attain that economic benefit by providing better forecasting, which in turn may possibly allow more water to be stored in New Bullards Bar Reservoir and Lake Oroville during dry periods and more water to be released in anticipation of incoming wet periods. These factors could possibly contribute to improved crop irrigation, output levels, and crop quality for the agricultural industry.

Agricultural output is significant for Butte and Yuba Counties. Agricultural revenues in Yuba County in 2015 were over $200 million, with significant production of rice, deciduous crops, and pasture. Agricultural revenues in Butte County in 2015 were over $730 million, with significant production of rice, deciduous crops, and almonds and pistachios (USDA, 2020). In addition, Lake Oroville is the main source of water for municipal, industrial, and agricultural uses of the SWP, accounting for 3.5 million ac-ft of the 5.7 million ac-ft capacity of the system. Extending the analysis of FIRO benefits across the entire SWP and to the San Joaquin River and Tulare Lake DWR hydrologic regions may be beyond the scope of this project.

8.4.2 Methods and Data

To estimate how FIRO can increase agricultural output, we will determine changes in land use using a farm budget and land value analysis. This analysis will determine the extent of land that additional water and better water quality will affect; from that estimate, we can determine how much additional agricultural output will result, as well as a dollar value using market prices for prevalent commodities—such as rice, pasture, and deciduous crops—in Butte and Yuba Counties.

We will evaluate annual avoided losses from agricultural production due to FIRO water management. Specifically, we will use the residual imputation method (also known as the residual value method) to compute the value of water by subtracting all known input costs from the total value of the crop. The remainder is attributed to water. This methodology will include:

- Determining the acreage of land and market value of prevalent crops. For New Bullards Bar and Lake Oroville, we can determine this from regional county crop reports.
- Determining the input costs per crop.
- Using the residual imputation method to calculate the value of a unit of water.
- Calculating the annual avoided losses due to FIRO by multiplying the estimated value of a unit of water by the increase in water supply available for agriculture that FIRO generates.

For this benefit, we are making an underlying assumption that producers are price takers on the market.

8.5 Hydropower Generation

8.5.1 Background

FIRO may lead to increased hydropower generation that would directly benefit consumers. The use of hydropower in place of fossil fuels also reduces carbon emissions.

In 2019, California used hydro-produced electricity totaling 19.2 percent of its in-state generation portfolio. The Edward Hyatt Powerplant at Oroville had a capacity of 644 megawatts (MW) in 2019 and generated 2,663,585 net megawatt-hours (MWh). The Colgate Powerplant at New Bullards Bar had a capacity of 315 MW in 2019 and generated 1,638,632 net MWh. This translates into enough electricity to power 390,000 households per year (CEC, 2020). Additional powerhouses that could be considered include Thermalito (DWR) and Narrows 1 and 2 (Yuba Water). Thermalito has a capacity of 115 to 120 MW and is now fully operational following the 2012 fire. The Thermalito Diversion Dam Powerplant has a 3 MW capacity. Narrows 1 and 2 had capacities of 12 and 55 MW and generated 46,910 and 266,252 net MWh in 2019, respectively.

8.5.2 Methods and Data

To quantify the economic difference that FIRO would make to hydropower generation, we will use the methods developed in the USBR FIRO Economic Benefits Methodology. This methodology estimates the future demand for electric power while defining the current system for generating resources, then evaluates the difference between the future demand and the current system's capabilities. The NED guidelines suggest estimating the future demand for electric power while defining the current system for generating resources, then evaluating the difference between the future demand and the current system’s capabilities. The NED procedures, however, are more extensive than what this project needs, since FIRO results in additional flow at times during the year that can be used for hydropower. Thus, the approach for this benefit category simplifies the NED approach by focusing solely on the value of the increased reservoir releases through hydropower turbines. This will involve:

- Identifying weekly market prices. California compiles these data, which can be used for Butte and Yuba Counties.
- Identifying the appropriate price to use (either the market price or the price that producers receive), which we will determine as we implement the method.
- Determining the additional generation that could occur due to FIRO, which we could do based on the findings of the viability assessment.
- Calculating the benefit by multiplying the price by the additional generation.

8.6 Environmental Services

8.6.1 Background

Improved reservoir management from FIRO can allow for more controlled water releases in anticipation of precipitation and increased storage for release during dry periods. These improved releases could possibly improve fish habitats. The specific species on the Yuba and Feather Rivers that may benefit include salmon; steelhead and rainbow trout; German browns; largemouth, smallmouth, and black bass; crappie; catfish; and bluegill.

In general, healthy habitats provide a benefit to society, as "studies have shown that regardless of direct interaction with salmon populations, many Californians hold a positive willingness to pay to ensure the long-term survival of salmon" (ECONorthwest, 2012).

Willingness-to-pay studies use stated preference methods to elicit how much people value a variety of goods and services. Washington state studied people's willingness to pay for increases in various fish populations. The results showed high variation in people's willingness to pay for different fish populations, but households highly valued every type of fish. The ranges ran from $9.92 to $28.84 per household for a 50 percent increase in a particular fish's population. Even with a conservative estimate of the number of households along the Yuba and Feather Rivers and a smaller increase in fish population, maintaining and improving fish populations still provides a significant economic benefit.

The use value of having healthier fish populations will benefit the local population, local businesses, and the tourism industry. The non-use, passive existence value of improved habitats is a benefit to society.

8.6.2 Methods and Data

To estimate a dollar value for improving fish habitats along the Yuba and Feather Rivers, we will use benefit transfer methods from the Washington state study described above, as well as least cost alternative methods described in the USBR FIRO Economic Benefits Methodology.

Least cost alternative methods identify alternatives to FIRO that would achieve the same change in fish populations and consider the associated costs. Some alternatives to FIRO include planting trees, developing new reservoirs or dams or modifying existing dams, and buying water rights. In the least cost alternative method, we choose the alternative with the least cost and use that cost as a proxy for the benefit of FIRO.

8.7 Recreation

8.7.1 Background

FIRO can lead to increases in recreation in the reservoirs and along the Yuba and Feather Rivers, as better reservoir management allows for additional water to be stored in New Bullards Bar and Lake

Oroville and higher levels of water to be released from the reservoirs. This will lead to a steadier flow of water along the Yuba and Feather Rivers, creating more opportunities for recreation. People directly benefit from receiving these increased opportunities and are willing to pay for recreation. Private businesses involved with tourism and recreational activities also benefit.

There is a market for recreational activities along the Yuba and Feather Rivers. Similar analyses for other areas also show the potential for economic benefits from recreation as a result of increased water supply. A study on the Colorado River showed that a 100,000 ac-ft increase in water over a year would result in more than 18,000 visits to nearby lakes and more than $350,000 in spending from tourism-related activities (Neher et al., 2013).

8.7.2 Methods and Data

To estimate the benefit of additional recreation due to FIRO, we will implement a benefit transfer analysis. We will identify studies that have evaluated travel costs or contingent values to obtain daily use values for recreation resulting from the water flow along the Yuba and Feather Rivers. We will use these dollar estimates in tandem with additional estimates of the current amount of recreation and the amount of recreation that FIRO will add to calculate the dollar added value that FIRO will bring to recreation along the Yuba and Feather Rivers.

The NED guidelines suggest using willingness-to-pay estimates from a travel cost method, contingent valuation method, or unit day value method. In addition, general steps involved with the valuation process include defining the study area, estimating the current recreation use, determining the future recreation with and without the proposed changes (in our case, FIRO implementation), and computing the benefit based on the difference in recreation and a determined valuation of that recreation. To the extent feasible with available studies, we will estimate increased recreation in the area rather than simply estimating the transfer of activities to New Bullards Bar and Lake Oroville from other activities.

This work will require estimating the increased level of (daily) recreational activity due to increased water levels at New Bullards Bar and Lake Oroville, or increased river flows downstream of the lake, and then applying a daily use value to those increased levels. One major consideration for this analysis is the seasonality of recreation and how reservoir elevation, river elevation, and river flow changes caused by FIRO correlate to seasonal variation in recreation. Our analysis will include:

- Determining the annual frequency for each type of recreational activity that occurs at New Bullards Bar and Lake Oroville and downstream.
- Determining the additional recreation, in days, that will occur due to FIRO.
- Estimating the daily use value for each recreation type. The U.S. Geological Survey Benefit Transfer and Use Estimating Model Toolkit provides a starting point for the daily use values. In addition, USACE’s unit day values for recreation are useful for our purposes.
- Estimating the value of increased recreation as the product of the increased levels of (daily) recreation and daily use values.

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Section 9— Hydrologic Engineering Management Plans for the Evaluation of FIRO Water Control Plan Alternatives

This section provides the framework through which specific Forecast Informed Reservoir Operations (FIRO) Water Control Plans (WCPs) can be formulated and evaluated objectively. The FIRO team has developed Hydrologic Engineering Management Plans (HEMPs) for both New Bullards Bar Dam (Section 9.2) and Oroville Dam (Section 9.3).

To meet the project objectives defined in Section 9.1, we developed a Simulation Plan, ensuring that the candidate WCPs are presented with events and historical periods that allow for robust and demonstrative results. Also, given the existing Forecast-Coordinated Operations (F-CO) Program, we considered how to perform joint reservoir operations associated with extreme flood events. Section 9.1 provides the Simulation Plan.

Section 9.4 identifies and addresses the relationship between the FIRO HEMP formulation and analysis and the evaluation of WCP alternatives associated with the U.S. Army Corps of Engineers (USACE) Sacramento District Water Control Manual (WCM) Update Project.

9.1 Simulation Plan

9.1.1 Background

This Simulation Plan informs the HEMPs created to evaluate WCP alternatives associated with New Bullards Bar Dam and Oroville Dam. The period of record (POR) for forecasts is much shorter than the POR of observations and does not include key flood events such as the December 1955 or December 1964 floods. To improve the robustness of the evaluation, this Simulation Plan combines a set of scaled events focused on flood risk reduction with a POR run for higher-performing alternatives that addresses the impacts of “false alarms” on water supply reliability.

In addition, this plan must address F-CO when indicated by the simulation of recommended releases of New Bullards Bar and Oroville Dam.

9.1.2 Objective

The overarching objective of the Yuba-Feather FIRO project is to improve flood risk management benefits across the basin without negatively impacting other uses, including water supply, hydropower production, recreation, and ecological benefits. As such, simulations will focus on selected scaled events of approximately one month in duration that more clearly define the performance difference between alternative WCPs. Once we have identified the more effective WCPs, we will perform a POR simulation to ensure that there are no (negative) impacts on water supply reliability or other authorized benefits.

9.1.3 Available Forecasts

Ensemble hindcasts based on the GEFS V10 reforecast are currently available from the California Nevada River Forecast Center (CNRFC) for water years 1985–2010. The hindcasts are available for the inflows to the two reservoirs and all local junction flows downstream to the confluence with the Bear River. These hindcasts have 60 members and an hourly time step, extend 15 days into the future, and are available once per day throughout the period. The CNRFC is currently updating the streamflow hindcasts using GEFS V12. It is likely that these newer (perhaps more skillful) hindcasts will be available before the work described by the HEMP begins.

9.1.4 Scaled Events

Because the POR of forecasts is limited to 26 years and does not include the flood of record, scaled events must be created to evaluate the effectiveness of candidate WCPs associated with more extreme events. The frequency of historical events is not uniform across a basin of this size, so the FIRO team will use scaling factors to approximate events larger than observed within the hindcast period. Table 9-1 shows the design dates and scaling factors selected for this evaluation.

Table 9-1. Scaled events.

Event	Simulation Start Date	Simulation End Date	Scaling Factors
February 1986	2/1/1986	3/1/1986	1.2, 1.4
January 1997	12/15/1996	1/15/1997	1.2, 1.4
January 2006	12/15/2005	1/15/2006	1.2, 1.4
February 2017	2/1/2017	3/1/2017	1.2, 1.4

The scaling factor is used as a multiplier for the forecast mean areal precipitation across the basin and for each computational six-hour period within the simulation window. This process generates both scaled streamflow forecasts and, when applied to the observed precipitation, “observations” of streamflow throughout the system.

The FIRO team will perform daily simulations of WCP operations starting with the first day of the design event and continuing through the last day of the design event, as shown in Table 9-1. The initial reservoir storage will be taken as either 1) the historical observed storage or 2) the top of conservation (using “dry” condition for Oroville) based on team engineering consensus. The time step of the daily simulations will be hourly. Hourly release decisions (t0 through t23) will be based solely on forecasts and observations available at the beginning of each day (t0). Simulated conditions downstream will be computed by combining these releases with simulated hourly local flows at all downstream junctions of interest associated with the design event and frequency. While normal flood operations forecasts are updated every six hours, the historical hindcasts are only available once per day. This is deemed adequate for the purpose of differentiating between the WCP alternatives and the WCM baseline.

9.1.5 Period of Record for Seasonal Simulations

Seasonal simulations are needed to better access the full range of impacts associated with the use of forecasts. Restricting the evaluation to known flood events fails to assess the impacts of “false alarms” or events that were forecasted to be significantly higher than what was observed. Additionally, the impacts of a proposed WCP on spring refill cannot be assessed without carrying the simulation through the refill period. Still, given that the primary motivation is improving flood risk management, the POR assessment will only be performed on a subset of the alternatives identified through the scaled event evaluation process.

It is understood that year-round simulation presents challenges associated with “incidental” storage and assumed demands and minimum releases. As a compromise, and with the understanding that evaluation only provides comparative results (with baseline and other candidates), we will take reservoir releases from the 10-year monthly mean sans 2017. We will compute these monthly mean releases as one of the “side studies” identified in Task 3 of Table 9-6 and Table 9-16.

Simulations of WCP operations will begin on January 1, 1985, with the observed storage in each reservoir and continue through September 30, 2017. The time step of the daily simulations will be hourly. Hourly release decisions (t0 through t23) will be based solely on forecasts and observations available at the beginning of each day (t0) as with the scaled simulations. We will compute simulated conditions downstream by combining these releases with observed (or computed) hourly local flows at all downstream junctions of interest available from the Central Valley Hydrology Study.

9.1.6 F-CO

Independent simulation of New Bullards Bar and Oroville Dam will not reflect the existing coordination framework designed to avoid exceeding established WCM operational limits at the confluence of the Yuba and Feather Rivers and downstream to the confluence with the Bear River.

This joint operation requires us to conduct simulations within the same ResSim model. The existing ResSim model may need some refinement to "balance" the model-coordinated releases based on percentage of available flood storage or some other measure. Refinement and formalization of this coordination process is part of FIRO development.

Once a commonly acceptable release pattern is established for each forecast day, the FIRO team will simulate the resulting downstream conditions using procedures described above for either the scaled event or simulation runs.

9.2 HEMP for New Bullards Bar Dam FIRO Evaluation of WCP Alternatives

9.2.1 Summary

Efforts to improve the coordinated operations of the New Bullards Bar and Oroville Dams formally began in 2006 with the F-CO Program. That program has been tremendously successful in developing a common operating picture for reservoir operators, improving the observation network, and integrating single-value and more recently ensemble streamflow forecasts into the coordinated decision-making process.

The FIRO program for the Yuba-Feather system is an extension of the F-CO effort and leverages the experience of FIRO efforts for Lake Mendocino and Prado Dam. The FIRO effort introduces research to improve forecasts and formally integrates streamflow forecasts into the water management decision process (WCP for USACE or Section 7 dams). An interagency, interdisciplinary Steering Committee was formed for the Yuba-Feather FIRO project in June 2019.

The objective of this HEMP is to identify, through appropriate detailed technical analyses and other considerations, candidate FIRO strategies for New Bullards Bar Dam, along with how USACE and Yuba Water might implement those strategies in real-time operations. Section 9.3 provides the HEMP for Oroville Dam. The Simulation Plan in Section 9.1 captures the process to ensure that the independent results from the New Bullards Bar and Oroville Dam HEMPs meet the objectives of the F-CO.

Yuba Water is currently adding a new water control structure to New Bullards Bar Dam that will dramatically improve the capacity to release stored water more quickly and at lower storage levels. This analysis assumes the conditions associated with this completed construction project.

The Yuba-Feather FIRO Steering Committee manages this HEMP. To be consistent with USACE guidance for conducting similar technical studies, the Steering Committee prepared this HEMP as "*…a technical* *outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem"* (Engineering Pamphlet 1110-2-9).

This HEMP identifies the following:

1. Objective and overview of technical study process to provide information needed for this assessment.
2. Requirements for all FIRO alternatives that will be considered. These are presented in Table 9-2.
3. Hard criteria as well as project and system-wide considerations. These are presented in Table 9-3, Table 9-4, and Table 9-5.
4. Tasks to be completed for the technical analysis. These are presented in Table 9-6.
5. Initial tentative performance metrics for FIRO alternatives evaluation. These are presented in Table 9-7.
6. Analysis tools and methods to be used for the study.
7. Candidate FIRO alternatives to be analyzed. These are presented in Table 9-8.
8. Project team members and their roles and responsibilities for conducting, reviewing, and approving the hydrologic engineering study. These are presented in Section 9.2.6 and Table 9-9 and Table 9-10.
9. Risks to the success of this study and mitigation actions are shown in Table 9-11.

9.2.2 Objective of Technical Analysis, Overview of Process, and Tasks to Be Completed

The objective of the hydrologic engineering study described herein is to identify and evaluate New Bullards Bar Dam FIRO alternatives in a systematic, defendable, repeatable manner, thus providing information to the Steering Committee so that it can identify the best FIRO strategy for New Bullards Bar Dam.

The process used to meet the hydrologic engineering study objective is a "nominate-simulate-evaluate-iterate" process, consistent with the process that USACE commonly uses for water resources planning studies. The project delivery team (PDT) will conduct the following technical analysis tasks in this process to support the New Bullards Bar Dam FIRO Viability Assessment:

1. Develop a set of feasibility criteria and performance metrics for assessing and comparing FIRO alternatives. This set will be applied to all alternatives, thereby permitting the PDT to compare and rank alternatives for the Steering Committee's consideration.
2. Nominate a set of alternative FIRO strategies that are screened to ensure they meet specified requirements (described below).
3. Simulate the river-reservoir system's performance with each FIRO strategy using a common set of meteorological and hydrological conditions. HEC-ResSim is likely to act as the "gatekeeper" for all alternatives to ensure that the physical constraints and attributes of the system are consistently applied.
4. Use the simulation results to evaluate the viability and performance of each strategy. The evaluation uses metrics identified in Task 1, comparing each alternative to the performance of the *without-project* condition (i.e., operation following the WCP included in the current WCM). If results of the evaluation inform refinements to FIRO strategies, the PDT will repeat the simulation and evaluation tasks with enhanced strategies to the extent that resources allow.

Use the technical analysis results to rank the alternatives and submit the rankings to the Steering Committee for consideration.

These tasks are described in more detail in Table 9-6. Major tasks are listed in column 1 and subtasks in column 3.

9.2.3 FIRO Alternatives to Be Evaluated

Selection of specific FIRO alternatives is a task to be completed as a component of the hydrologic engineering study (see below). Requirements of all candidate FIRO strategies are shown in Table 9-2. Table 9-3, Table 9-4, and Table 9-5 show additional constraints and objectives that the proposed alternatives should meet.

Table 9-2. Requirements of all alternative FIRO strategies.

ID (1)	Description (2)
1	The candidate FIRO strategy must satisfy all relevant USACE engineering regulations (ERs), including but not limited to the following: • ER 1105-2-100: *Planning Guidance Notebook* • ER 1105-2-101: *Risk Assessment for Flood Risk Management Studies* • ER 1110-2-240: *Water Control Management* • ER 1110-2-1156: *Safety of Dams Policy and Procedures* • ER 1110-2-1941: *Drought Contingency Plans* • EM 1110-2-3600: *Management of Water Control Systems* • ER 1110-2-8156: *Engineering and Design Preparation of Water Control Manuals* • EM 1120-2-1420: *Engineering Requirements for Reservoirs*
2	The analytical tools required for implementing the candidate FIRO strategy must be compatible with USACE's CWMS software. In addition, results of any analyses completed with software that USACE has not currently certified for use must be demonstrated to produce results consistent with USACE software results.
3	Streamflow forecasts used by the candidate FIRO strategy must be those that the National Weather Service's CNRFC has provided. Simulated streamflow forecasts must be consistent with the skill characteristics of those issued by the CNRFC. As appropriate for the alternative, the forecast used can be ensemble and/or single value.
4	The FIRO strategy must satisfy the hard (inviolable) operation constraints shown in Table 9-3.
5	The FIRO strategy should represent and to the extent possible meet the operation objectives shown in Table 9-4 and Table 9-5.
6	Software development needed to implement the FIRO alternative must be limited for the viability assessment, as the objective is to select from amongst a set of readily available (or nearly so) strategies.
7	Simulations should be computed at an hourly time step.

Table 9-3. Hard (inviolable) operational constraints that all FIRO strategies must satisfy.

ID (1)	Limiting Condition (2)	Description (3)
1	Must satisfy New Bullards Bar WCM emergency spillway release diagram (ESRD)	Meet all specific requirements stated on current ESRD.
2	Must adhere to physical constraints and system properties as codified in the F-CO ResSim configuration	The operational F-CO ResSim configuration holds the physical and regulatory limits associated with storage, release, and conveyance. In order to improve the potential to compare alternatives, this configuration will be used to condition all model-recommended releases.
3	Must satisfy limits on release rate of change	Releases must not increase more than 10,000 cfs or decrease more than 5,000 cfs in any two-hour period (1972 WCM, Ch. 7, “Limitations on Releases”). Release rate of change is governed by the potential impacts to the levees and on the fisheries environment as well as public safety.
4	Must not require a frequency of forecast updates other than what is currently available	Forecasts are issued a maximum of four times per day in major flood events. Under normal conditions, forecasts are issued two times per weekday in winter and once per day otherwise under normal conditions. For alternative evaluation purposes, forecast updates will be once per day.
5	Must not assume that storage is available in Marysville Reservoir	The 1972 WCM operation assumes storage is available in Marysville Reservoir. Marysville Reservoir was never built.
6	Must include function of new secondary spillway	The FIRO alternatives must incorporate the function of the new secondary spillway with the capacity and associated attributes available at the time of the analysis.

Table 9-4. Operational considerations that should be evaluated in the hydrologic engineering study.

ID (1)	Operational Consideration (2)	Description (3)
1	Satisfy 1972 WCM flood management objectives[1]	Meet all objectives stated on the current flood control diagram.
2	Avoid releases that exceed downstream limitations	The flow limits stated in the USACE Regulation for Flood Control were designed to be observed assuming construction of the Marysville Dam. Without the Marysville Dam in place, meeting these flow objectives is more difficult during major flood events due to the lower amount of flood storage capacity and the uncontrolled flows from the South and Middle Yuba Rivers. When this unregulated flow and the New Bullards Bar Reservoir inflow and elevation are high, it is possible that the flow in the Yuba River will exceed the maximum flow target of 120,000 cfs on the Yuba River at Marysville, even with minimal New Bullards Bar Dam releases. Flows at the confluence with the Feather River should be limited to 300,000 cfs and flows at the confluence with the Bear River should be limited to 320,000 cfs.
3	Consider levee erosion potential	Both the rate of release and duration of a given channel stage are a concern for levee erosion.
4	Consider conditional surcharge effects on downstream flow constraints	The alternative should consider the effect of dam surcharge on downstream channel constraints.
5	Balance flood control and water supply benefits	The flood control operation should consider the ability to meet water supply targets during the spring refill period and summer.
6	Balance flood control and hydropower benefits	The flood control operation should consider hydropower production by releasing through the Colgate Powerplant when possible, without compromising flood releases.

Notes:

(1) The USACE-prescribed operational flood control rules for New Bullards Bar Dam and Reservoir are contained in the New Bullards Bar Dam flood control manual, specifically Chart A-6 of Appendix A, “Standing Instructions to Dam Tenders Including Emergency Spillway Operation and Flood Control Regulations,” within the *Report on Reservoir Regulations for Flood Control, New Bullards Bar Dam, North Yuba River, California, Sacramento* (USACE, 1972c).

Table 9-5. Operational considerations that should be evaluated in the hydrologic engineering study.

ID (1)	Operational Consideration (2)	Description (3)
1	Implementation of F-CO of New Bullards Bar Reservoir and Lake Oroville	Under the F-CO Program, the California Department of Water Resources (DWR) and Yuba Water coordinate releases from Oroville and New Bullards Bar during large events to avoid flooding at the confluence of the Feather and Yuba Rivers and downstream. Specifically, releases are coordinated to avoid exceeding 300,000 cfs on the Feather River below the confluence with the Yuba River and 320,000 cfs below the confluence with the Bear River.
2	Operational resiliency	The FIRO alternative should be resilient to a wide range of hydrologic events within the watershed. For example, the operation should be resilient to a range of storm-centering and events of key frequencies occurring within the Yuba and Feather watersheds.

Table 9-6. Tasks and subtasks to be completed for hydrologic engineering study of FIRO strategies.

Major Task (1)	Description (2)	Subtasks (3)
Task 1. Select performance metrics.	Both quantitative and qualitative measures of performance will be identified. Methods of computation of quantitative measures will be described.	**Task 1.1.** With appropriate input from subject matter experts (SMEs), formulate candidate set of quantitative and qualitative measures of performance. Define methods for assessing these for typical FIRO strategies. Screen set to select feasible metrics for ALL likely alternatives to permit objective comparison of strategies. Prepare a technical memo. Submit to Steering Committee for review. **Task 1.2.** Receive comments from Steering Committee. Revise selected set of performance metrics as required. **Task 1.3**. If necessary, design, develop, and test software applications (scripts, spreadsheets, etc.) to apply selected metrics.
Task 2. Nominate/ formulate alternative FIRO strategies that will be considered.	Each alternative FIRO strategy to be considered will be identified and described, along with the method by which the strategy's performance will be evaluated.	**Task 2.1**. With appropriate input from SMEs, formulate a candidate set of FIRO strategies to be considered. Describe each strategy in memo and submit proposed list/memo to Steering Committee for approval. **Task 2.2.** Receive comments from Steering Committee and revise list as appropriate. Get Steering Committee agreement to proceed with comparison. **Task 2.3**. Identify software applications that will be used to model FIRO strategies.
Task 3. Conduct side studies.	PDT will identify, conduct, document, and incorporate outcomes of "side studies" that affect the simulation and evaluation of alternatives.	**Task 3.1.** Identify any additional "side studies" that must be completed to provide information required for simulation. Details of side studies will be identified in this subtask, with scope of work and schedule submitted to Steering Committee for approval. **Task 3.2.** Undertake and complete side studies, as approved by Steering Committee. Document findings. Incorporate findings in selected FIRO strategy models or procedures.
Task 4. Simulate performance with each alternative.	Each alternative FIRO strategy will be simulated with the HEC-ResSim model with a consistent set of hydrologic boundary conditions and system constraints (identified in Table 9-3).	**Task 4.1.** Considering all FIRO strategies to be evaluated, identify boundary conditions and initial states of the system to be considered in simulation for comparison. Document findings. **Task 4.2.** Simulate performance of New Bullards Bar Dam with candidate strategies. Prepare technical memo describing application of each strategy. Prepare a database of results (for use in Task 5).

Major Task (1)	Description (2)	Subtasks (3)
Task 5. Using results of simulation, evaluate each alternative in terms of identified performance metrics.	Each alternative FIRO strategy will be analyzed, and the appropriate performance metric statistics computed.	**Task 5.1.** Using a database of results from the HEC-ResSim simulation of each FIRO strategy (from Task 4.2), apply software applications (scripts, spreadsheets, etc.) from Task 1.3 to compute performance metrics for each strategy. **Task 5.2.** Revise FIRO strategies and performance metrics as necessary to ensure fair, repeatable comparisons. This subtask acknowledges initial uncertainty about compatibility of strategies and metrics. **Task 5.3.** Document results of evaluation in technical memo.
Task 6. Compare the alternatives by comparing the metrics.	Each alternative FIRO strategy evaluation will be compared against the baseline and against each other.	**Task 6.1.** Using results from Task 5, prepare charts, tables, etc., to compare performance of strategies. Prepare a technical memo with this information and submit to Steering Committee for further information. **Task 6.2.** Refine strategies if evaluation and comparison expose opportunities for “quick gains” through minor adjustments to strategies. Repeat Task 4.2–Task 5.1 with revised results. **Task 6.3.** Prepare a final technical memo on simulation, evaluation, and comparison. Submit for Steering Committee review. Receive Steering Committee comments and revise technical memo as needed.
Task 7. Brief Steering Committee on findings and facilitate the selection of a preferred alternative.	Each alternative FIRO strategy comparison will be scrutinized, a preferred alternative will be identified, and all findings will be documented and presented to the Steering Committee.	**Task 7.1.** Using results of comparison from Task 6, rank alternatives considering individual metrics from Task 1. Document findings. **Task 7.2.** Provide comparisons and rankings to Steering Committee.

9.2.4 Metrics for Evaluating Viability and Efficiency of Alternatives

The PDT will evaluate the efficiency of FIRO with a set of measurable statistics. These will be used in the same manner (to the maximum extent possible) to assess each alternative objectively. Selection of the specific metrics and stipulation of the method for computing or calculating those metrics is a task that the PDT will complete as a component of this study.

Table 9-7 provides an initial, tentative list of metrics, and Table 9-8 provides an initial description of alternatives.

Table 9-7. Tentative list of metrics for evaluation of FIRO alternatives (listed in Table 9-8).

ID (1)	Metric Description (2)	Category (3)	Likely Method of Computation (4)
M1	Flood season maximum discharge frequency from New Bullards Bar Dam.	Flood risk management	Frequency curve. See Simulation Plan.
M2	Flood season maximum pool elevation frequency function of New Bullards Bar Dam.	Flood risk management	Frequency curve. See Simulation Plan.
M3	Flood season maximum flow-frequency curves at key downstream locations.	Flood risk management	Frequency curve. See Simulation Plan and Central Valley Hydrology Study frequency analysis. Key downstream locations are Yuba River at Marysville, Feather River at Yuba City, Yuba and Feather River confluence, and Feather River near Nicolaus.
M4	Pass the standard project flood (SPF) without exceeding 50,000 cfs release.	Flood risk management	Reservoir routing. Also analyze events of similar frequency to the SPF but different event patterns. It is anticipated that the WCM update effort will address the events rarer than the SPF, including the probable maximum flood (PMF).
M5	M1–3 frequency curves with consideration of climate change.	Flood risk management	Frequency analysis with DWR Central Valley Flood Protection Plan climate change projections.
M6	Reservoir storage at the end of flood season (spring refill).	Water supply	Reservoir routing. See Simulation Plan. Potentially include detailed metrics on changes in reservoir storage levels.
M7	Hydropower production.	Hydropower	Frequency curve. See Simulation Plan. Quantify volume passed through Colgate Powerplant.

Table 9-8. Tentative candidate FIRO alternatives to be elevated.

ID (1)	Alternative Strategy (2)	Description (3)
1	Baseline	Per 1972 WCM.
2	TBD	Per Task 2, Table 9-6. Leverage information in Yuba Water evaluation of secondary spillway function.

9.2.5 Bookend Analysis

To better understand the maximum benefit of forecasts, the PDT will configure and run the alternatives (other than baseline) with full foresight of future streamflow conditions in the next 15 days (perfect forecasts).

The “bookends” will be established by Alternative 1 and the results of the perfect forecast simulations for the other alternatives. The assessment of other alternatives will provide the current position between the two “bookends” using currently available forecasts.

9.2.6 Project Delivery Team Members and Their Roles

The PDT for evaluating FIRO alternatives includes SMEs who will complete the analyses described herein, report on the findings and understandings, and recommend a single approach to be taken by the Center for Western Weather and Water Extremes (CW3E) and managers who will oversee the work effort. PDT members are identified in the box below.

New Bullards Bar Dam FIRO Alternatives Evaluation Technical Analysis PDT Members

- Yuba-Feather FIRO Steering Committee
- Yuba Water technical staff and consultants
- USACE Headquarters staff
- USACE Engineer Research and Development Center (ERDC) staff
- USACE South Pacific Division (SPD) staff
- USACE Sacramento District (SPK) staff
- CW3E, Scripps Institute of Oceanography at the University of California, San Diego. Includes Robert K. Hartman Consulting Services and Sonoma Water staff under contract to support FIRO efforts.

The PDT members have one of four roles consistent with established project management planning, as shown in Table 9-9. These roles vary by hydrologic engineering task. Table 9-10 shows roles assigned to PDT members for the analysis described herein.

Table 9-9. Project roles.

ID (1)	Role (2)	Description of Duties (3)
R	Responsible	Responsible for completing the analyses described herein.
A	Accountable	Answerable for correct and thorough completion of task, ensures requirements are met, and delegates work to those responsible.
C	Consulted	As SMEs, offer opinions through two-way communication with those responsible and accountable for conducting analyses.
I	Informed	Keeps up to date on progress through two-way communication.

Table 9-10. PDT roles by task.

Major Task	Steering Committee	Yuba Water Tech Staff	USACE HQ	USACE ERDC	USACE SPD	USACE SPK	CW3E
Task 1. Select performance metrics.	I	R	I	C	C	R	R
Task 2. Nominate/formulate alternative FIRO strategies that will be considered.	C	R	I	C	C	R	R
Task 3. Conduct side studies.	C	R	I	C	C	R	R
Task 4. Simulate performance with each alternative.	I	R	I	I	I	C	R
Task 5. Using results of simulation, evaluate each alternative in terms of identified performance metrics.	I	R	I	I	I	C	R
Task 6. Compare the alternatives by comparing the metrics.	I	R	I	I	C	C	R
Task 7. Brief Steering Committee on findings and facilitate the selection of a preferred alternative.	I	R	I	I	I	R	R

9.2.7 Schedule for Completion of Technical Analyses

The schedule for the technical analysis will be developed as the workplan is completed and the effort transitions into the PVA. The schedule is linked and will be coordinated with the WCM Update effort.

9.2.8 Risks to Success of Study

Table 9-11 shows risks to the success of this study and accompanying mitigation actions.

Table 9-11. Project risks.

Potential Failure Mode (1)	Actions PDT Can Take to Mitigate (2)
Simulation or evaluation software does not function as expected.	Limit analysis to use of software that is readily available and has been stress tested.
Necessary data—including hydrological, meteorological, water use, and vulnerability data—are not readily available.	Limit analysis to use of best available data.
Key personnel are not available to complete tasks.	Ensure backup staff for all critical tasks.
Critical path tasks fall behind schedule due to unforeseeable distractions and disruptions.	Limit project activities to those that are necessary to satisfy objectives.
PDT disagrees about technical analysis procedures.	Defer to PDT project assignments (see above).
Nature of alternative FIRO strategy prevents evaluation with selected metrics.	Disqualify alternatives from further consideration unless metrics can be adjusted and uniformly applied for all alternatives.

9.3 HEMP for Oroville Dam FIRO Evaluation of WCP Alternatives

9.3.1 Summary

As explained in Section 9.2, the F-CO Program for New Bullards Bar and Oroville dams has been tremendously successful in developing a common operating picture for reservoir operators, improving the observation network, and integrating single-value and (more recently) ensemble streamflow forecasts into the coordinated decision-making process. The objective of this HEMP is to identify, through appropriate detailed technical analyses and other considerations, candidate FIRO strategies for Oroville Dam, along with how USACE and DWR might implement them in real-time operations. Section 9.2 provides the HEMP for New Bullards Bar Dam. The Simulation Plan in Section 9.1 captures the process to ensure that the independent results from the New Bullards Bar and Oroville Dam HEMPs meet the objectives of the F-CO Program.

The DWR State Water Project is in the process of completing a Comprehensive Needs Assessment (CNA) for Oroville Dam as a result of the 2017 Oroville Dam spillway incident. This HEMP will begin with the assumption that the physical conditions of Oroville Dam will remain unchanged. Pending the CNA and associated planning, the FIRO team may change the assumption of Oroville Dam's physical attributes.

The Yuba-Feather FIRO Steering Committee manages this HEMP. To be consistent with USACE guidance for conducting similar technical studies, the Steering Committee prepared this HEMP as "*…a technical outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem"* (Engineering Pamphlet 1110-2-9).

This HEMP identifies the following:

1. Objective and an overview of the technical study process to provide information needed for this assessment.
2. Requirements for all FIRO alternatives that will be considered, as presented in Table 9-12.
3. Hard criteria as well as project and system-wide considerations, as presented in Table 9-13, Table 9-14, and Table 9-15.
4. Tasks to be completed for the technical analysis, as presented in Table 9-16.
5. Initial tentative performance metrics for FIRO alternatives evaluation, as presented in Table 9-17.
6. Analysis tools and methods to be used for the study.
7. Candidate FIRO alternatives to be evaluated, as presented in Table 9-18.

Project team members and their roles and responsibilities for conducting, reviewing, and approving the hydrologic engineering study, as presented in Section 9.3.6, Table 9-19 and Table 9-20.

9.3.2 Objective of Technical Analysis, Overview of Process, and Tasks to Be Completed

The objective of the hydrologic engineering study described herein is to identify and evaluate Oroville Dam FIRO alternatives in a systematic, defendable, repeatable manner, thus providing information to the Steering Committee so that it can identify the best FIRO strategy for Oroville Dam.

The process used to meet the hydrologic engineering study objective is a "nominate-simulate-evaluate-iterate" process, consistent with the process that USACE commonly uses for water resources planning studies. The project delivery team (PDT) will conduct the following technical analysis tasks to support the Oroville Dam FIRO Viability Assessment:

1. Develop a set of feasibility criteria and performance metrics for assessing and comparing FIRO alternatives. This set will be applied to all alternatives, thereby permitting the PDT to compare and rank alternatives for the Steering Committee's consideration.
2. Nominate a set of alternative FIRO strategies that are screened to ensure they meet specified requirements (described below).
3. Simulate the river-reservoir system's performance with each FIRO strategy using a common set of meteorological and hydrological conditions. HEC-ResSim will act as the "gatekeeper" for all alternatives to ensure that the physical constraints and attributes of the system are consistently applied.
4. Use the simulation results to evaluate the viability and performance of each strategy. The evaluation uses metrics identified in Task 1, comparing each alternative to the performance for the *without-project* condition (i.e., operation following the WCP included in the current WCM). If results of the evaluation inform refinements to FIRO strategies, the PDT will repeat the simulation and evaluation tasks with enhanced strategies to the extent that resources allow.
5. Use the technical analysis results to rank the alternatives and submit the rankings to the Steering Committee for consideration.

These tasks are described in more detail in Table 9-2. Major tasks are listed in column 1, and subtasks in column 3.

9.3.3 FIRO Alternatives to Be Evaluated

Selection of specific FIRO alternatives is a task to be completed as a component of the hydrologic engineering study (see below). Requirements of all candidate FIRO strategies are shown in Table 9-12, while Table 9-13, Table 9-14, and Table 9-15 show additional constraints and objectives that the proposed alternatives should meet.

Table 9-12. Requirements of all alternative FIRO strategies.

ID (1)	Description (2)
1	The candidate FIRO strategy must satisfy all relevant USACE ERs, including but not limited to the following: • ER 1105-2-100: *Planning Guidance Notebook* • ER 1105-2-101: *Risk Assessment for Flood Risk Management Studies* • ER 1110-2-240: *Water Control Management* • ER 1110-2-1156: *Safety of Dams Policy and Procedures* • ER 1110-2-1941: *Drought Contingency Plans* • EM 1110-2-3600: *Management of Water Control Systems* • ER 1110-2-8156: *Engineering and Design Preparation of Water Control Manuals* • EM 1120-2-1420: *Engineering Requirements for Reservoirs*
2	The analytical tools required for implementing the candidate FIRO strategy must be compatible with USACE's CWMS software. In addition, results of any analyses completed with software that USACE has not currently certified for use must be demonstrated to produce results consistent with USACE software results.
3	Streamflow forecasts used by the candidate FIRO strategy must be those that the National Weather Service's CNRFC has provided. Simulated streamflow forecasts must be consistent with the skill characteristics of

ID (1)	Description (2)
	those issued by the CNRFC. As appropriate for the alternative, the forecast used can be ensemble and/or single value.
4	The FIRO strategy must satisfy the hard (inviolable) operation constraints shown in Table 9-13.
5	The FIRO strategy should represent and to the extent possible meet the operation objectives shown in Table 9-14. and Table 9-15.
6	Software development needed to implement the FIRO alternative must be limited for the viability assessment, as the objective is to select from amongst a set of readily available (or nearly so) strategies.
7	Simulations should be computed at an hourly time step.

Table 9-13. Hard (inviolable) operational constraints that all FIRO strategies must satisfy.

ID (1)	Limiting condition (2)	Description (3)
1	Must satisfy Oroville Dam WCM emergency spillway release diagram (ESRD)	Meet all specific requirements stated on current ESRD.
2	Must adhere to physical constraints and system properties as codified in the F-CO ResSim configuration	The operational F-CO ResSim configuration holds the physical and regulatory limits associated with storage, release, and conveyance. In order to improve the potential to compare alternatives, this configuration will be used to condition all model-recommended releases.
3	Must satisfy limits on release rate of change	Releases must not increase more than 10,000 cfs or decrease more than 5,000 cfs in any two-hour period (1970 WCM, Ch. 7, “Limitations on Releases”). Release rate of change is governed by the potential impacts to the levees and on the fisheries environment as well as public safety.
4	Must not require a frequency of forecast updates other than what is currently available	Forecasts are issued a maximum of four times per day in major flood events. Under normal conditions, forecasts are issued two times per weekday in winter and once per day otherwise under normal conditions. For alternative evaluation purposes, forecast updates will be once per day.
5	Must not assume that storage is available in Marysville Reservoir	The 1970 WCM operation assumes storage is available in Marysville Reservoir. Marysville Reservoir was never built.

Table 9-14. Operational considerations that should be evaluated in the hydrologic engineering study.

ID (1)	Operational consideration (2)	Description (3)
1	Satisfy 1970 WCM flood management objectives[1]	According to the 1970 WCM, the maximum flood control space requirement was based primarily on protecting urban and agricultural areas along the Feather River below the reservoir against winter floods (rain or rain augmented by snowmelt) up to the magnitude of the SPF,[2] with permissible releases limited to a maximum of 150,000 cfs (Ch. 4, "Hydrologic Basis for Design"). Thus, to meet this design objective, the alternative should pass the SPF without releasing greater than 150,000 cfs.
2	Avoid use of the emergency spillway to the maximum extent possible	The emergency spillway is an uncontrolled outlet that is partially lined. Use of the emergency spillway could produce channel sedimentation and encroachment into the reservoir surcharge pool.
3	Avoid releases that exceed downstream limitations	Except for emergency operation, Feather River flows should not exceed 150,000 cfs at Oroville, nor should they exceed 180,000 cfs and 300,000 cfs above and below the confluence with the Yuba River, respectively. To the extent possible, the Feather River below Bear River should be limited to 320,000 cfs (1970 WCM, Ch. 7, "Limitations on Releases").
4	Consider levee erosion potential	Both the rate of release and duration of a given channel stage are a concern for levee erosion.
5	Balance flood control and water supply benefits	The flood control operation should consider the ability to meet water supply targets during the spring refill period and summer.
6	Balance flood control and hydropower benefits	The flood control operation should consider hydropower production by releasing through Hyatt Powerplant when possible, without compromising flood releases.

Notes:

(1) It is anticipated that the USACE WCM update effort will address dam safety considerations (e.g., passing the PMF). At this time for the FIRO effort, ESRD operation is presumed to be unchanged from the 1970 WCM.

(2) 1970 WCM Chart 11, "Routing of Standard Project Flood to Determine Flood Control Space," shows the reservoir passes both the SPF for wet conditions and dry conditions without exceeding 150,000 cfs. Both scenarios should be considered during alternative development.

Table 9-15. System-wide operational considerations that should be evaluated in the hydrologic engineering study.

ID (1)	Operational consideration (2)	Description (3)
1	Implementation of F-CO of New Bullards Bar Reservoir and Lake Oroville	Under the F-CO Program, DWR and Yuba Water coordinate releases from Oroville and New Bullards Bar during large events to avoid flooding at the confluence of the Feather and Yuba Rivers and downstream. Specifically, releases are coordinated to avoid exceeding 300,000 cfs on the Feather River below the confluence with the Yuba River and 320,000 cfs below the confluence with the Bear River.
2	Operational resiliency	The FIRO alternative should be resilient to a wide range of hydrologic events within the watershed. For example, the operation should be resilient to a range of storm-centering and events of key frequencies occurring within the Yuba and Feather watersheds.

Table 9-16. Tasks and subtasks to be completed for hydrologic engineering study of FIRO strategies.

Major task (1)	Description (2)	Subtasks (3)
Task 1. Select performance metrics.	Both quantitative and qualitative measures of performance will be identified. Methods of computation of quantitative measures will be described.	**Task 1.1.** With appropriate input from SMEs, formulate a candidate set of quantitative and qualitative measures of performance. Define methods for assessing these for typical FIRO strategies. Screen set to select feasible metrics for ALL likely alternatives to permit objective comparison of strategies. Prepare a technical memo. Submit to Steering Committee for review. **Task 1.2.** Receive comments from Steering Committee. Revise selected set of performance metrics as required. **Task 1.3**. If necessary, design, develop, and test software applications (scripts, spreadsheets, etc.) to apply selected metrics.
Task 2. Nominate/ formulate alternative FIRO strategies that will be considered.	Each alternative FIRO strategy to be considered will be identified and described, along with the method by which the strategy's performance will be evaluated.	**Task 2.1**. With appropriate input from SMEs, formulate a candidate set of FIRO strategies to be considered. Describe each strategy in memo and submit proposed list/memo to Steering Committee for approval. **Task 2.2.** Receive comments from Steering Committee and revise list as appropriate. Get Steering Committee agreement to proceed with comparison. **Task 2.3**. Identify software applications that will be used to model FIRO strategies.
Task 3. Conduct side studies.	PDT will identify, conduct, document, and incorporate outcomes of "side studies" that affect the simulation and evaluation of alternatives.	**Task 3.1.** Identify any additional "side studies" that must be completed to provide information required for simulation. Details of side studies will be identified in this subtask, with scope of work and schedule submitted to Steering Committee for approval. **Task 3.2.** Undertake and complete side studies, as approved by Steering Committee. Document findings. Incorporate findings in selected FIRO strategy models or procedures.

Major task (1)	Description (2)	Subtasks (3)
Task 4. Simulate performance with each alternative.	Each alternative FIRO strategy will be simulated with the HEC-ResSim model with a consistent set of hydrologic boundary conditions and system constraints (identified in Table 9-13.).	**Task 4.1.** Considering all FIRO strategies to be evaluated, identify boundary conditions and initial states of the system to be considered in simulation for comparison. Document findings. **Task 4.2.** Simulate performance of Oroville Dam with candidate strategies. Prepare technical memo describing application of each strategy. Prepare a database of results (for use in Task 5).
Task 5. Using results of simulation, evaluate each alternative in terms of identified performance metrics.	Each alternative FIRO strategy will be analyzed, and the appropriate performance metric statistics computed.	**Task 5.1.** Using a database of results from the HEC-ResSim simulation of each FIRO strategy (from subtask Task 4.2), apply software applications (scripts, spreadsheets, etc.) from Task 1.3 to compute performance metrics for each strategy. **Task 5.2.** Revise FIRO strategies and performance metrics as necessary to ensure fair, repeatable comparisons. This subtask acknowledges initial uncertainty about compatibility of strategies and metrics. **Task 5.3.** Document results of evaluation in technical memo.
Task 6. Compare the alternatives by comparing the metrics.	Each alternative FIRO strategy evaluation will be compared against the baseline and against each other.	**Task 6.1.** Using results from Task 5, prepare charts, tables, etc., to compare performance of strategies. Prepare a technical memo with this information and submit to Steering Committee for further information. **Task 6.2.** Refine strategies if evaluation and comparison expose opportunities for “quick gains” through minor adjustments to strategies. Repeat Task 4.2–Task 5.1 with revised results. **Task 6.3.** Prepare a final technical memo on simulation, evaluation, and comparison. Submit for Steering Committee review. Receive Steering Committee comments and revise technical memo as needed.
Task 7. Brief Steering Committee on findings and facilitate the selection of a preferred alternative.	Each alternative FIRO strategy comparison will be scrutinized, a preferred alternative will be identified, and all findings will be documented and presented to the Steering Committee.	**Task 7.1.** Using results of comparison from Task 6, rank alternatives considering individual metrics from Task 1. Document findings. **Task 7.2.** Provide comparisons and rankings to Steering Committee.

9.3.4 Metrics for Evaluating Viability and Efficiency of Alternatives

The PDT will evaluate the efficiency of FIRO with a set of measurable statistics. These will be used in the same manner (to the maximum extent possible) to assess each alternative objectively. Selection of the specific metrics and stipulation of the method for computing or calculating those metrics is a task that the PDT will complete as a component of this study.

Table 9-17 provides an initial tentative list of metrics, and Table 9-18 provides an initial description of alternatives.

Table 9-17. Tentative list of metrics for evaluation of FIRO alternatives (listed in Table 9-18.).

ID (1)	Metric description (2)	Category (3)	Likely method of computation: (4)
M1	Flood season maximum discharge frequency from Oroville Dam.	Flood risk management	Frequency curve. See Simulation Plan.
M2	Flood season maximum pool elevation frequency function of Oroville Dam.	Flood risk management	Frequency curve. See Simulation Plan.
M3	Flood season maximum flow-frequency curves at key downstream locations.	Flood risk management	Frequency curve. See Simulation Plan and Central Valley Hydrology Study frequency analysis. Key locations are Feather at Gridley, Feather River at Yuba City, Yuba and Feather River confluence, and Feather River near Nicolaus.
M4	Pass the SPF without exceeding 150,000 cfs release.	Flood risk management	Reservoir routing. Also analyze events of similar frequency to SPF but different event patterns. It is anticipated that the WCM update effort will address the events rarer than the SPF, including the PMF.
M5	M1–3 frequency curves with consideration of climate change.	Flood risk management	Frequency analysis with DWR Central Valley Flood Protection Plan climate change projections.
M6	Reservoir storage at end of flood season (spring refill).	Water supply	Frequency curve. See Simulation Plan.
M7	Hydropower production.	Hydropower	Frequency curve. See Simulation Plan. Quantify volume passed through Hyatt Powerplant.

Table 9-18. Candidate FIRO alternatives to be evaluated.

ID (1)	Alternative strategy (2)	Description (3)
1	Baseline WCM	Current operations as defined in the 1970 WCM.
2	TBD	Per Task 2, Table 9-16.. Leverage information in DWR CNA for Oroville Dam.
3		
4		
5		

9.3.5 Bookend Analysis

To better understand the maximum benefit of forecasts, the PDT will configure and run alternatives (other than baseline) with full foresight of future streamflow conditions in the next 15 days (perfect forecasts).

The “bookends” will be established by Alternative 1 and the results of the perfect forecast simulations for the other alternatives. The assessment of other alternatives will provide the current position between the two “bookends” using currently available forecasts.

9.3.6 Project Delivery Team Members and Their Roles

The PDT for evaluating FIRO alternatives includes SMEs who will complete the analyses described herein, report on the findings and understandings, and recommend a single approach to be taken by CW3E and managers who will oversee the work effort. PDT members are identified in the box below.

Oroville Dam FIRO Alternatives Evaluation Technical Analysis PDT Members

- Yuba-Feather FIRO Steering Committee
- SWP technical staff and consultants
- USACE Headquarters staff
- USACE ERDC staff
- USACE SPD staff
- USACE SPK staff
- CW3E, Scripps Institute of Oceanography at the University of California, San Diego. Includes Robert K. Hartman Consulting Services and Sonoma Water staff under contract to support FIRO efforts.

The PDT members have one of four roles consistent with established project management planning, as shown in Table 9-19. These roles vary by hydrologic engineering task.

Table 9-20 shows roles assigned to PDT members for the analysis described herein.

Table 9-19. Project roles.

ID (1)	Role (2)	Description of Duties (3)
R	Responsible	Responsible for completing the analyses described herein.
A	Accountable	Answerable for correct and thorough completion of task, ensures requirements are met, and delegates work to those responsible.
C	Consulted	As SMEs, offer opinions through two-way communication with those responsible and accountable for conducting analyses.
I	Informed	Keeps up to date on progress through two-way communication.

Table 9-20. PDT roles by task.

Major Task	Steering Committee	SWP Tech Staff	USACE HQ	USACE ERDC	USACE SPD	USACE SPK	CW3E
Task 1. Select performance metrics.	I	R	I	C	C	R	R
Task 2. Nominate/formulate alternative FIRO strategies that will be considered.	C	R	I	C	C	R	R
Task 3. Conduct side studies.	C	R	I	C	C	R	R
Task 4. Simulate performance with each alternative.	I	R	I	I	I	C	R
Task 5. Using results of simulation, evaluate each alternative in terms of identified performance metrics.	I	R	I	I	I	C	R
Task 6. Compare the alternatives by comparing the metrics.	I	R	I	I	C	C	R
Task 7. Brief Steering Committee on findings and facilitate the selection of a preferred alternative.	I	R	I	I	I	R	R

9.3.7 Schedule for Completion of Technical Analyses

The schedule for the technical analysis will be developed as the workplan is completed and the effort transitions into the PVA. The schedule is linked and will be coordinated with the WCM Update effort.

9.3.8 Risks to Success of Study

Table 9-21 shows risks to the success of this study and accompanying mitigation actions.

Table 9-21. Project risks.

Potential Failure Mode (1)	Actions PDT Can Take to Mitigate (2)
Simulation or evaluation software does not function as expected.	Limit analysis to use of software that is readily available and has been stress tested.

Necessary data—including hydrological, meteorological, water use, and vulnerability data—are not readily available.	Limit analysis to use of best available data.
Key personnel are not available to complete tasks.	Ensure backup staff for all critical tasks.
Critical path tasks fall behind schedule due to unforeseeable distractions and disruptions.	Limit project activities to those that are necessary to satisfy objectives.
PDT disagrees about technical analysis procedures.	Defer to PDT project assignments (see above).
Nature of alternative FIRO strategy prevents evaluation with selected metrics.	Disqualify alternatives from further consideration unless metrics can be adjusted and uniformly applied for all alternatives.

9.4 Existing Studies, Expected Contribution to WCM Update Project, and Relationship with F-CO Program

9.4.1 Leveraging of Existing Studies

A substantial amount of work has already taken place that demonstrates the effectiveness of using existing streamflow forecasts to guide reservoir release decisions for both Oroville and New Bullards Bar dams. These documents, referenced in Section 2, are the Oroville Dam CNA and the Yuba Water Agency's study to assess the effectiveness of a secondary spillway at New Bullards Bar Dam. These studies have influenced the configuration of the HEMPs described earlier and will be leveraged to identify potential FIRO WCP alternatives for evaluation.

9.4.2 Expected Outcomes and Relationship with WCM Update Project

As a result of the FIRO WCM update workshops, the focus of the WCP evaluations associated with the Preliminary Viability Assessment (PVA) have shifted. Traditionally, the PVA HEMP would be used to refine the simulation process and identify promising alternatives leading to a more conclusive evaluation associated with the Final Viability Assessment. Here, with the WCM update project running concurrently, the approach needs to be a little different. The goal of the coordinated FIRO/WCM effort is to inform the WCM update project so the WCP alternatives evaluated there are crafted with additional insight gained through the FIRO effort. Instead of focusing on a specific approach, the PVA evaluation process will cast a slightly "wider net" and focus on developing recommendations associated with FIRO WCP attributes that may lead to more robust and efficient WCPs in the updated WCMs.

9.4.3 Relationship with F-CO Program

The existing F-CO program has been exceptionally successful in developing collaborative protocols and a common operating picture through which the combined releases and unregulated streamflow in the Yuba-Feather basin can be better managed to avoid levee challenges in the Feather River from Yuba City to the confluence with the Sacramento River. The initial approach for the HEMPs will be to first develop FIRO WCPs for each reservoir independently and then develop candidate methodologies for sharing the burden of larger events when coordination is needed. The approaches explored will be identified and developed by the teams responsible for the HEMP development.

Section 10— Scoping the Yuba-Feather FIRO Preliminary Viability Assessment

10.1 Key Questions to Be Addressed in the Preliminary Viability Assessment

This work plan documents a wealth of existing information that will be used to develop the Preliminary Viability Assessment (PVA) for the Yuba-Feather Forecast Informed Reservoir Operations (FIRO) project. This information will need to be supplemented by additional research, studies, modelling and analysis to address the following key questions to assess FIRO viability:

1. How skillful are current weather and water forecasts? (Use to establish a baseline from which improvements can be measured.)
    a. For each forecast element, establish metrics and estimate skill.
        i. Atmospheric river (AR) landfall, intensity, and duration.
        ii. Precipitation forecasts.
        iii. Snow-level forecasts.
        iv. Surface air temperature forecasts.
        v. Streamflow/inflow forecasts (deterministic and ensemble)
            - Archived California Nevada River Forecast Center (CNRFC) deterministic forecasts (2005–Present).
            - Updated Hydrologic Ensemble Forecast Service hindcasts (GEFSv12, 1990–2019).
    b. Create hierarchical format (table) to describe how each weather element contributes to streamflow forecast uncertainty.
    c. Explore "conditional uncertainty" where the forecast error changes as a function of the current or forecast state.

2. What additional observational data are needed to increase accuracy of precipitation forecasts, especially from extreme events driven by ARs, to support research and FIRO now and in the future?
    a. Pursue a high spatial resolution precipitation data set to support research and an improved understanding of physical processes in complex terrain.
    b. Work to establish near real-time data accessibility through GOES and/or the California Data Exchange Center.
    c. Undertake an assessment of data transmission reliability, especially during significant storm events.
    d. Pursue enhancements to the observational network including, but not limited to, all-weather precipitation gages, soil moisture, snow water equivalent (including the Airborne Snow Observatory), snow density, and instrumentation to aid in assessing and modeling the snowpack's energy budget.

3. What research and analysis are needed to increase accuracy and reliability of meteorological forcings for hydrologic models (e.g., precipitation, snow level, temperature), especially from extreme events driven by ARs, to support FIRO now and in the future?
    a. Pursue research that leads toward an improved understanding of the physical processes associated with extreme AR events, including the Sierra barrier jet, orographic forces, and modulation that affects precipitation efficiency.

   b. Pursue improved snow level forecasts associated with significant precipitation events, including snow level bending.
   c. Pursue improved precipitation forecasts associated with significant precipitation events.
   d. Pursue predictive capacity for weather phenomena that affect localized AR impacts, including but limited to barrier jets, mesoscale waves, and snow level bending.
   e. Explore machine learning to improve prediction of meteorological forcings.

4. What additional information and analysis is needed to increase accuracy and reliability of runoff and streamflow forecasts to support FIRO?
   a. Evaluate and recommend improvements of California Department of Water Resources (DWR) and CNRFC seasonal runoff forecasts to inform Lake Oroville New Bullards Bar Reservoir refill decision-making after flood events and Water Control Manual (WCM) spring refill curve updates.
   b. Assess the contribution of antecedent watershed conditions (e.g., soil moisture, snowpack state) and AR-related weather phenomena (e.g., rain on snow, latent heat advection) to runoff variability during extreme runoff events.

5. What are the lead-time requirements for Oroville and New Bullards Bar operations?
   a. Time needed to secure critical infrastructure.
   b. Time needed to evacuate people.
      i. Consider both pool area and areas downstream.
      ii. Leverage DWR and Federal Energy Regulatory Commission’s Emergency Action Plan (EAP) at risk and the National Weather Service Sacramento’s dam break resources.
   c. Time needed to increase releases to a specified target.
   d. Explore ramping rates for pre-releases from the conservation pool.
   e. Explore the interplay between skill at various lead times and the magnitude of the FIRO Space. Consider the objective of the functional equivalent of replacing the flood control capacity of Marysville Dam.

6. What Water Control Plan (WCP) alternatives and attributes should be investigated in the FIRO Hydrologic Engineering Management Plan (HEMP) to best inform the WCM update process?
   a. Define required data and methodologies.
   b. Refine/develop consensus on simulation plan.
   c. Refine/develop consensus on evaluation metrics.
   d. Define process for strategy selections and select themes that will inform the WCM update effort.
   e. Execute HEMP-related studies with identified teams and resources.
   f. Identify appropriate FIRO reservoir triggers (e.g., inflow volume, forecast time horizon, model run to run consistency) and ensemble exceedances and integration into the Forecast-Coordinated Operations (F-CO) Decision Support System (DSS).
   g. Investigate F-CO DSS forecast time horizon beyond current five-day window.
   h. Determine the viability/value of FIRO operation for larger floods such as 200- and 500-year floods.

7. How can FIRO and the WCM updates be most effectively integrated? Includes alignment of timing, studies, modeling, data needs, and analysis.
    a. Refer to outcomes and results from the FIRO WCM workshop series and develop guidelines for moving forward.

8. What are the joint operations gaps that need to be filled for FC-O and FIRO to be fully integrated?
    a. Develop and document a clear nexus between FIRO and F-CO evolution.
    b. Develop methodologies for proportioning releases from Oroville and New Bullards Bar when releases are controlled by downstream targets.
    c. Identify and develop the decision support tools and elements needed to support the viability assessment, interim operations, and long-term FIRO application in the Yuba-Feather basin.

9. What FIRO concepts can be applied towards an adaptive management approach as forecast skill improves? How can the process work for triggering incremental improvements?
    a. Explore, refine, and establish FIRO Space concept in U.S. Army Corps of Engineers terminology and policy.
    b. Explore and develop a WCP/WCM framework that naturally adapts to improvements in forecast skill.
    c. Create a FIRO 2.0 prototype element for a WCM update and test its potential limitations within an evaluation framework.
    d. Establish the potential for using thresholds of forecast skill above which additional reservoir operations flexibility can be implemented.
    e. Document a process for how this forecast evaluation framework will be formulated, including reservoir operator input.

10. Are existing Corps Water Management System (CWMS) tools going to be adequate for FIRO?
    a. Ascertain USACE Sacramento District's plans for using CWMS.
    b. Ensure HEC-HMS has been properly calibrated at all relevant locations within the basin.
    c. Ensure all watershed and structural features are adequately represented for operational decision support.
    d. Determine if any features/capabilities need to be added to HEC-ResSim.
    e. Explore how CWMS integrates with FIRO in the future.

11. What are the economic benefits of FIRO and how can we leverage other investments?

10.2 Team Organization to Address Key Questions

Eight new teams will be formed to address the work and investigations identified in Section 10.1. Leveraging insight from the FIRO WCM update workshops, these teams will also coordinate their efforts with those of the WCM update effort. The teams, along with the key questions (Section 10.1) to be addressed, are shown in Table 10-1.

Table 10-1. Yuba-Feather FIRO PVA work teams.

Team Name	Section 10.1 Assignments
Communications*	
Forecast Verification**	1
Observation	2
Meteorology	3
Hydrology***	4
Water Resources Engineering**	5,6,8,10
WCM Update (Leadership Team)**	7,9
Economic Benefits***	11
Decision Support Tools**	cross-cutting

* Existing Yuba-Feather FIRO team. Picks up coordination from FIRO-WCM alignment workshop.
** Active coordination with WCM update project.
*** Possible coordination with WCM update project.

Team leadership and membership will be determined later and will make use of volunteers identified in the FIRO-WCM alignment workshops.