2.2 Enhanced Monitoring

2.2.1 Overview

This task supports the overall FIRO objective to use state of the art monitoring to operate reservoirs and addresses the need identified in the Preliminary Viability Assessment (PVA) to develop new methods for data collection and monitoring. Additionally, the PVA called for observational enhancements including additional soil moisture, precipitation, stream gauges, vertically profiling radars, radiosondes, and more. This augmentation of the existing instrumentation network in the Russian River supports watershed monitoring and provides crucial data to address research questions and initialize models which will lead to improved forecasts. In addition, the observational datasets are critical to evaluating the skill of the models which produce the forecasts that are the foundation of FIRO. This subsection will focus on the offshore and onshore atmospheric observations. For details on the hydrologic observations of the landscape, including soil moisture and streamflow, please see Section 2.5.

This task has produced the following accomplishments:

- Successful airborne reconnaissance field campaigns held during 2016, 2018, 2019, and 2020 to observe ARs before they make landfall on the west coast (section 2.2.2)
- Installation of a ground-based atmospheric sensor network, including vertically pointing radars, disdrometers, GPS-Met stations, among other relevant observations (section 2.2.3)
- Embedding these observations into FIRO process-based research studies (AR science, DA, West-WRF; sections 2.3.4, 2.3.7).
- Implemented a multi-agency observation network in the Russian River Basin above Lake Mendocino, with measurements including rainfall, soil moisture, streamflow, and hydrogeochemistry (section 2.2.4).
- Near real time availability of observations for operational monitoring (situational awareness), data assimilation as appropriate, addressing research questions (sections 2.2.2, 2.2.3, 2.2.4).

2.2.2 Atmospheric River Reconnaissance

Atmospheric River Reconnaissance (AR Recon; Ralph et al., 2020) is an airborne field campaign designed to improve forecasting of impactful West Coast weather events at 0-5 days lead times. Currently significant issues with flood predictions are caused primarily by errors in forecasts of AR landfall location, intensity, and duration (see Section 2.3.3). PI Marty Ralph, CW3E, with support from NOAA Co-PI Vijay Tallapragada, has formed and led the AR Recon program team consisting of academic experts, global numerical weather prediction centers (including NOAA's National Weather Service, the European Centre for Medium-Range Weather Forecasts - ECMWF, and the Naval Research Laboratory), forecasters, flight directors, and modelers, to organize the complex logistics of aircraft operations, crews, and dropsondes, and to ensure the data are available in real-time for ingest into Numerical Weather Prediction (NWP) models.

AR Recon combines new observations, modeling, data assimilation and forecast verification methods to improve the science and predictions of landfalling ARs. AR conditions over the northeast Pacific are measured using dropsondes from up to three aircraft simultaneously. Additionally, novel airborne radio occultation observations are being tested, and drifting buoys with pressure sensors have been deployed (leveraging funding from NOAA and California Department of Water Resources). As part of this program, new AR targeting and data collection methods have been developed, assimilation and forecast impact experiments are ongoing, and better understanding of AR dynamics is emerging.

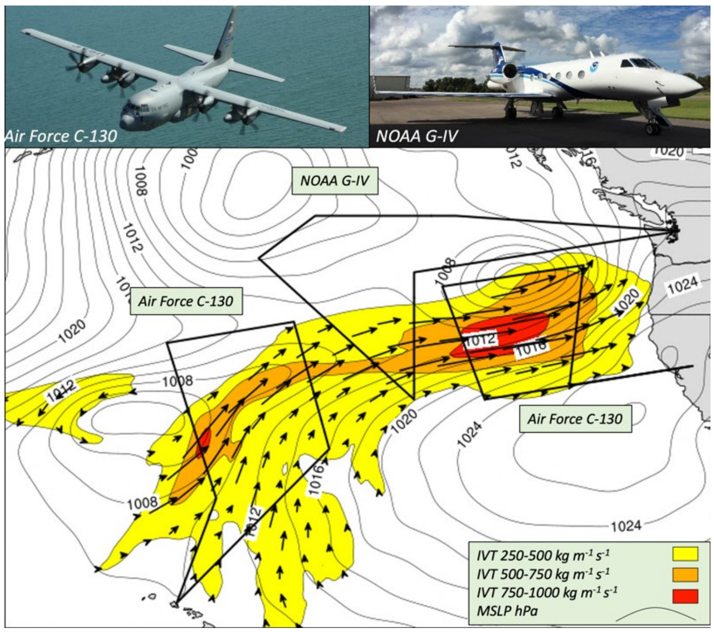

Figure 2.2.1 AR Recon targeting concept using 3 aircraft sampling sensitive regions in and near the AR. In addition to physically based targeting, quantitative methods are used to identify regions of large initial condition error impacts, which largely match the location of the AR outlined here.

AR Recon observations are assimilated in near real-time by global operational forecast models, and the collected data are also crucial to improve our understanding of the physical and dynamical processes that define AR characteristics. AR Recon field campaigns in winters 2016, 2018, 2019, and 2020 have deployed 1312 dropsondes from aircraft during 32 missions so far. In June 2019, AR Recon was added as a critical feature of the Office of the Federal Coordinator for Meteorology's official National Winter Season Operations Plan to support improved outcomes for emergency preparedness and water management in the West. This was the first update to the document since 2014 and was largely based on the successful demonstration of the forecast benefits from, and execution of, missions during 2016, 2018, and 2019. Beginning in the 2018 season, the CW3E and partners have demonstrated the feasibility of deploying three aircraft simultaneously to sample sensitive regions over the Northeast Pacific.

Operational, targeted flight planning is a key component of the AR Recon program. During the field campaign a team of forecasting experts focuses on important features, like mesoscale frontal features (Martin et al., 2019), that have been shown to cause serious forecast errors and that occur within the geographic reach of AR Recon operations. Quantitative methods such as the moist adjoint (Doyle et al., 2012; Reynolds et al., 2019) and, since the 2019 season, ensemble-based sensitivity analysis (Torn and Hakim, 2008) are used to analyze the forecast information and indicate the upwind regions over the ocean that, if sampled, are the most likely to result in an improved precipitation forecast over targeted regions of interest. Targeting AR Recon observations based on two independent sensitivity methods increases confidence in the robustness of that targeting. In the majority of cases both the adjoint and ensemble sensitivity analyses highlighted forecast sensitivity along AR cores and edges (Reynolds et al., 2019).

The second key component of AR Recon is modeling and data assimilation work conducted under the auspices of the AR Recon Modeling and Data Assimilation Steering Committee led by PI Marty Ralph (Table 2.2.1). The Steering Committee formalizes the collaboration between several leading global operational NWP centers to quantify the added benefit provided by the dropsondes using data denial hindcasts. The Steering Committee has developed Terms of Reference for participating organizations and is developing and executing a five-year work plan for AR Recon data assimilation efforts.

Table 2.2.1 AR Recon modeling and data assimilation steering committee membership (Table 2 from Ralph et al., 2020).

Name	Title	Institution	Role
F. Martin Ralph	Director – Center for Western Weather and Water Extremes	Scripps Institution of Oceanography, UC San Diego	AR Recon PI and Steering Committee Co-Chair
Vijay Tallapragada	Chief, Modeling and Data Assimilation Branch, National Center for Environmental Prediction	National Oceanic and Atmospheric Administration	AR Recon co-PI and Steering Committee Co-Chair
James Doyle	Senior Scientist, Marine Meteorology Division	Naval Research Laboratory	AR Recon Adjoint Modeling Lead and Steering Committee Member
Aneesh Subramanian	Assistant Professor	University of Colorado, Boulder	AR Recon Data Assimilation Lead and Steering Committee Member
Luca Delle Monache	Deputy Director – Center for Western Weather and Water Extremes	Scripps Institution of Oceanography, UC San Diego	Data Assimilation Steering Committee Member

Chris Davis	Associate Director, Mesoscale and Microscale Meteorology Laboratory	National Center for Atmospheric Research	AR Recon Observation Targeting Lead and Steering Committee Member
Florian Pappenberger	Director of Forecasts	European Centre for Medium-Range Weather Forecasts	Data Assimilation Steering Committee Member

To date, the AR Recon observations have enabled multiple studies advancing our understanding of AR structure and evolution offshore and improving the ability of models to reproduce these features. Ralph et al. (2017) used dropsonde observations to assess total AR water vapor transport in the Northeast Pacific, which is on average 2.6 times larger than the average liquid water discharge from the Amazon River. Guan and Waliser (2017) used dropsonde observations to document remaining significant challenges in representing ARs in models. Lavers et al. (2018) showed that, while the ECMWF model can reproduce ARs fairly well, challenges remain in representing key aspects of the vertical structure of the storms. These studies illustrate that dropsondes are useful for diagnosing errors and improving model representations of ARs. Additional studies using dropsonde observations to advance process-based understanding of ARs are described in Section 2.3.4.

The challenge associated with AR forecasting is attributed, at least in part, to the scarcity of Eastern Pacific in situ observations (Stone et al., 2019). Using computed Forecast Sensitivity Observation Impact for each dropsonde variable, and comparing dropsonde benefits to the impacts of the North American radiosonde network, Stone et al. (2019) found that the reconnaissance soundings have significant beneficial impact, with per observation impacts more than double those from the North American radiosonde network (Figure 2.2.2). The 24-h global forecast error reduction from the reconnaissance soundings is 1/3 to 3/4 as large as that from the North American radiosonde network.

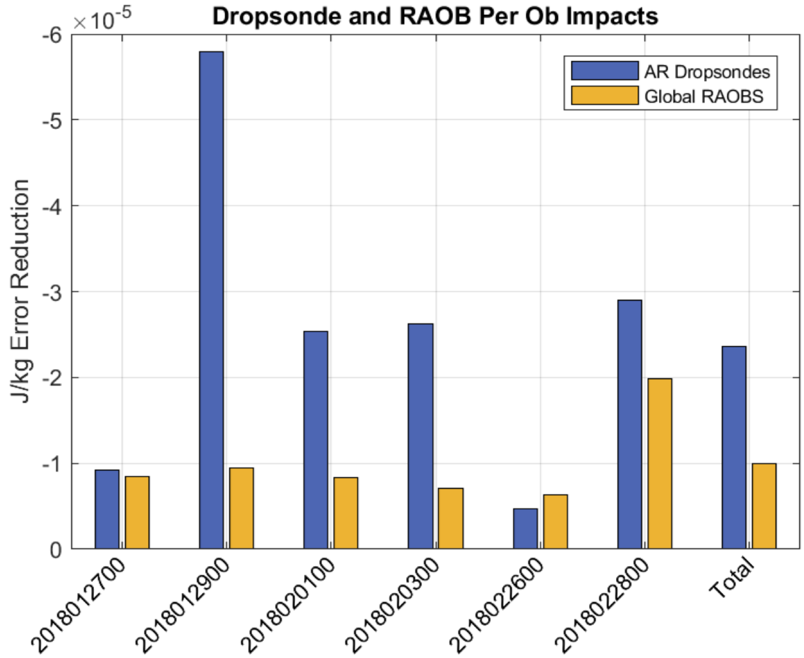

Figure 2.2.2 Comparison of AR dropsonde and global radiosonde observations (RAOB) in terms of observation error reduction (10-5 J kg-1) for each of the six IOPs, and for their average (adapted from Stone et al. 2019).

The AR Recon research team has also performed an in-depth analysis of the availability of observations over the Northeast Pacific Ocean when ARs are present. Major limitations have been identified in the satellite observations over these areas due primarily to the presence of cloud cover and heavy precipitation. For instance, although GOES-16 Atmospheric Motion Vector (AMV) winds from GOES-16 were intended to fill data sparse oceanic regions, very few AMV winds are observed within the ARs themselves. Observation density within ARs in the lower troposphere is 20% that found at similar altitudes outside of ARs. The key cause of the gap is that high clouds often overlay ARs, blocking VIS- and IR-satellite-based measurements. This gap can be filled with the data collected by dropsondes (Section 2.3.7, Figure 2.3.9). Specifically, data collected during the 15 AR Recon IOPs in 2016, 2018, and 2019 amounted to about 99% of available humidity observations, 75% of temperature observations, and 50% of wind observations within AR objects, within near-surface to middle troposphere levels (Zheng et al. 2020, accepted pending revision).

CW3E is also developing performance metrics focused on ARs affecting the Western U.S., including landfall location error, and other object-based assessments of the accuracy of fields such as IVT and precipitation (Wick et al. 2013; Nardi et al. 2018; DeHaan et al. in prep). These metrics are necessary to assess the forecast-improvement value of using the dropsondes over land to better characterize AR characteristics like intensity, duration, orientation, and landfall location, and associated precipitation patterns. Along with traditional verification approaches, the new metrics are currently implemented in data denial experiments where the performance of simulations without the dropsondes is compared to simulations that include them. These metrics will help us to quantify baseline skill and maximize benefits from FIRO.

2.2.3 Ground-based atmospheric sensor network

The atmospheric portion of the hydrometeorological campaign supporting FIRO is an enhancement of preexisting monitoring efforts in the Russian River. Important monitoring efforts were originally established as part of the NOAA Hydrometeorological Testbed (HMT) program, which includes the Atmospheric River Observatory (ARO) located in Bodega Bay. The increase in station density is a major accomplishment of FIRO at Lake Mendocino. The scientific goals of the FIRO instrumentation campaign are to observe and monitor the watershed during cool-season AR events. The instrumentation provides near-real time observations of atmospheric conditions within the watershed that are of operational value to forecasting partners in the National Weather Service, as well as providing data for model verification and answering scientific questions about AR-driven precipitation in the Russian. Distributed atmospheric, precipitation, soil moisture, and streamflow observations help to quantify the magnitudes and spatial variability of water vapor transport, precipitation, soil moisture, and streamflow rates during AR events. This section will focus on the atmospheric measurements, including radiosondes, vertically pointing radars, disdrometers, and surface meteorology. Soil moisture and streamflow measurements are discussed in Section 2.2.4.

Most of the stations report in near real time on the CW3E website and are being transmitted to other appropriate data repositories. The network additions include two radar stations, and, during storms, two radiosonde release locations. Data from the radiosondes are transmitted to the World Meteorological Organization’s Global Telecommunications System, so that they can be assimilated into global operational NWPs, akin to the AR Recon efforts described in section 2.2.2. Radiosondes are also provided directly to interested National Weather Service Offices in the Western Region, including Monterey, Eureka, Sacramento, and Reno. These offices have reported that it is extremely valuable to have these soundings available, in order to assess model performance and add to the information they use when blending model outputs to produce forecasts. We have altered the presentation of the data to respond to NWS requests to make products more usable; e.g. adding freezing levels to visualizations, and providing all data in text format as well as graphically.

The data are also useful for model verification. During an impactful late season AR in April 2018, radiosondes released as part of the FIRO effort verified a GFS forecast of two peaks in IVT over the Russian River basin that the operational analysis did not incorporate (Figure 2.2.3).

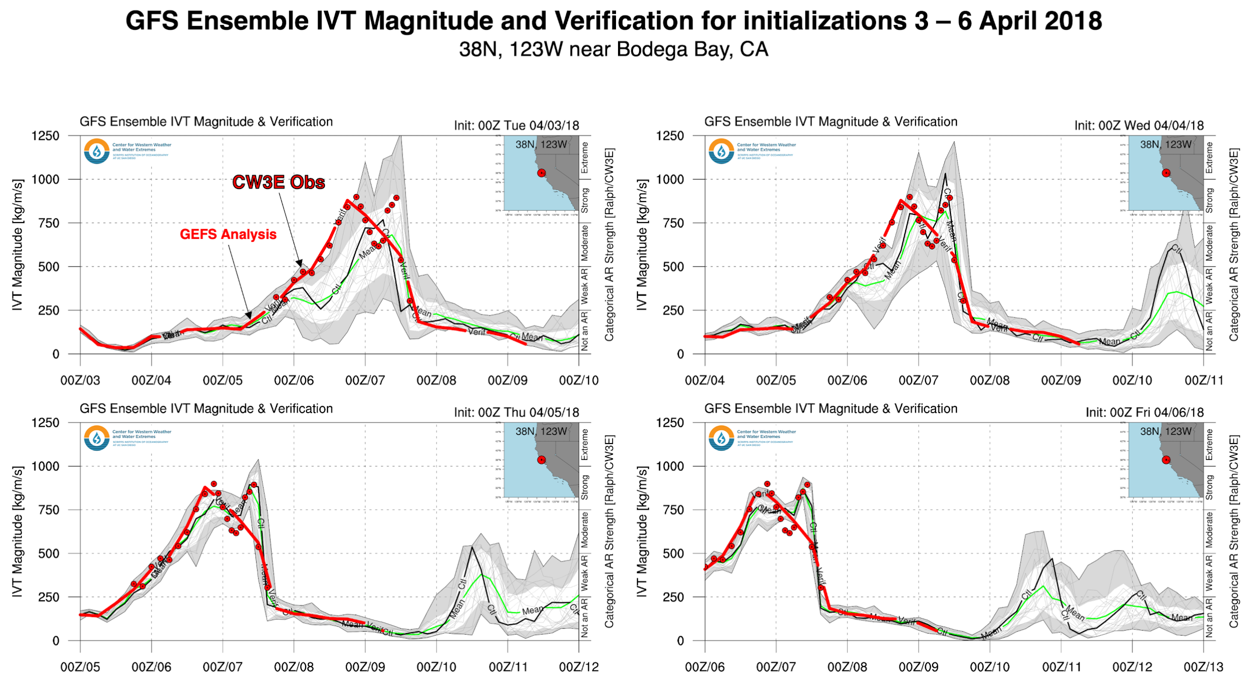

Figure 2.2.3 CW3E observations at the Bodega Bay ARO (red dots) compared with the GFS forecast from four different lead times (gray shade; green and black lines) and the GFS analysis (red line). Figure credit to Jay Cordeira.

To supplement our understanding of the effect of terrain on precipitation processes at high spatial resolution, the FIRO effort supported installation of ten stand-alone precipitation gauges in remote parts of the Lake Mendocino watershed. These gauges also serve to support model verification efforts. All atmospheric stations installed in support of FIRO are listed in Table 2.2.2.

Table 2.2.2 Meteorological sites installed in support of FIRO. Hydrological sites are described in Section 2.2.4.

Site Name	Lat, Lon (°)	Elevation	Station Type	Near Real Time
Bodega Bay	38.32, -123.07	15	Radiosonde and radar	Yes
Ukiah Water Treatment Plant	39.16, -123.19	183	Radiosonde	Yes
Potter Valley Central	39.32, -123.10	289	Radar	Yes

Deerwood	39.20, -123.16	280	Surface meteorology and soil moisture	Yes
Frost	39.30, -123.08	310	Precipitation	No
Potter Valley North	39.36, -123.11	404	Surface meteorology and soil moisture	Yes
Yellowjacket Ridge	39.33, -123.18	706	Precipitation	No
Boyes Creek Canyon	39.34, -123.16	317	Surface meteorology and soil moisture	Yes
Antler Point	39.34, -123.17	405	Precipitation	No
North Cow Mountain	39.18, -123.08	1041	Surface meteorology and soil moisture	Yes
North Cow Mountain Hillside	39.18, -123.08	1055	Precipitation	No
Windy Gap	39.23, -123.00	834	Surface meteorology and soil moisture	Yes
Green Pond	39.24, -123.01	694	Precipitation	No
Pasture Ridge	39.24, -123.02	521	Precipitation	No
Upper Pond	39.28, -123.14	530	Precipitation	No
Cow Pie Pasture	39.28, -123.11	317	Precipitation	No
White Creek Solar Panel	39.28, -123.12	402	Precipitation	No

Hell's Delight Canyon	39.27, -123.15	620	Surface meteorology and soil moisture	Yes
Redwood Valley Pineview	39.29, -123.30	379	Precipitation	No

In addition to providing crucial monitoring enhancements for situational awareness, the datasets presented have also been used to improve process-based understanding of ARs. Descriptions of results from these studies can be found in Section 2.3.4.

2.2.4 Russian River Hydrometeorological Observing Network (RHONET)

A newly enhanced multi-agency monitoring network in the Russian River Basin above Lake Mendocino now provides forcing data for developing atmospheric and hydrologic models, and observations to better understand the hydrological processes in the basin. This network has been named the ***Russian River Hydrometeorological Observing Network (RHONET)***, and collects data associated with extreme AR events that lead to flooding in the Russian River basin (Figure 2.2.4).

The U.S. Geological Survey monitors flow at 27 sites in the Russian River basin. NOAA ESRL-PSD, DWR, SCWA, USGS, and USACE collaborate in precipitation and soil moisture monitoring programs. In the Upper Russian River, ESRL-PSD installed precipitation and soil moisture monitoring sites, and CW3E installed a network of meteorological, soil moisture, and stream gauges. Observation locations were selected to best represent variability of soil moisture and precipitation within the watershed, according to topography, slope, soil type, and land cover. Soil moisture is measured at 12 locations; NOAA Potter Valley station collects data at 10 cm, 15 cm, and 50 cm; five NOAA stations and six CW3E stations collect data at 5, 10, 15, 20, 50, and 100 cm. For the six-station CW3E stream gauge network, we have developed rating curves that convert stage data to streamflow (Figure 2.2.5). Rating curves are based on surveys on all instrumented tributaries, staff plate photographs taken with time lapse cameras, and manual streamflow measurements at high and low flows during winter 2018. Measurement and safety protocols were developed and agreed to by CW3E, Sonoma Water, and ERDC.

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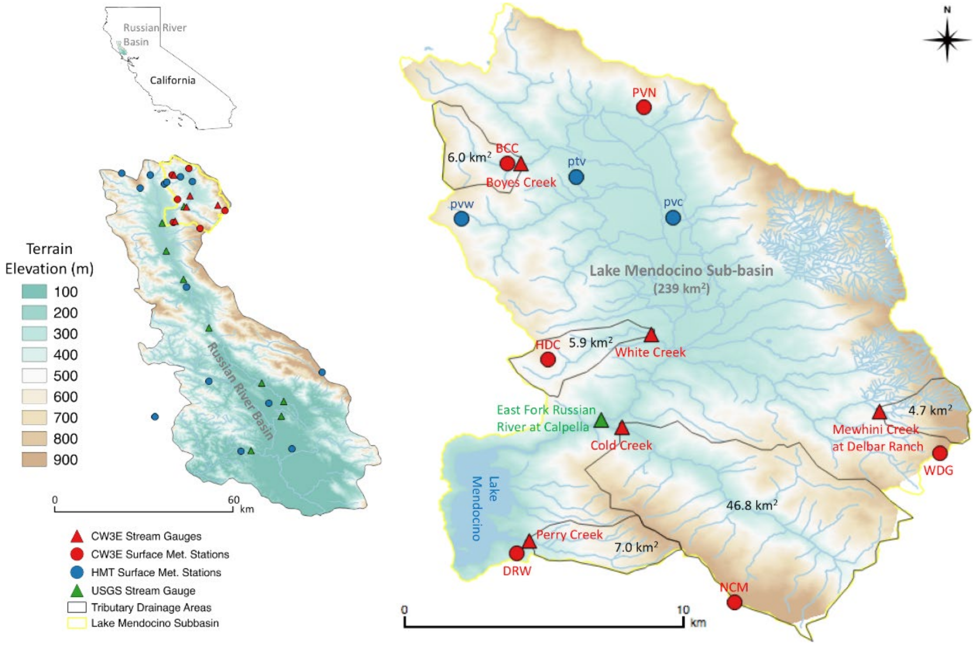
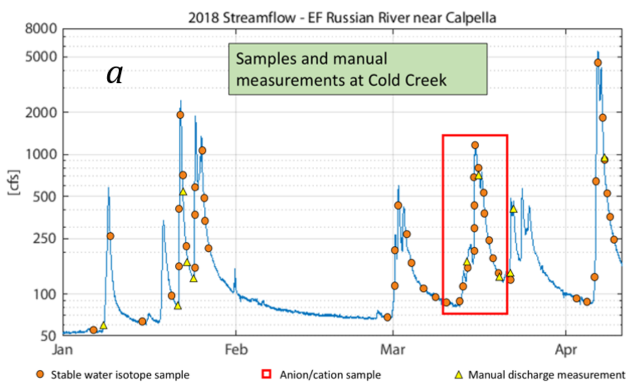


Figure 2.2.4 Locations of CW3E and NOAA surface meteorological stations with soil moisture observations and of CW3E and USGS stream gauges in the Russian River Basin (left) and within the Lake Mendocino Sub-basin (right).

For storms during 2017-18, we evaluated whether new precipitation gauge data allows improvements on the previous precipitation product. Previously we used the California-Nevada River Forecast Center (CNRFC) gridded precipitation (4-km, 6-hourly) downscaled to hourly timesteps using the temporal pattern from hourly NLDAS precipitation data. Observations at the new gauges were added to the NLDAS data to improve the hourly temporal pattern. Comparisons with and without the new gauged precipitation (in data denial experiments) showed that the new estimate produced more accurate hourly QPEs: higher correlations, smaller root-mean-squared errors, and smaller biases. Improvements were larger at lower elevation sites.

We used hydrograph separation techniques based on stable-isotopic compositions of precipitation, stream water, and groundwater to determine streamflow sources during precipitation events. The source water contribution totals (overland flow versus groundwater) from isotope and chloride analysis will be used to inform the construction and calibration of USACE's Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. A key issue in hydrologic modeling on flood and longer time scales is how precipitation is partitioned between overland and subsurface routes as water moves from the land surface into the stream channel. A model can be set up to emphasize one pathway vs the other, and seemingly accurate streamflow results can come from either setup, unless careful attention is paid and measurements taken to determine which is the more realistic representation. The hydrograph-separation procedures that we applied in the Russian River help ensure that we have the correct descriptions of precipitation partitioning at the land surface, and therefore that the model will be reliable under other future or more extreme precipitation conditions.

Using ISCO automated samplers, stream-water samples were collected at three Lake Mendocino tributaries; precipitation samples were taken with a modified ISCO sampler at the geographic center of the watershed; and groundwater samples were manually retrieved from springs. All samples were analyzed for Oxygen-18 (18O) and Deuterium (D). Results show the watershed is a well-mixed system and that the isotopic signatures of each source are not distinctly different from one source to another during events in winter 2018.



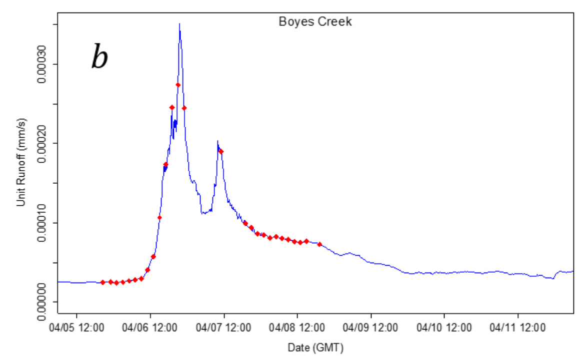


Figure 2.2.5 (a) Hydrograph from the USGS gauge at the Russian River near Calpella, with sample collections and manual measurements overlaid. (b) Example of the Boyes Creek runoff series created using a CW3E rating curve.

In addition to 18O and D, hydrograph separation can also be performed using geochemical tracers like chloride, specific conductivity and silicon dioxide. Chloride samples were collected and analyzed for a March 2018 precipitation event. Results showed that the percentage of streamflow from overland flow (new precipitation) ranged from 35% to 89% at Cold Creek. High contributions of overland flow occurred during the rising limb and only fell below groundwater contributions after the streamflow returned to pre-event levels.

The RHONET network provides high-quality, valuable data on precipitation, Lake Mendocino inflow volumes, flow sources and soil moisture. Soil moisture observations provide critical information on the antecedent wetness state of the watershed, which has implications for the run-off produced from precipitation events. Precipitation observations can be used to develop forcing data products to drive the GSSHA, West-WRF, and WRF-Hydro models. Streamflow observations are essential to calibrate and verify the models.

2.2.5. Conclusions and Recommendations

The efforts to enhance observations throughout the FIRO project have significantly improved the monitoring capabilities in the watershed. Research has shown that the network as it exists in 2020 is sufficient to support FIRO viability if maintained at the current levels (Sumargo et al., 2020; Section 2.3., Section 2.5, and references therein). The ongoing quantification of the benefits of the data collected during AR Recon to AR forecasts show that continuing the international, multi-agency effort is a critical component to improve forecasts as part of FIRO. Observing the atmosphere before, during and after extreme events are fundamental to the research to support FIRO, and useful to partners making real-time forecasts (Section 2.2.3). Continued efforts to maintain the observations that are currently available are important to supporting FIRO at Lake Mendocino beyond the FVA.

Listed below are recommendations to enhance the benefits of FIRO:

- Continue to integrate monitoring data into modeling and analysis studies to improve process-based understanding of ARs and their impacts.
- Continue storm-based sampling with airborne reconnaissance and ground-based radiosondes to directly feed into operational numerical weather prediction models to improve the representation of the initial state of the atmosphere.
- Maintain RHONET to support long-term process understanding, model improvements, and even (eventually) model inputs for improved hydrologic predictions.
- Upgrade all hydrometeorological stations to report in near real time to maximize the utility of the data.
- Continue data dissemination to NOAA Hydrometeorology Testbed, California Data Exchange Center, the Global Telecommunications System, and others as they are identified.
- Evaluate the sensor network regularly to identify potential gaps that can be addressed to maximize FIRO benefits. Examples include additional streamflow and soil moisture instrumentation in the lower part of the basin.
- Explore opportunities to add instrumentation relevant to FIRO to observation stations being installed for other purposes, such as wildfire preparedness.