Profiling of Soil Moisture Variability and Its Role in Rainfall-Runoff Generation in Northern California's Russian River Watershed

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Abstract

Capturing watershed-scale runoff response remains difficult, in part because of heterogeneous land surface characteristics in mountainous regions. This challenge has impacted our progress in understanding soil moisture role in modulating rainfall-runoff process. Situated in Northern California, the Russian River watershed is frequented by atmospheric rivers (ARs) that bring most of the significant rainfall events to the area and are associated with almost all of the floods. To observe the precipitation in this watershed, NOAA Hydrometeorology Testbed has installed 14 telemetered stations across the watershed since 2005, each with 2-minute soil moisture volumetric water content (VWC) sensors at 6 depths. The Center for Western Weather and Water Extremes at the University of California San Diego has installed 6 more stations since 2017. Understanding soil moisture variability is crucial for hydrologic modeling and operations, particularly flood prediction. This high resolution soil moisture observation network allows comprehensive analysis of soil moisture variability. For instance, correlation analysis of 2-minute VWC at 10-cm depth reveals a uniform shallow-layer soil moisture behavior with correlations of >0.8 at most locations and across different seasons, demonstrating the network's utility in capturing spatial and temporal soil moisture variabilities. Following this result, we investigate how antecedent soil moisture condition modulates the rainfall-runoff process. We include precipitation and stream discharge records from the same stations and nearby USGS gauges. A series of AR events in February 2019 offers a prime example. The February 2nd and Valentine's Day ARs saturated the soil in most parts of the watershed and resulted in minor flooding. Percentile rank analysis indicated the subsequent February 26th-27th ARs recorded the highest event total rainfalls since 2017 at most gauges. Consequently, the February 26th-27th ARs resulted in rapid runoff responses and widespread flooding. This example also reveals the spatial variation in antecedent soil moisture VWC "threshold" where runoff generation becomes efficient. Work is ongoing to profile this threshold variation within the watershed, and preliminary analysis suggests a range from <0.2 to >0.5 at 10-cm depth.

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Background and Motivation

- Antecedent soil moisture influences the magnitude of runoff response during atmospheric river (AR) precipitation events (Ralph et al., 2013; Cao et al., 2019).
- The role of soil moisture in modulating runoff generation during AR events requires a more thorough investigation.
- The Russian River Watershed in California has a uniquely dense network of hydrometeorological instrumentation including soil moisture (Sumargo et al., *in revision*).

Hydrometeorological Observation Network in the Russian River Watershed

2-minute precipitation, soil moisture volumetric water content (VWC), and stream discharge measurements from:

- 19 NOAA Hydrometeorology Testbed (HMT) and CW3E surface meteorological stations
  - VWC is measured at 5-, 10-, 15-, 20-, 50-, and 100-cm depths.
- 15 USGS and CW3E stream gauges

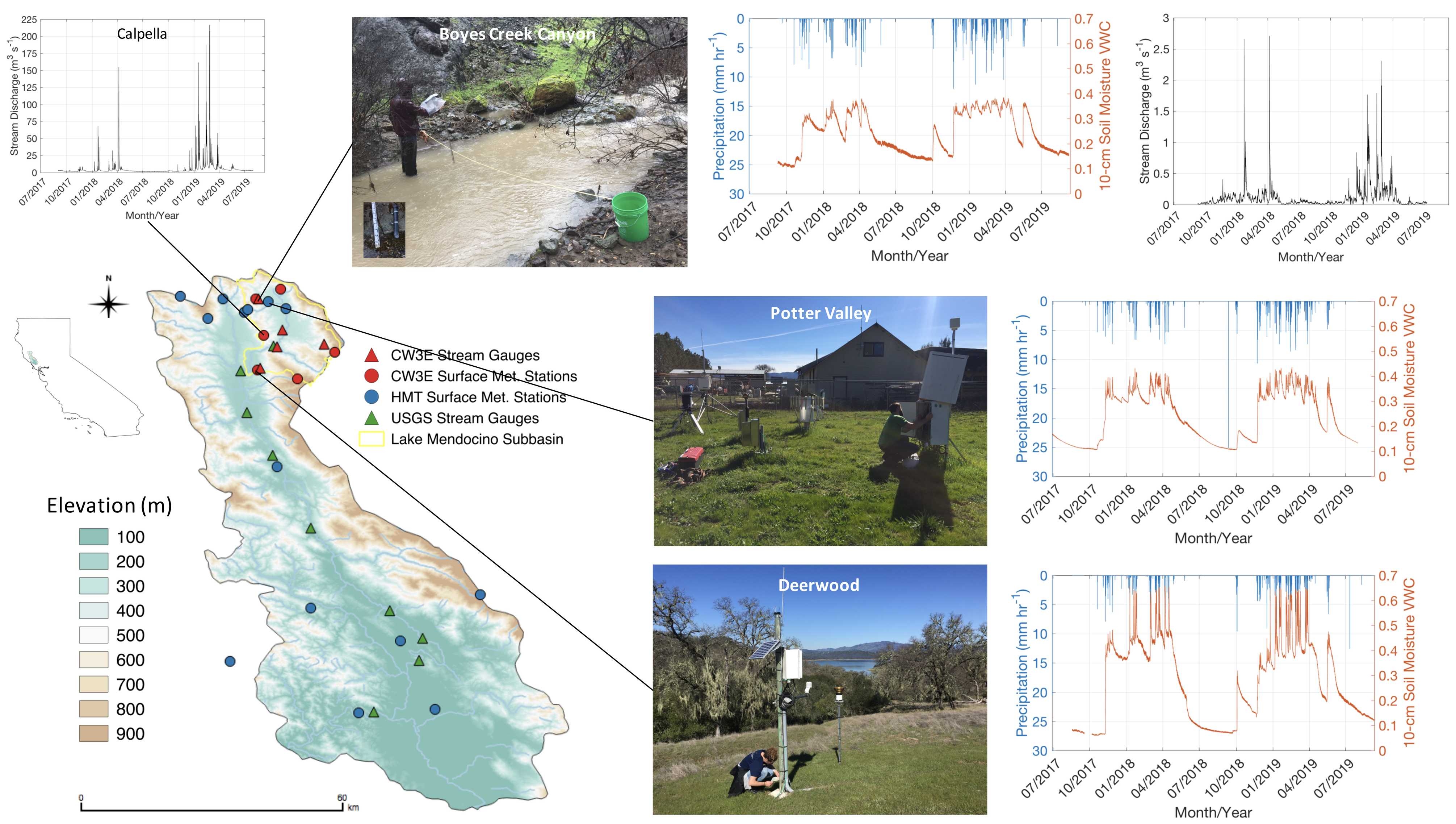

Figure 1. Terrain base map of the Russian River Watershed, showing the locations of surface met. stations and stream gauges. The inset map shows the watershed's location in California. The photos show the Boyes Creek (BCC) stream gauge and Deerwood (DRW) and Potter Valley (ptv) surface meteorological stations. Also shown are the hourly total precipitation and 10-cm soil moisture VWC at BCC, DRW, and ptv and stream discharges at BCC and East Fork Russian River at Calpella (ERC) from water year (WY) 2017 onward.

Is Soil Moisture Spatially Correlated?

- High soil moisture VWC correlations (>0.8) across all seasons:
  - Highest in autumn and spring (>0.9), lowest in winter (<0.9).
- Largely uniform soil moisture behavior across the watershed and across different seasons
  - High correlations in winter indicates this pattern largely persists despite the soil saturation and frequent ARs.

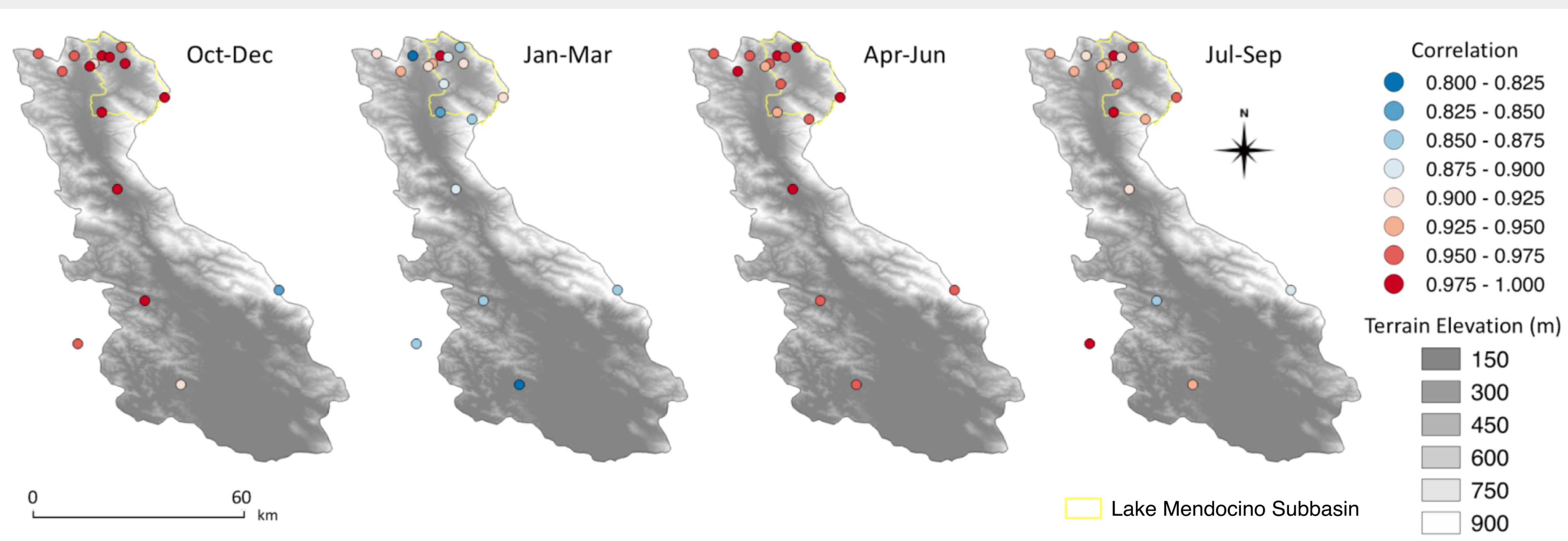

Figure 2. Terrain base maps of 10-cm soil moisture VWC correlations between CW3E BCC and other CW3E and HMT sites in the Russian River Watershed for autumn (Oct-Dec), winter (Jan-Mar), spring (Apr-Jun), and summer (Jul-Sep) of WY 2018. Only correlations with statistical significances ≥95% confidence level are included.

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Soil Moisture Field Capacity and Normalization

Site-to-site VWC and VWC_{FC} variations reflect the variation in local soil characteristics and environment.

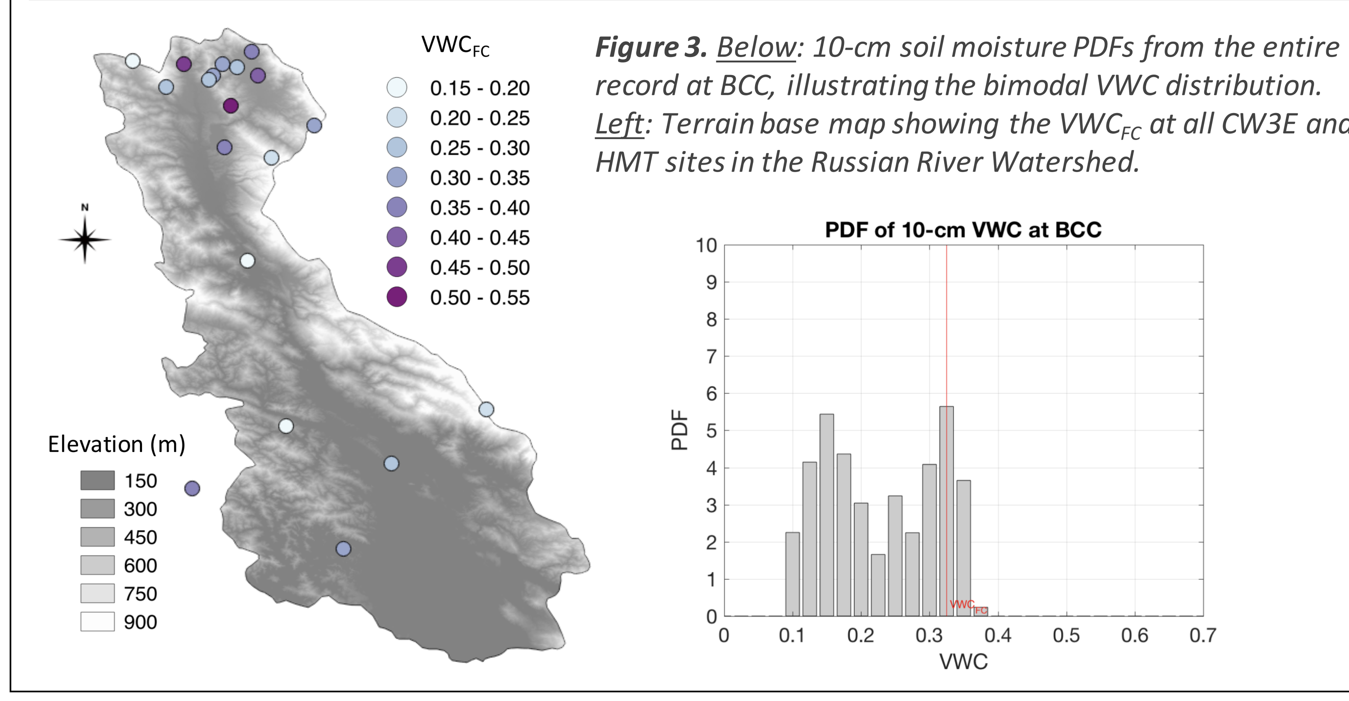

Figure 3. Below: 10-cm soil moisture PDFs from the entire record at BCC, illustrating the bimodal VWC distribution. Left: Terrain base map showing the VWC_{FC} at all CW3E and HMT sites in the Russian River Watershed.

- Soil moisture field capacity (VWC_{FC}) is identified using the probability density function (PDF) of VWC.
- VWC_{FC} is needed to "normalize" the spatially variable VWC:

$$VWC_n = (VWC - VWC_{PWP})/(VWC_{FC} - VWC_{PWP})$$

where: VWC_n = normalized VWC; VWC_{PWP} = permanent wilting point.

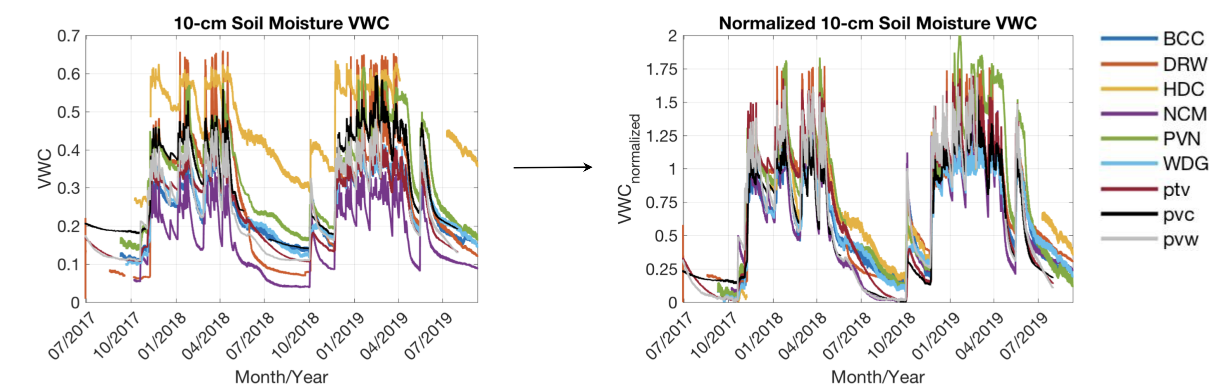

Figure 4. WYs 2018-2019 10-cm soil moisture VWC (left) and VWC_n (right) at 9 CW3E and HMT surface met. stations in the Lake Mendocino Subbasin.

Precipitation and AR Events in the Lake Mendocino Area

- Lake Mendocino Basin mean-areal precipitation is used to identify precipitation events.
- Integrated vapor transport (IVT) derived from integrated water vapor (IWV) flux observed at Bodega Bay AR Observatory is used to identify AR events (Wilson et al., *in preparation*).

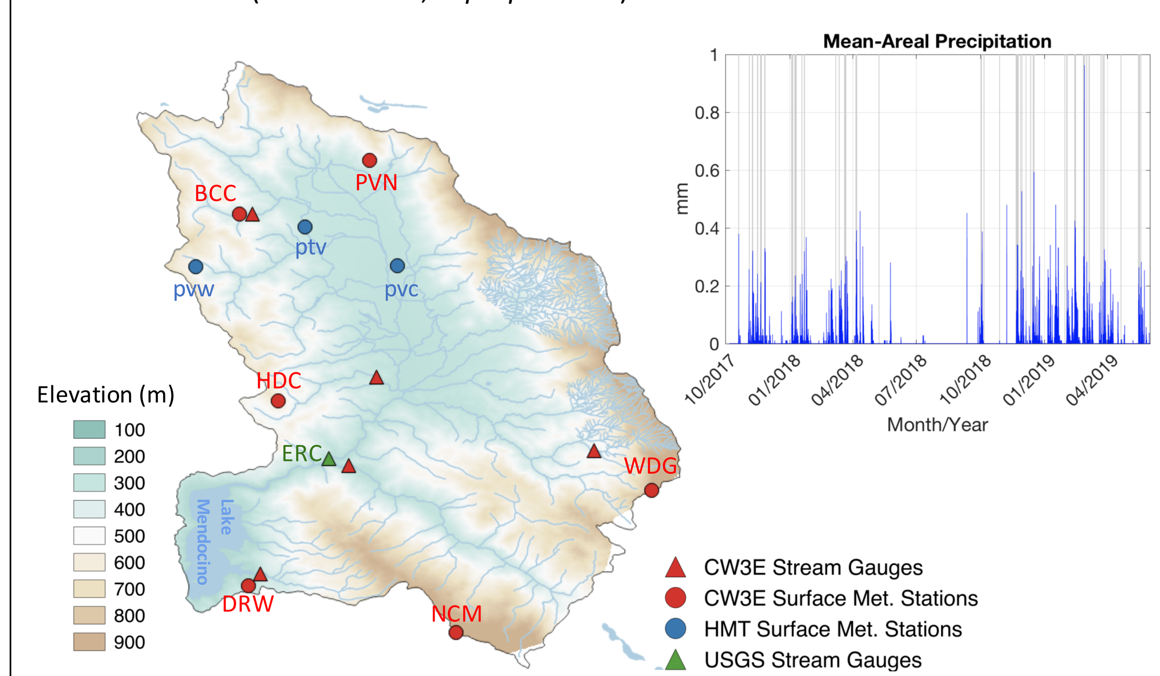

Figure 5. Left: Terrain base map showing the locations of surface met. stations and stream gauges in the Lake Mendocino Subbasin. Right: 2-minute mean areal precipitation time series for WY 2018 onward (blue), with indicators of AR condition (gray).

How Does Antecedent Soil Moisture Condition Modulate Runoff Generation?

- Soil moisture threshold behavior indicates where runoff generation becomes efficient ($VWC_n \cong 0.9$-1).
- Site-to-site threshold variation reflects the variation in local soil processes and runoff generation.
- Profiling the threshold behavior is also useful for:
  - Understanding the hydrology of the watershed,
  - Hydrologic model calibration and verification, and
  - Hydrologic applications (e.g., runoff and flood forecasting).

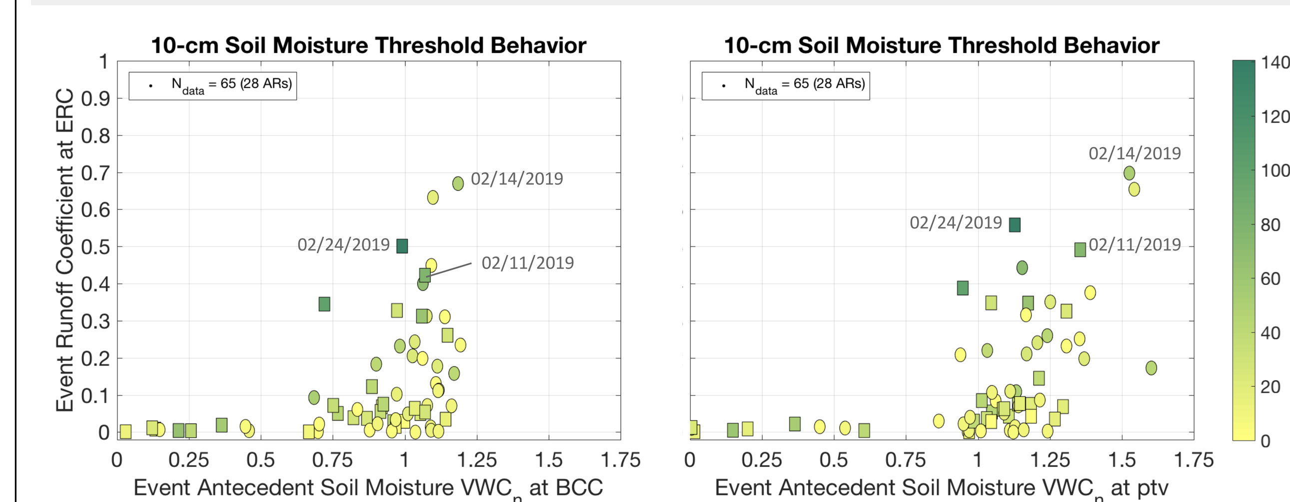

Figure 6. Event antecedent 10-cm VWC_n at BCC (left) and ptv (right) vs. runoff coefficient at USGS East Fork Russian River gauge at Calpella (ERC), demonstrating soil moisture threshold behavior. The colors denote the event total precipitations. Squares (Circles) denote AR (non-AR) events.

Operational Significance

- Forecast Informed Reservoir Operations (FIRO) at Lake Mendocino
- Gridded Surface Subsurface Hydrologic Assessment (GSSHA) and Weather Research and Forecasting-Hydro (WRF-Hydro) model calibration, evaluation, and streamflow forecast

WRF-Hydro is skillful at simulating VWC fluctuations associated with precipitation events, but tends to be low biased compared to observations → Calibration effort is ongoing.

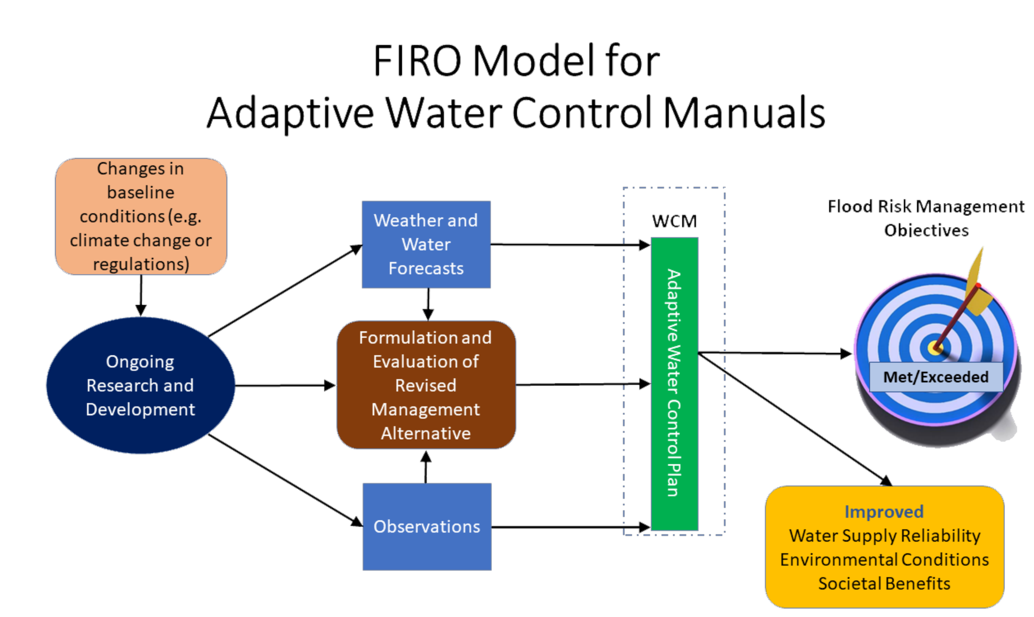

Figure 7. Diagram illustrating the FIRO process to develop an adaptive water control manual. Taken from https://cw3e.ucsd.edu/firo

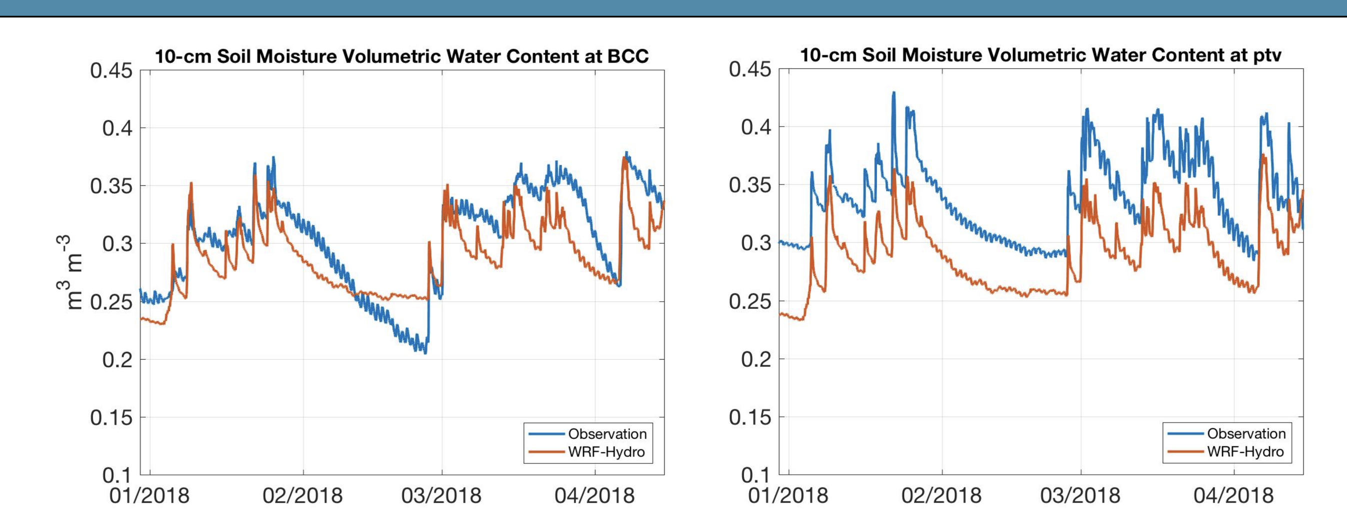

Figure 8. WRF-Hydro and observed 10-cm VWC at BCC and ptv over the January-April 2018 period, illustrating the variability in model skill in simulating VWC.

Station	Correlation	RMSE	NSE	Mean Bias	Elevation (m)
DRW	0.85	0.17	-5.84	-0.16	280
pvc	0.78	0.12	-4.06	-0.11	289
ptv	0.92	0.05	-1.35	-0.05	303
BCC	0.82	0.03	**0.57**	-0.01	317
PVN	0.75	0.14	-4.28	-0.13	420
pvw	0.89	0.06	**0.11**	-0.04	518
HDC	0.68	0.27	-31.14	-0.27	646
WDG	0.73	0.05	-0.33	-0.04	834
NCM	0.88	0.07	-0.5	0.06	1031

Table 1. Statistics exemplifying WRF-Hydro performance in simulating 10-cm VWC at 9 CW3E and HMT sites in the Lake Mendocino Subbasin. Boldface numbers indicate significant skills over the mean.