Section 2.5. Hydrologic Model Improvement

2.5.1 Overview

New hydrologic modeling capabilities and hydrologic observations are being investigated to identify ways to improve streamflow forecasts associated with AR events over the Lake Mendocino catchment. These investigations support the FIRO objective to better operate reservoirs for authorized purposes using precipitation and hydrologic forecasts. We specifically address the recommendation made in the FIRO PVA to evaluate emerging watershed and runoff forecast systems such as the NOAA National Water Model (NWM) and USACE's Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. These enhanced watershed runoff models represent key physical processes, including surface-groundwater interactions, and integrate uncertainty associated with observations, model states and formulation, and future (meteorological) forcings.

Accomplishing this requires a core collaboration between the Army Corps' Engineer Research and Development Center (ERDC) and CW3E to link West-WRF forecast input data to the GSSHA distributed model. CW3E has installed and is maintaining hydrometeorological field instrumentation in the Russian River watershed in support of model and forecast development, calibration, and forecasts. A primary research question is whether state-of-the-art atmospheric and hydrologic models at Lake Mendocino can combine to improve simulations and forecasts of stream flows and lake levels, especially during large precipitation events. To address this question, we will use hydrologic observations to develop better understanding of Upper Russian River hydrology. We will then assess how best to simulate and predict this hydrology, by testing the effects of model spatial resolution, precipitation source/type/resolution, and forecast lead time on hydrologic modeling results.

Highlights of this task include the following accomplishments:

- Developed, calibrated, and verified WRF-Hydro and GSSHA distributed hydrologic models of the Lake Mendocino watershed (sections 2.5.2, 2.5.3)
- Developed infrastructure to ingest West-WRF meteorological forcing into GSSHA and WRF-Hydro (section 2.5.2)
- Developed a novel calibration technique using distributed soil moisture information to set parameters in the WRF-Hydro gridded hydrologic model (section 2.5.3)

2.5.2 GSSHA Model

Improvements in tracking, understanding and prediction of the hydrology of Russian River basin provide a stronger basis for application of FIRO at Lake Mendocino. In this task a state of the art atmospheric and hydrologic modeling system formed by coupling the West-WRF and GSSHA models for the Upper Russian River watershed above the Hopland gauge was demonstrated. West-WRF meteorological forcing is used to drive the GSSHA model, which is a physics-based, spatially explicit hydrologic model that continuously simulates processes relevant to the hydrologic response of a watershed including rainfall distribution, plant interception, surface retention, evapotranspiration, vertical infiltration, 2D overland flow, 1D channel flow, 2D groundwater flow for the unconfined aquifer system and surface water-groundwater interaction, lake/reservoir levels, and snow accumulation and melt. Although GSSHA is not the operational model used in FIRO, this research points a way forward toward how improved operational forecasts, and meteorological-hydrological model coupling schemes, can improve future FIRO outcomes.

Critical elements were:

- Gathering, analyzing, and preparing existing data; filling historical data gaps with RHONET data
- Developing hydrologic models of varying resolutions.
- Coupling the hydrologic models to the West-WRF atmospheric model.
- Calibrating and validating the models to streamflow, reservoir level, and soil moisture records.
- Incorporating the GSSHA model into the UCAR data assimilation (DA) system.
- Assessing the impact of utilizing DA for GSSHA modeling, specifically at Lake Mendocino

We gathered and co-mingled spatial data sets needed to run GSSHA in the Russian River. These included maps of bedrock elevation land use, soil type, stream network and cross-sections. The depth to bedrock map combined new and existing USGS ground penetrating radar data, USGS borehole data, and NRCS data on impervious soil layers. In addition, we developed infrastructure to ingest West-WRF output into GSSHA. The ERDC *gsshapy* toolkit was modified to extract and reformat the necessary variables for driving GSSHA from West-WRF output in netCDF format. Precipitation forcing from alternate datasets, e.g., CNRFC and CNRFC-mod QPEs, can also be converted to GSSHA format using the *gsshapy* toolkit. The GSSHA model was also modified to allow the incorporation of operational hydraulic control structures.

We analyzed the effect of model resolution on simulations of the Russian River. Models at 270 m, 100 m, and 50 m resolution were developed for the entire Upper Russian River watershed, while a smaller domain, focusing on the Lake Mendocino watershed, was simulated at 30m resolution.

GSSHA models were calibrated starting with the lowest resolution (270m) surface water model for a single event (during December 2004), followed by increasing the resolution to 100m and 50m, extending the calibration time period (4 Dec 2004 - 15 May 2005, 01 Jan 2018 - 15 Apr 2018 for the 270m models, and 4 Dec 2004 - 17 Dec 2005, 27 Feb 2018 - 20 Mar 2018 for the 100m models), and finally adding the GSSHA groundwater component to create a fully coupled surface water/groundwater GSSHA model.

Selected models were calibrated for surface and groundwater parameters, and two forcing data sets (gauge precipitation; West WRF data). Observed flow data included USGS flow gauging stations in the primary river channel, and CW3E stations in secondary and tertiary creeks above Lake Mendocino for the 2018 calibration period. Because of the complexity of the models and the many parameters that need calibration, an automated procedure, the Model-Independent Parameter Estimation & Uncertainty Analysis (PEST) software, was used on the High Performance Computing (HPC) clusters at ERDC to arrive at optimal parameter values for each model calibration. During calibration, model performance was judged by weighted differences between observed and simulated daily flow volumes, event-based volumes, and event-based peak flow rates at the USGS and CW3E gauging stations. The performance of the calibrated model was evaluated based on several goodness of fit metrics.

The calibrated models utilizing the RHONET precipitation gages and West-WRF 1d lead forecast were capable of simulating flows and reservoir levels during the calibration period. Figure 2.5.1 shows observed and GSSHA simulated daily flows at USGS gages near Calpella and Hopland, for the 270m resolution model with one day forecast lead time West-WRF precipitation and meteorological output for the calibration period from 01 Jan 2018 to 15 Apr 2018. The GSSHA precipitation and hydrometeorological data set was created by using the one day forecast lead West-WRF forecast to create a serially complete series for the calibration period, using the tools described in the "Infrastructure Development" section above. This allowed the GSSHA model to run continuously for the calibration period.

The GSSHA model matches between simulated and observed event-based volumes and peak flow rates (Figure 2.5.2) had NSE scores for the Calpella and Hopland stations of 0.97 and 0.88, respectively. Other statistics for the USGS stations for the 270m and 100m resolution models with West WRF forcing data are listed in Table 1. Calibrations using the RHONET data significantly improved compared to calibrations with the historical data from 2004. A complete description and results of the calibration can be found in Appendix F.

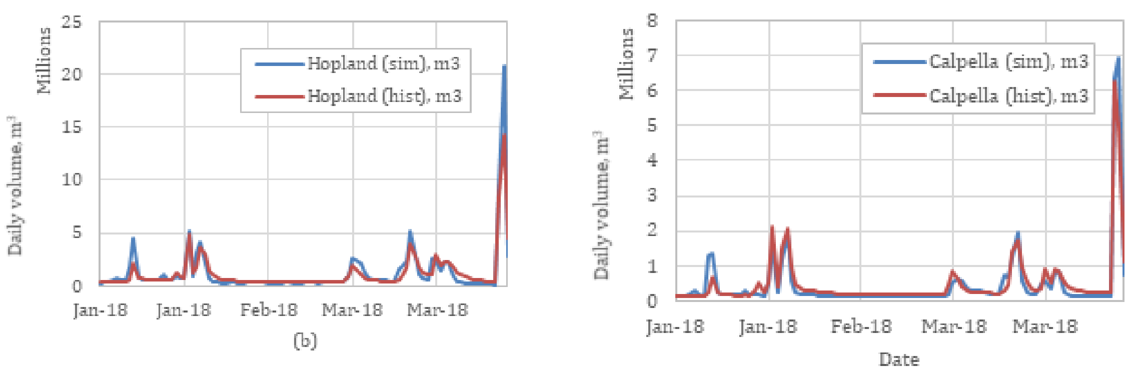

Figure 2.5.1 Simulated vs. Observed daily flow volumes at (a) Calpella, and (b) Hopland, for the 270m resolution GSSHA model with West WRF precipitation and hydrometeorological forcing data.

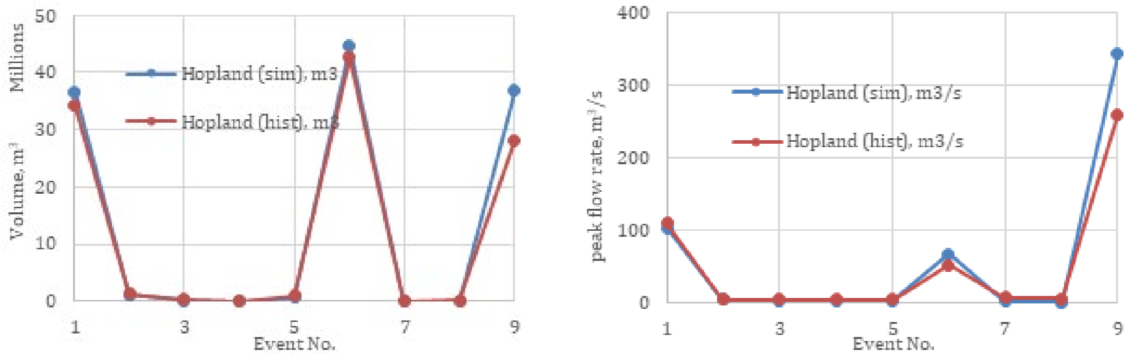

Figure 2.5.2 Simulated vs. Observed event-based volumes and peak flow rates at the USGS station near Hopland for the 270m GSSHA model with West WRF forcing data. These 9 events occurred between 1/3/2018 and 4/8/2018 and were between 15 min - 37 days in length. Accumulated volume and maximum discharge for these events were used as part of the performance measure during model calibration.

Table 2.5.1 Calibration metrics for the event-based volumes at key USGS gauging stations, using the same events as in Figure 2.5.4

		Hopland	Calpella	Ukiah
270m res.	NSE	0.97	0.96	0.99
	R' m^3	0.98	0.96	0.99
100m res.*	NSE	0.78	0.94	0.82
	R' m^3	0.99	0.99	0.99
** 100m res models calibrated for a sub-period due to long model run times*				

Model Verification and Assessment

The calibrated models were then applied to a separate verification period (05Dec2018 - 15April2019) to assess the prediction capability of the GSSHA models. Similar to calibration, the verification process compares observations to the GSSHA models at two resolutions (270m, 100m) and with different forcing data sets.

Daily observations are compared to flow volumes simulated by the 270m resolution model in Figure 2.5.3, with the model driven by the RHONET gauge precipitation and hydrometeorological forcing data at Calpella and Hopland. The model, applied to the selected verification period, simulates observed flow volumes at key locations within the Lake Mendocino watershed.

We compared the one day forecast between the CNRFC operational hydrologic model and the 270m resolution WestWRF-GSSHA model for two winter periods. For 2018 winter season, West-WRF/GSSHA is in calibration mode, while for 2019 winter season it is in verification mode. The CNRFC model is calibrated on previous data and is in verification mode for both periods. NSE model performance values are shown for Calpella and Ukiah gages (Table 2.5.2), and hydrographs are shown for the Calpella gage (Figure 2.5.3).

As expected, the GSSHA model outperformed the CNRFC model in 2018, because GSSHA was calibrated for this period. In 2019, the CNRFC model outperformed the GSSHA model, which is also expected because both models are in verification mode, but the CNRFC model has been calibrated over a longer period of time and therefore has a more robust calibration.

As the West-WRF forecast lead time is increased, comparisons to observed flows deteriorated with the West-WRF/GSSHA model (not shown). Most of the difference in the flow results can be attributed to the meteorological forecast, which trended toward increasing underprediction of the precipitation as the lead time increased. These results, along with validations of simulated reservoir levels, are presented in Appendix F.

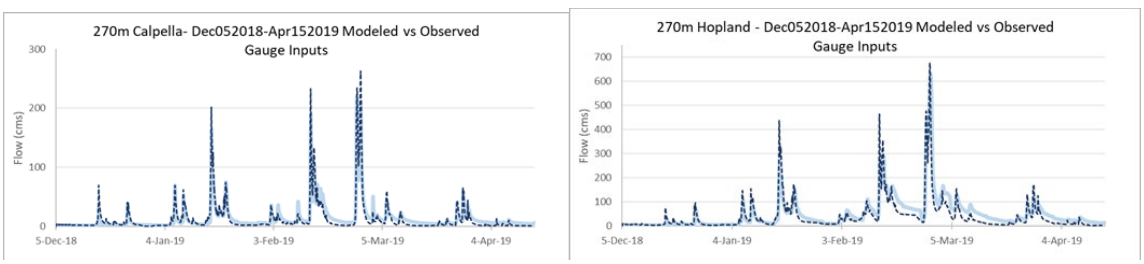

Figure 2.5.3 Simulated vs. Observed flow volumes at (a) Calpella, and (b) Hopland, for the 270m resolution GSSHA model with RHONET gauge precipitation and hydrometeorological forcing data.

Table 2.5.2 Comparison of CNRFC and GSSHA/West-WRF 1 day forecast of daily volumes at selected gages.

Simulation Period	Gage	CNRFC NSE	270m GSSHA/West-WRF NSF
2018	Capella	0.42	0.88
2018	Ukiah	0.56	0.78
2019	Capella	0.92	0.63
2019	Ukiah	0.89	0.59

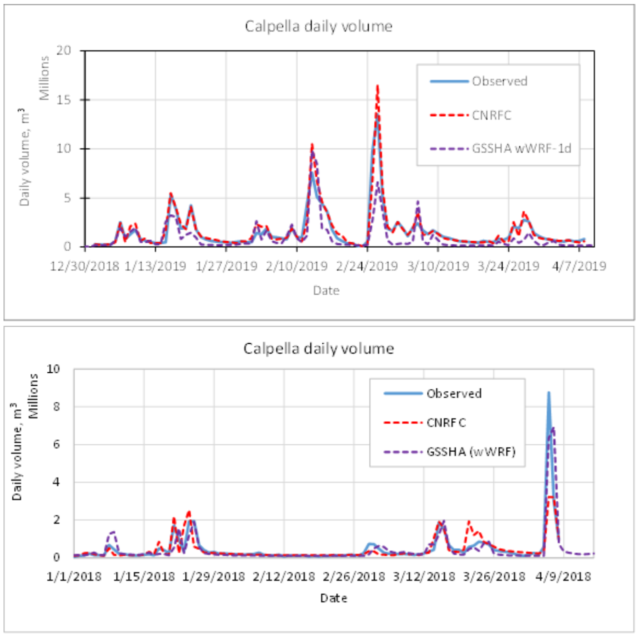

Figure 2.5.4 Comparison of CNRFC and GSSHA/West-WRF 1-day forecast flows at Capella.

The calibrated GSSHA models were used to estimate the water balance of the Upper Russian River watershed. The October 1, 2018 - Sept 30, 2019 period was simulated with a 100m resolution model using the RHONET gage data. The basin wide total precipitation for this period was 120 cm. Of that approximately half infiltrated and half became runoff. Evapotranspiration was very close to the amount of infiltration. Groundwater recharge was 12% of infiltration. Basin wide, flows are primarily from surface and shallow near surface flows rather than groundwater. Streams in the Upper Russian River both receive and contribute water to the subsurface (groundwater) depending on location and time of year, but the streams were simulated to receive about twice as much water from groundwater as leaked from the streams into the groundwater. About 10% of the flow at the Hopland gage is estimated to derive from net groundwater inputs. Surfaces flows into and from the lake are also the primary components of the lake's water balance, with rainfall, ET, and (primarily) losses to groundwater being only about 20% of that balance, with rainfall and ET being roughly equivalent, and seepage from the lake bottom being 10% of inflows The complete annual water balance for the watershed and the reservoir is presented in Appendix F.

The GSSHA model was able to simulate flows and reservoir levels at Lake Mendocino utilizing RHONET, West-WRF, or CNRFC precipitation to force the model. Calibrations utilizing the RHONET network of precipitation and stream gages were significantly better than the results using the historical network from 2004-2005.When calibrated using one day West-WRF forecasts for the 2018 season, the model provided excellent hindcasts when forced 1D West-WRF or CNRFC forcing data. The models were useful for understanding the basin hydrology and water balance. Accuracy decreased as the WestWRF forecast lead time increased. A systematic decrease in forecast total precipitation was noted as the forecast lead time increased. Calibration of GSSHA using different WestWRF lead times could possibly improve flow and reservoir level forecast for those lead times. Using observed data to initialize the model state before each event and assimilating the data into the model runs would also likely improve model forecasts at longer lead times.

GSSHA sensitivity to forcings

We evaluated the sensitivity of GSSHA's hydrologic predictions to the meteorological forcings used to drive the models. For example, Figure 2.5.4 (upper panels) shows four West-WRF forecasts of an AR event, each using different sea surface temperature estimates. When the 270-m resolution GSSHA model of Lake Mendocino is forced with these forecasts, the model produces substantially different peak flow forecasts (Figure 2.5.4, lower panel), as flow responds to bursts of heavier rainfall within the AR. We tested GSSHA sensitivity to default (single rain gauge), West-WRF and CNRFC-mod precipitation inputs. Distributed rainfall data rather than a single gauge was required for accurate peak-flow simulations. All GSSHA forecasts under-simulated the observed baseflows and simulated peak flows arrived too early. GSSHA drive by CNRFC-mod yielded the most realistic peak flows.

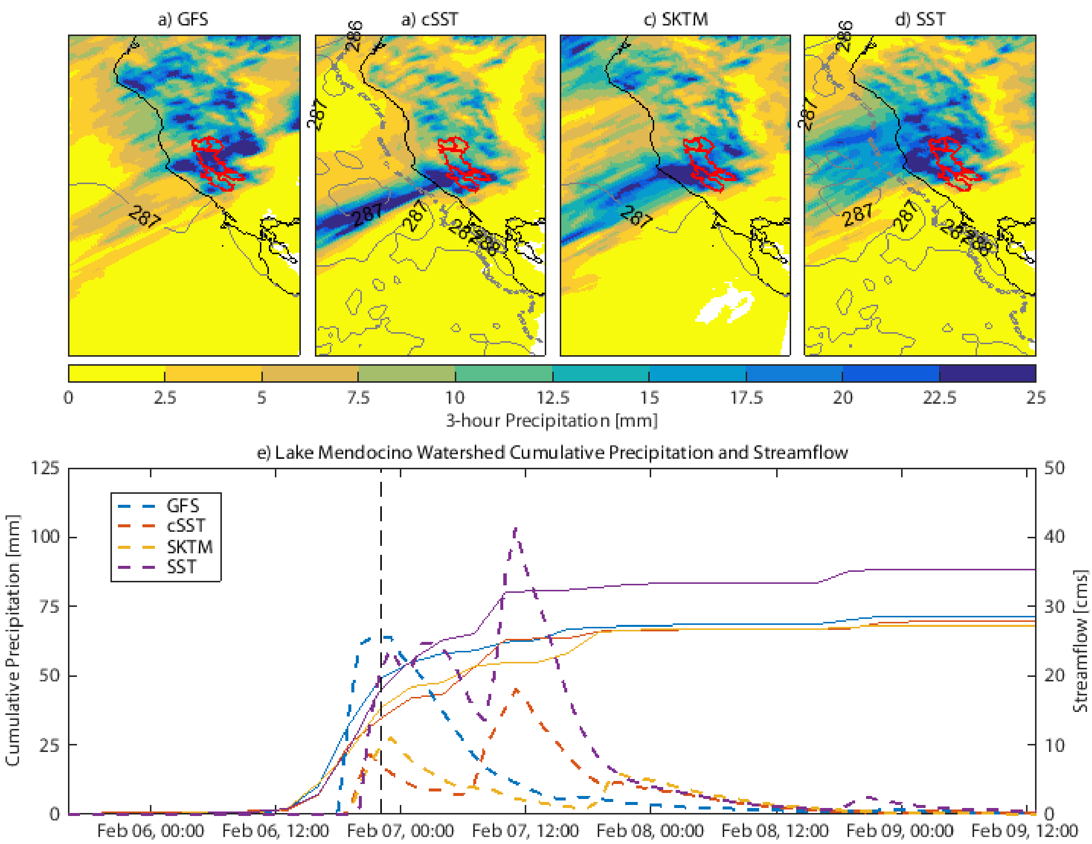

Figure 2.5.4 Upper panels: West-WRF forecast precipitation fields at 3 km resolution under four sea surface temperature boundary condition scenarios during the February 6-9, 2015 AR event. The Russian River watershed is shown in red. Lower panel: Streamflow response of the Lake Mendocino watershed to the four scenarios. Cumulative precipitation is shown in solid lines and streamflow hydrographs are shown in dashed lines.

GSSHA sensitivity to West-WRF ensembles

Meteorological forecasts will always be uncertain, so ensemble flow forecasting is valuable for putting even the best (single) forecast into its proper context and for managing hydrologic and flood risks objectively. We used GSSHA to test West-WRF ensemble precipitation forecasts (section 2.3.6). Ensemble forecasts help to estimate flood risk and quantify flow forecast uncertainty due to meteorological uncertainty.

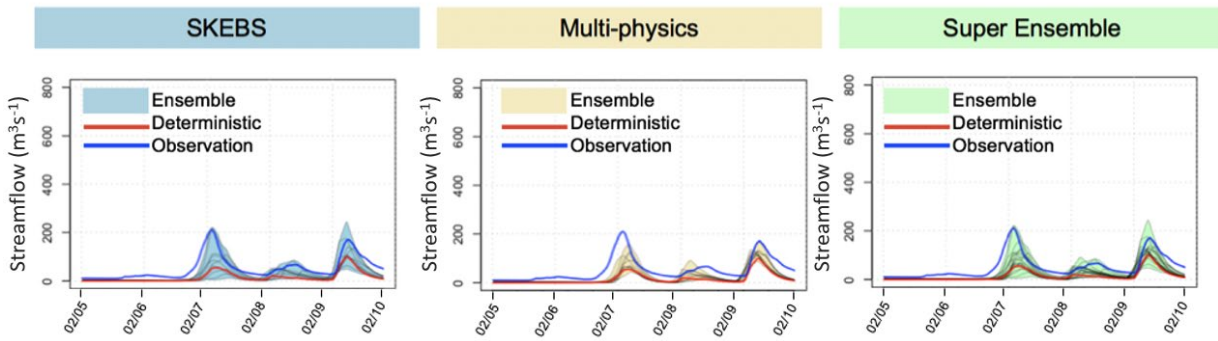

Figure 2.5.5 GSSHA streamflow output at the Calpella gauging station, from deterministic and ensemble West-WRF, compared to USGS observation station for the period of Feb.5th 0400z to Feb.10th 0400z 2017. Three ensembles are tested, (Left) 10-member Stochastic Kinetic Energy Backscatter Scheme, (Center) 10-member Multi-Physics ensemble, (Right) 20-member Super ensemble (combination of SKEBS and multi-physics).

We tested whether ensemble forecasts captured the forecast uncertainties, i.e. whether uncertainties are well represented by ensemble scatter from the ensemble described in Section 2.3.6. Figure 2.5.5 shows ensemble streamflow forecasts during the February 2017 Oroville Event. The ensemble forecasts, like the deterministic forecasts, were biased too low on average, but observed flows were within the ensemble spread in many cases. These kinds of experiments showed that, specifically, the SKEBS forecast ensemble included observed flood peaks within its range more often than did the multi-physics ensemble. These experiments illustrate ensemble methods can be used to characterize forecast uncertainties, but also that more research will be needed to improve that characterization.

2.5.3 WRF-Hydro

This task investigated an atmospheric and hydrologic modeling system formed by coupling the West-WRF and WRF-Hydro models. We developed a WRF-Hydro v5.0 (1 km) model for Lake Mendocino watershed (Figure 2.5.6), mirroring the National Water Model (NWM) configuration. The NWM is a U.S.-wide hydrologic model developed by the Office of Water Prediction (https://water.noaa.gov/about/nwm). A combined West-WRF and WRF-Hydro system is particularly advantageous for FIRO because the WRF-Hydro model is available nationwide through the NWM. This means that the hydrologic model used is part of (and leverages) the national efforts and resources associated with the NWM. Thus WRF-Hydro offers an opportunity to scale the use and investments of distributed hydrologic modeling from an official and national tool. We evaluated model skill at simulating streamflow and soil moisture in the watershed, using forcings from the National Land Data Assimilation System v2 as well as West-WRF output.

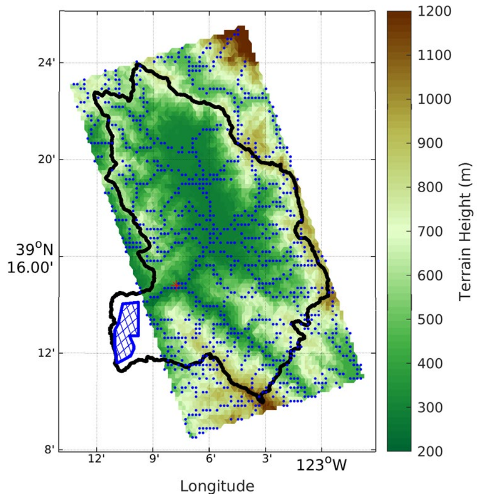

Figure 2.5.6 Lake Mendocino Watershed domain (black outline) and terrain (shaded) in the WRF-Hydro model.

We compared WRF-Hydro streamflow and soil moisture simulations to observed streamflow and soil moisture during the series of ARs between February 5-11, 2017. The simulation provided insight into model runoff and soil moisture processes, and several model deficiencies were identified including overprediction of peak flows and responses to early AR impacts when soils are dry. Simulated hydrograph recession rates were too slow, due to over-prediction of slow, subsurface contributions. This suggests that slow moisture fluxes in the soil column are being misrepresented or estimated in ways that contribute to streamflow error.

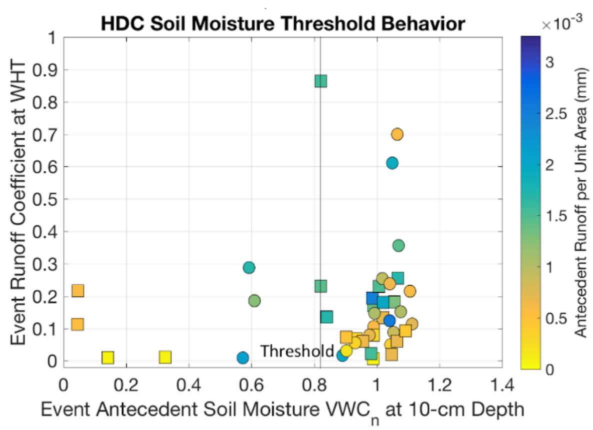

Figure 2.5.7 Runoff coefficient at Whites Creek as a function of normalized antecedent soil moisture at nearby Hell's Delight Canyon, colored according to antecedent runoff. High runoff coefficients occur when antecedent soil moisture and runoff are both high.

To address this soil-moisture concern, we used RHONET soil moisture data, together with information from our field teams and from the hydrograph separation research described above, to understand how wet antecedent conditions contribute to sustained hydrologic response, high river flows and flooding. Figure 2.5.7 shows that high-precipitation runoff efficiencies only occur if antecedent soil moisture is high and antecedent runoff (used as a proxy for groundwater levels) is also high. The results show that accurate antecedent soil moisture values are required for accurate flow predictions.

We evaluated spatial correlation of observed and modeled soil moisture content to determine the uniformity of soil moisture fluctuations across the basin. On a seasonal time-scale, strong correlations (>0.8) were observed in all seasons. Correlations are strongest in autumn and spring (>0.9) during soil wet-up and dry-down periods. Correlations are weakest in winter (0.8-0.9) as soils are wet throughout the basin, but differences in soil properties and levels of saturation impact site to site comparisons (Figure 2.5.8). Soils at some sites have less capacity to hold water and so may reach saturation more quickly. Spatial differences in precipitation rates and amounts also contribute to the modest loss of site to site correlations in the wet season. The decorrelation of soil moisture during AR periods reveals spatial variations in soil moisture that are not well simulated by WRF-Hydro, which predicts consistently highly correlated soil moisture. Our ongoing work seeks to improve this issue.

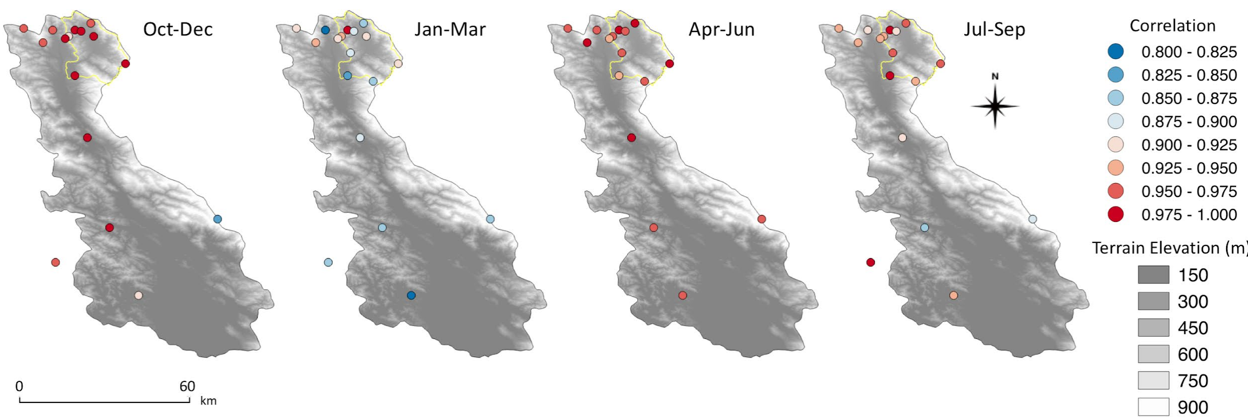

Figure 2.5.8 Pearson's correlation maps of soil moisture content at 10-cm depth for autumn (Oct-Dec), winter (Jan-Mar), spring (Apr-Jun), and summer (Jul-Sep) of WY 2018. Correlations are shown in relation to Boyes Creek Canyon site.

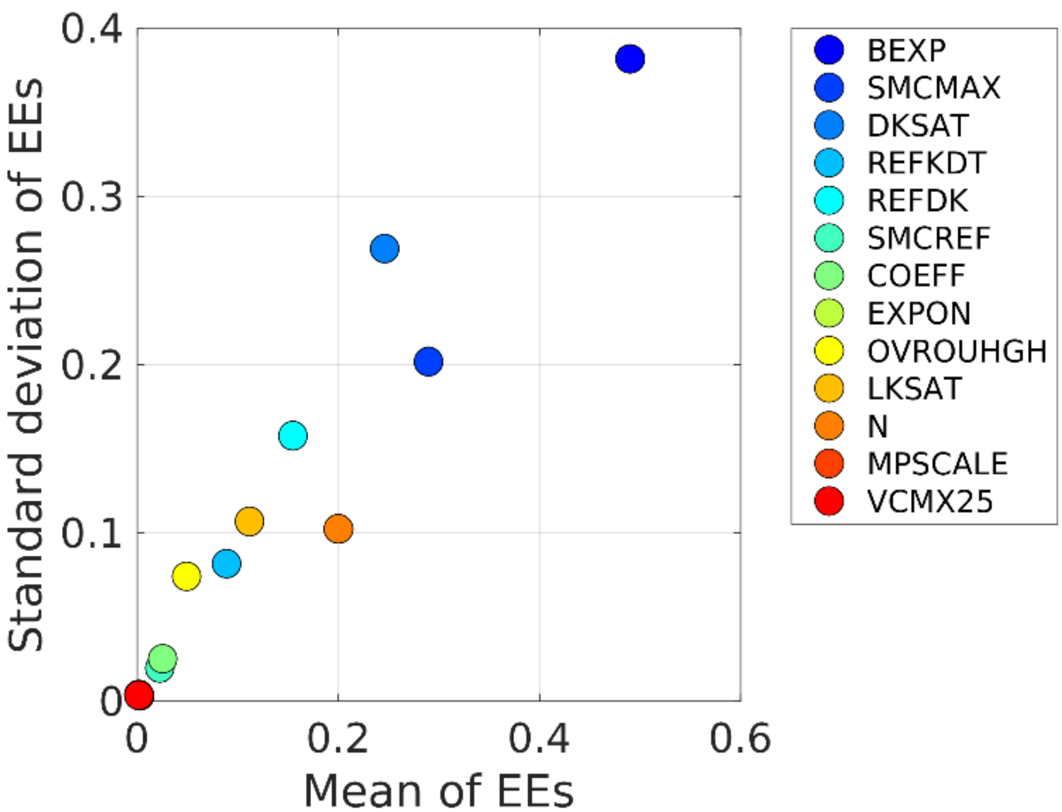

Figure 2.5.9 Mean vs standard deviation of the Elementary Effects (EEs) for WRF-Hydro soil parameters. Each EE is the ratio between the difference in the Nash-Sutcliff efficiency of the streamflow and the change in parameters between two experiments.

We are developing a new calibration technique using distributed soil moisture information to set soil parameters in WRF-Hydro. Calibration is needed because, although WRF-Hydro captures synoptic-to-annual variations in soil moisture, it underestimates local spatial and temporal variations. We used sensitivity analysis to determine which parameters affect soil moisture simulations most and thus that should be addressed (modified) in calibrating the model. We explored parameter sensitivities for 13 model parameters. Moisture maximum (SMCMAX), beta exponent (BEXP), saturated soil hydraulic conductivity (DKSAT), runoff/infiltration rate (REFKDT) and Manning's Roughness (N) are the parameters that are most important to get right in the Lake Mendocino watershed model.

2.5.4 Conclusion and Recommendations

Hydrologic models that make reliable streamflow forecasts are basic to FIRO's success. In light of this, we developed an interagency collaboration to develop and test GSSHA and NWM hydrology models to support FIRO. To improve our understanding and thus the structure of the hydrologic models and forecasts, we have integrated observations, model development and verification, and ensemble development. Results indicate that physics-based models can accurately estimate flows and lake levels given accurate rainfall estimates and are suitable for use in FIRO applications. Utilizing the data from RHONET significantly improved hydrologic model performance we seek to improve estimates of initial conditions, model parameter variation, and streamflow predictive uncertainty. As physics based hydrologic models are sensitive to precipitation estimates, ultimately accurate flow estimates require improvements in longer term meteorological forecasts. These improvements in understanding provide underlying context for potential USACE and CNRFC improvements in modeling and operational practices.

Several recommendations to enhance hydrologic modeling benefits to FIRO are:

- Develop methods to produce representative ensembles that more fully capture meteorological and hydrological uncertainty.
- Focus on meteorological and hydrologic model improvements that will be beneficial across multiple watersheds as FIRO extends beyond Lake Mendocino.
- Analyze West-WRF and NWM reanalyses and observations to improve understanding and representations of pre- and post-storm land surface and drainage processes and fluxes that control soil moisture dry-down and wet-up rates.
- Analyze the influence of spatial variation in meteorological and hydrological variables, on the contributions of various tributaries to flows into the Lake Mendocino Reservoir.
- Continue soil moisture calibration.
- Develop an operational version of West-WRF/GSSHA to demonstrate potential applicability for FIRO