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Type of Project: Cooperative

Project Title: Regional Optimization of WRF-Hydro forecasts for the Contiguous US

UCAR Award Number: [FILL IN]

Date: 19 August 2017

Summary of Project Objectives:

During the past 30 years, flooding events have cost the US $7.96 Billion per year and have resulted in an average of 82 fatalities per year (National Weather Service, 2015). The physical processes that affect this immediate danger to life and property carry a high degree of epistemic uncertainty, particularly for flooding associated with localized convective precipitation. This uncertainty of physical processes creates challenges for the developers of hydrologic models. **Despite this challenge, accurate flood forecasting remains essential for all areas of government (from local to federal), including the National Oceanic and Atmospheric Administration (NOAA) National Water Center (NWC).**

To improve hydrologic forecast products as they move to centralized water forecast operations across the US, the NWC National Water Model (NWM), which is based on the WRF-Hydro computational architecture (Gochis et al. 2015), recently became operational. The NWM uses WRF-Hydro with the Noah-MP Land Surface Model (LSM) operationally for the Contiguous US (CONUS) to produce a range of streamflow and hydrologic forecasts. This national model is a physically based alternative to regional lumped hydrologic models that are implemented locally by River Forecast Centers (RFCs), such as the Sacramento model (SAC-SMA) model (Burnash 1995; Hogue et al. 2000). Even when run in a semi-distributed configuration, the SAC-SMA is unable to resolve streamflow pulses associated with heavy, localized, precipitation events (John Lhotak, Colorado Basin RFC, personal communication 2015). Recent improvements to high performance computing technology have allowed for the development of high dimensionality spatially-distributed hydrologic models, such as WRF-Hydro. These modeling systems allow for physical processes, including land-surface infiltration and surface runoff, to be explicitly computed.

To complement this development of the NWM, research to determine effective methods to calibrate a model at this scale is still needed. The calibration methods utilized may need to be partially dependent on forcing precipitation. WRF-Hydro does not at present represent channel loss caused by infiltration, which is an important component of the water budget in semi-arid regions such as the southwest CONUS (e.g. Goodrich et al. 2004).

This COMET collaborative project contributes to advancing the NWC's implementation of WRF-Hydro by regionally calibrating the different components and developing a channel loss capability for this modeling system. We have considered the effects of channel loss on the water balance for arid regions. Thus the objectives for this project were originally as follows:

1. Development of a physically based channel loss algorithm to allow for exchanges between streamflow in the channels and water within the land surface.
2. Calibration of WRF-Hydro for selected catchments in the southwest and Midwest region of the CONUS with dense observations, making use of spatial regularization techniques.
3. Analysis of the statistical characteristics of forcing precipitation and their effects on hydrologic model calibration and streamflow.
4. Extension of parameters optimized in selected basins to other catchments throughout each region. This includes selection of catchments that the NWC is using to test HL-RDHM configurations that are based on the Snow-17 and SAC-HTET LSMs.

Project Accomplishments and Findings

Changes to Project Scope

The project scope originally included calibration of WRF-Hydro in the Midwest CONUS, in addition to the southwest. This analysis was removed from the scope of work due to delays in obtaining the model code, and due to the efforts of the research team being directed towards improving the model for the southwest CONUS. The project also originally included calibration of WRF-Hydro using NLDAS-2 precipitation forcing; however, this was deemed to be impractical, as early testing revealed that the NLDAS-2 precipitation dataset was unable to sufficiently resolve winter snowfall events in the high terrain of Arizona. The elimination of this segment of the project also caused us to remove our analysis of extreme precipitation events.

These changes to the project scope refocused our efforts exclusively towards evaluating WRF-Hydro in the southwest, by including the effects of channel infiltration. As a result of this change to the scope, more emphasis was also placed on evaluating the physical states of WRF-Hydro, including soil moisture. The calibration methods developed within this cooperative project have allowed the University of Arizona research team to obtain funding from NOAA Federal Funding Opportunity (FFO) NOAA-OAR-OWAQ-2017-2005122, FY 2017 Joint Technology Transfer Initiative (JTTI), to continue this work on a larger scale in the southwestern US.

The final parameter sets derived from this analysis will be provided to the NWC, to test in basins where HL-RDHM has been executed that are near our calibration domains. The WRF-Hydro simulations produced as part of this project may also be used by the NOAA Office of Water Prediction, where they will be evaluated against HL-RDHM simulations. The calibrated parameter sets will be passed to the WRF-Hydro model development team at NCAR for further evaluation. These updated parameters may be included in future NWM configurations.

WRF-Hydro NWM Configuration

WRF-Hydro (Gochis et al. 2015) is a parallelized distributed hydrologic model that may be run in standalone mode when forced by atmospheric surface data and precipitation, or in coupled mode when connected with the WRF-ARW atmospheric model (Skamarock et al. 2008). Atmospheric forcing data include incoming short wave radiation, incoming longwave radiation, specific humidity, air temperature, surface pressure, and near surface wind (both u and v components). The WRF-Hydro model uses the Noah-MP LSM (Niu et al. 2011) to resolve vertical fluxes within the soil moisture column and for exchanges with the atmosphere. Noah-MP is configured using gridded NWM soil variables with 1-km grid resolution. A priori Noah-MP parameter quantities in WRF-Hydro are computed based on values derived from Rawls et al. (1982) from STATSGO soil types in the model domain. NWM WRF-Hydro resolves horizontal fluxes on a 250m-grid resolution routing grid. Since the routing grid cells are four times smaller than the Noah-MP grid cells, spatially varying quantities on the 250m routing grid are aggregated back to the 1-km grid during model time steps when Noah-MP is called and disaggregated back to the 250m routing grid after the vertical fluxes within Noah-MP are computed.

Subsurface and surface routing are resolved on the 250m routing grid. Subsurface flow on the WRF-Hydro grid computes changes to the surface head in the 2m Noah-MP soil column using Dupuit-Forcheimer assumptions, where the hydraulic gradient is based on differences in the surface head along the steepest gradient in eight possible directions around a routing grid point. If sub-surface flow causes a model grid point to become saturated, exfiltration is computed and this resultant water ponding is then routed as surface runoff. Surface flow is computed using diffusive wave routing based on the steepest gradient around each grid cell (Julien et al. 1995; Ogden et al. 1997). Details of the surface and subsurface routing schemes of WRF-Hydro are discussed in greater detail in Gochis et al. (2015).

When surface flow reaches a grid cell with a channel, it is mapped to the model channel network. The NWM channel network is based on the National Hydrography Dataset (NHD) Plus Version 2 (NHDPlusV2) (McKay et al. 2012). In the present study, we added a channel infiltration parameter that is physically representative of the channel bed conductivity (ms^{-1}) (ChannK). Flow in the channels is computed using an iterative Muskingum-Cunge function for each reach. This routing scheme is more computationally efficient than other WRF-Hydro configurations (e.g. 1D diffusive wave routing) and has the capability to be mapped to specific rivers and reaches that may be of interest to emergency managers and stakeholders during a flood event; however, it is not able to resolve backwater flow (Gochis et al. 2015), which may be important in some flooding situations.

Baseflow in WRF-Hydro is computed using an exponential bucket model. All water that infiltrates out of the Noah-MP LSM is mapped to a groundwater catchment, which corresponds to the NHD plus version 2 channel reaches. Water from this bucket is then returned to the channel reach that directly corresponds to its underlying bucket. This is a poor representation of baseflow in ephemeral channels in semi-arid environments, as the depth to groundwater is often high in the southwest CONUS. In many cases, water from the channels infiltrates to recharge the local aquifer (e.g. Blasch et al. 2004). To prevent unrealistic baseflow from appearing in the channel network, we effectively disable the baseflow bucket model by setting the SLOPE parameter of Noah-MP to zero everywhere, except where the underlying baseflow bucket is associated with a perennial channel. An example of this a priori parameter modification is shown in Figure 1, for Beaver Creek in the Verde basin.

WRF-Hydro Channel Infiltration Function

The WRF-Hydro routing scheme assumes trapezoidal channel geometry, and the length and slope of specific reaches is specified in the NHDplus Version 2 dataset. If a channel volume is computed using the Muskingum-Cunge routing scheme of the WRF-Hydro model, the rate of infiltration rate can be inferred from the wetted perimeter of the channel and the infiltration rate of the soil. A cross-section of a WRF-Hydro channel is shown in Figure 2. If the volume of water in a channel reach is known, the height of the water (h) and the wetted perimeter (p) may be calculated by the following procedure. First, the cross sectional area (a) of the water may be computed by dividing the volume by the length of the reach, *assuming that height is constant along the entire length of the reach*. It follows that cross sectional area is equivalent to:

$$a = h\left(w + w_s\right)$$

We can compute w_s as a function of the riverbank slope (s) and the height of the water (see figure 2). Note that s is equivalent to the parameter ChSlp in WRF-Hydro. This may be written as:

$$a = h\left(w + \frac{h}{s}\right) = wh + \frac{1}{s}h^2; w_s = \frac{h}{s}$$

Since area is known based on the volume of water in the channels, the previous equation can be solved for h using the quadratic function. From h, we can compute the wetted perimeter (p):

$$p = w + \sqrt{h^2 + \left(\frac{h}{s}\right)^2} = w + \sqrt{\frac{h^2}{s^2}\left(s^2 + 1\right)}$$

Due to the effects of channel roughness, wetted perimeter will be reduced, as water will tend to flow through lower areas within the channel, but not in elevated areas. This would reduce the wetted perimeter during periods of low flow. To address the reduction of wetted perimeter due to surface heterogeneity of the channel bed, one solution is to use an empirical equation, as was used for KINEROS2 (Woolhiser et al. 1990), a semi-distributed hydrologic model that accounts for channel infiltration in semi-arid regions like the southwest CONUS. KINEROS2 computes a corrected wetted perimeter (p_e) for a channel using the function below:

$$p_e = \min\left[\frac{h}{b\sqrt{w}}, 1\right]p ,$$

where b is set to a constant value of 0.15. We can cast channel infiltration (I), in m^3s^{-1}, as:

$$I = klp_e$$

$$p_e = \min\left[\frac{h}{b\sqrt{w}}, 1\right]p .$$

Note that l is the length of a channel reach. For WRF-Hydro, we assume b to be constant and prescribe a priori values of k to be equivalent to the saturated soil conductivity of Noah-MP (DKSAT). In calibration, these values of k are adjusted by a scalar multiplier constant, a simple form of spatial regularization.

Model Calibration

To update the routing scheme and parameters, we found that WRF-Hydro had to first be calibrated to eliminate water balance errors, as the initial NWM parameter set caused the model to produce excessive runoff. This calibration used 250 iterations of the Dynamically Dimensioned (DDS) search algorithm (Tolson and Shoemaker 2007). This algorithm is capable of converging to near optimal parameter sets with fewer iterations than the widely used Shuffled Complex Evolution function (e.g. Duan et al. 1992), which can require ~10,000 iterations to converge to an optimal solution. This calibration simulation utilized the updated configuration of NWM WRF-Hydro, with the added channel infiltration function, in the Walnut Gulch Experimental Watershed (WGEW). WGEW is a useful test site for the NWM, as estimates of channel loss from this basin have previously been computed in this basin (e.g. Goodrich et al.

2004), and it has a dense precipitation gauge network that can be used to derive forcing precipitation for WRF-Hydro. This eliminates uncertainty that can be introduced from other precipitation forcing products, such as NCEP Stage-IV that have known deficiencies in the southwest US (e.g. Zamora et al. 2014).

The calibration was based on optimization of the Kling-Gupta Efficiency (KGE), which equally weights the model correlation, water balance, and variance errors (Gupta et al. 2009). For these simulations only, the Noah-MP time step was reduced from 60 (the setting for the NWM) to 15 minutes, as this allowed the model to produce output, including streamflow, at 15-minute temporal resolution. This permitted analysis of streamflow at high temporal resolution, which is needed to adequately evaluate the model routing parameters for a small drainage area. Calibrated model parameters, determined through prior sensitivity testing included ChannK (channel conductivity), DKSAT (saturated soil conductivity), REFKDT (runoff scaling), and SMCMAX (soil porosity). SMCMAX and DKSAT were computed by multiplying the initial NWM parameters by a constant, and REFKDT and ChannK were assumed constant throughout the WGEW model domain. Initial DKSAT values and the terrain within WGEW are shown in Figure 3. Note that DKSAT, according to the NWM a priori parameters, is constant at $3.37*10^{-6}$ everywhere in WGEW, except in the extreme upper basin. This makes the calibration problem in WGEW relatively simple compared to other basins. The model was forced using NLDAS-2 atmospheric data and regridded WGEW gauge-based precipitation.

Following initial calibration of the model, a sensitivity analysis was performed for the channel parameters, with the goal of improving the model correlation coefficient (i.e. the timing of streamflow events). This analysis showed (as might be expected) that Manning's N had the greatest effect on the modeled time of concentration during runoff events. The model, with default channel parameters, tends to systematically produce streamflow too quickly following storm events; however, this systematic error can be partially corrected for by doubling Manning's N. The effects of this adjustment may be due to initial NWM parameters under-estimating roughness parameters in ephemeral streams and the NHD dataset underestimating the length of stream channels, therefore underestimating runoff time of concentration once it reaches a channel (Carl Unkrich, USDA-ARS, personal communication, 2017).

After the adjustment to Manning's N, the model was recalibrated with a Noah-MP time step of 60 minutes, consistent with the NWM configuration. For this stage of the calibration, the channel conductivity was set to an a priori value based on underlying soil data and then calibrated by adjustment of a scalar multiplier. In addition to the aforementioned calibration parameters (described above), soil conductivity was adjusted by an addition constant in conjunction with the scalar multiplier. The adjusted parameters and configuration for the model calibration are shown in Table 1. To demonstrate the potential application of these calibration methods in an operational setting that could be applied to the NWM, the model was also calibrated using NCEP Stage-IV precipitation as forcing, in an otherwise identical configuration to the model calibration described above (Table 1).

The calibration methods described above in WGEW were also applied to the Babocomari River in the San Pedro basin and Sycamore and Beaver Creeks in the Verde River basin (Figure 4). The model was run from WY 2009-2012 for calibration in all basins, except for Beaver Creek, where it was run from WY 2011-2014 to avoid a snowfall event that was not adequately captured by the forcing precipitation. Except in Walnut Gulch, where streamflow is only observed during the monsoon season (i.e. the end of a water year), the first year of the four-year simulations was omitted and considered as spin-up. Initial model states were derived by executing WRF-Hydro with Stage-IV precipitation forcing from WY2007-2015. This methodology to compute initial conditions is consistent with the practices of the NCAR WRF-Hydro development team. This long-term spin-up is needed to allow the model state variables to reach equilibrium. This is particularly true for the baseflow bucket model (Aubrey Dugger, NCAR-RAL, Personal Communication, 2017). The model state at the end of WY 2015 was used as initial conditions for calibration.

Due to the effects of snowmelt and baseflow exfiltration into perennial channels, additional parameters were considered in these basins (Table 1). These parameters included BEXP (Clapp-Hornberger Coefficient), SLOPE (Noah-MP Bottom Drainage Scaling), and Expon (Exponential constant for baseflow model). SLOPE and Expon were only calibrated in perennial channels and their associated catchments, and otherwise set to zero. BEXP and SLOPE were multiplied by constants, while Expon was calibrated directly and assumed to be constant everywhere where groundwater was accounted for. 500 (instead of 250) iterations of the DDS search algorithm were used for Beaver Creek and Sycamore Creek, to account for the increased number of uncertain parameters.

Calibration Results with Walnut Gulch Gauge Precipitation

Results from this analysis will be included in a manuscript that will be submitted to *Journal of Hydrometeorology* later this year. All calibrated simulations are compared to an NWM configuration with original NWM parameters and the added channel infiltration function. This control version of WRF-Hydro also disables the baseflow bucket model everywhere in the model domain, except for NHD catchments associated with ephemeral channels. Optimized model parameters following DDS calibration are shown in Table 2. These parameter values are for all calibration results for the project. Note that KGE was rescaled so that it is optimized at zero. Higher values of our computed KGE have lower skill. When computing KGE, data points associated with observed daily mean streamflow of zero were not considered. Table 3 shows the model skill, including KGE normalized to zero, correlation coefficient, percent bias, and percent bias for the coefficient of variation. These results show improved model skill scores following calibration and KGE values of near zero (meaning increased skill) for Walnut Gulch with gauge precipitation forcing.

In Walnut Gulch, where precipitation errors were minimized by use of gauge-based forcing, calibration was able to eliminate water balance errors (Figure 5). Flashy peaks of runoff produced by the control simulation that are not consistent with observations were eliminated, reducing the error of the coefficient of variation and improving the model correlation coefficient, also shown in Figure 5. For this simulation only, we considered hourly streamflow data, and the bottom left panel of Figure 5 shows a 48-hour sample where WRF-Hydro was able to capture hourly peak streamflow. The calibrated NWM had a KGE of 0.28 (0.71), a correlation coefficient of 0.81 (0.81) compared to hourly observations for the calibration (evaluation) periods. Results from Table 3 also demonstrate the added value of channel infiltration, as WRF-Hydro was calibrated with the same forcing data but with channel infiltration set to zero everywhere. Calibrating WRF-Hydro without channel infiltration caused KGE to converge to 0.19, as REFKDT increased, to increase soil infiltration before the water reached the channels (Table 2). This simulation produced lower correlation coefficients (Table 3).

WGEW 5-cm soil moisture observations were compared to the area average of Noah-MP 0-10 cm soil moisture. Calibration of the NWM in Walnut Gulch increased the positive bias of near-surface soil moisture, averaged throughout the basin; however, it also increased the correlation coefficients of the same quantity (Table 4). This suggests that the calibration may have improved the timing of the modeled surface fluxes and ultimately the water balance; however, further analysis of ET fluxes in WGEW is needed to confirm this. A sample of the modeled soil moisture data with and without calibration is shown in Figure 6. These results also show that including channel infiltration removed some of the positive soil moisture bias following calibration. All of the Walnut Gulch soil moisture observations and the basin average are plotted alongside the modeled basin averages in Figure 6.

Calibration Results with Stage-IV Precipitation

WRF-Hydro was also calibrated with Stage-IV forcing precipitation in other basins in Arizona (Figure 4), including Walnut Gulch. In Walnut Gulch, calibration was able to reduce water balance errors; however, the correlation coefficients showed little improvement outside of the calibration period (Figure 7).

In the Babocomari basin, which has more heterogeneous terrain than Walnut Gulch, calibration yielded less improvement. While calibration did improve the water balance, correlation coefficients remained low outside of the calibration period (Figure 8). As the Babocomari River and Walnut Gulch are across from each other on the San Pedro River, these results suggest that both basins may be subject to similar precipitation timing errors. Figure 8 shows that while calibration improved cumulative streamflow, and ultimately reduced model bias, the timing of individual events continued to be prone to errors. This suggests that uncertainties from the WSR-88D radar, which is subject to beam blockage in this area (e.g. Zamora et al. 2014), may be partly responsible for these observed errors. Note that WSR-88D radar and available gauge observations used to derive NCEP Stage-IV precipitation (Lin and Mitchell 2005). For this basin, where soil depth tends to be variable (Robert Zamora, NOAA HMT, Personal Communication 2017), the simplified Noah-MP configuration and spatial regularization scheme may not be sufficient for calibration. These issues will eventually be addressed in later NWM versions, as efforts are ongoing to develop a version of WRF-Hydro that permits the depth of the soil columns of Noah-MP to vary (David Gochis, NCAR-RAL, Personal Communication, 2017).

Beaver Creek, is the only catchment analyzed that depends on snowmelt. Figure 9 shows that for the calibration period, WRF-Hydro is able to capture realistic snowmelt. Stage-IV precipitation observations missed a snow event in Spring 2011, which prevented the calibrated model from producing runoff, and forcing the change of the calibration period. Calibration was able to somewhat reduce the negative bias of the model; however, WRF-Hydro still had a difficult time capturing baseflow (see sample hydrographs in Figure 9). These results suggest that a more realistic groundwater scheme for WRF-Hydro is needed. They also underscore the effects of precipitation uncertainty on the model output.

Calibration yielded little improvement in the Sycamore Creek catchment (Figure 10). Calibration produced a low channel infiltration parameter, which didn’t adequately eliminate the spurious flashy peaks discussed previously, although they were somewhat reduced. The NHD dataset showed that the riparian area associated with perennial streamflow was further upstream, meaning water could still infiltrate from the downstream channel, and this may not have been a realistic representation of the catchment hydrogeology. Keeping channel infiltration low, likely helped the model preserve the peak streamflow during observed events. The cumulative streamflow plot in Figure 10 shows that the NWM drastically over-estimated a major runoff event early in evaluation period, which leads to high bias and reduced model skill. While the calibrated solution for this basin is more realistic, it tended to over-estimate some events during the evaluation period more than the control simulation. This may have been one reason why the calibrated NWM had lower skill than the control simulation, based on KGE. More analysis is needed to determine the causes of these errors and the role of precipitation forcing errors in causing them.

Application to Larger Domains

The control parameter sets and calibrated parameters were applied in the NWM to the entire San Pedro and Verde River basins. In the San Pedro domain, streamflow in the adjacent Rillito River basin was also considered. This analysis also applied the aforementioned doubling of Manning's N everywhere in the channel network domains, for the calibration simulations only. The percent bias and correlation coefficients from these simulations, spanning the period from WY2009-2016 are plotted for all available USGS gauges in Figures 11-14. The simulations were initialized at the beginning of WY2008, with initial conditions from NWM wrfinput files, thus allowing for one-year of spin-up. These preliminary results demonstrate the potential to apply the calibrated model parameters to larger domains. This analysis demonstrates a proof of concept for simple spatial regularization of NWM parameters.

In the San Pedro and the adjacent Rillito basin, the control NWM without channel loss tended to have a systematic high bias, especially for downstream reaches (Figure 11). This was observed in Walnut Gulch and the Babocomari River when calibration was performed. Note that the Rillito flows northwest, and the San Pedro flows north. Calibrating the model with Stage-IV forcing and channel loss reduced bias everywhere, regardless of which calibration basin (Babocomari or Walnut Gulch) was used. When the model was calibrated with gauge data, a negative bias formed, likely due to differences between the gauge-based and Stage-IV precipitation products. When channel loss was not activated, calibration still produced high bias in some reaches, particularly downstream in the San Pedro and Rillito basins. Calibrating the model did little to improve correlation coefficients (Figure 12), which are more subject to precipitation forcing errors. This suggests that future calibration efforts may be more effective if they are designed to match the streamflow climatology (i.e. the flow duration curve) rather than observed streamflow.

In the Verde basin, including channel infiltration reduced positive bias along some reaches (Figure 13). There was even a negative bias in some upstream reaches, possibly due to snowmelt errors (discussed above). Application of calibrated parameters from Beaver Creek led to modest improvements to model bias. The parameters from Sycamore Creek caused the model to yield a consistent negative bias throughout the Verde River basin. This may reflect the possible precipitation forcing errors in the Sycamore Creek basin, discussed above. More analysis is needed to understand these patterns. As in the San Pedro Basin, calibration yielded little improvement to model correlation coefficients (Figure 14). The parameter set from Beaver Creek produced better correlation coefficients.

The results described above show modest improvements in NWM model performance from the addition of channel infiltration and calibration of parameters, particularly for reducing model bias caused by water balance errors. More analysis is needed to evaluate the application of the calibrated parameters derived as part of this project for larger domains and to identify cases where the derived parameters are not physically consistent with the hydrologic response of a catchment or larger basin.

Summary of Calibration Results

The results from this project demonstrate 1) the added value of the channel infiltration function for improving calibrated WRF-Hydro skill scores (including KGE, correlation coefficient, and percent bias) under idealized conditions in Walnut Gulch (Table 3) and 2) the added value of calibration, particularly for water balance. The Hydrographs in Figures 7-10 also demonstrate that calibration of the NWM with channel infiltration is able to produce more physically consistent hydrologic responses than the same model with original NWM parameters. Despite these successes, the calibration results were affected by precipitation uncertainties, particularly in areas like the Babocomari River basin, where the NCEP Stage-IV precipitation coverage is limited (e.g. Zamora et al. 2014). Calibration of WRF-Hydro in the Verde River basin was also affected by baseflow, which is not well resolved in the WRF-Hydro structure, and snowmelt. As both the NLDAS-2 and Stage-IV precipitation datasets have a difficult time resolving snowfall, this uncertainty will be a challenge for future calibration efforts, throughout the southwest region, for the NWM.

Preliminary results from the calibrated NWM with channel infiltration in the larger San Pedro and Verde Basins show that the changes to the NWM implemented as part of this project yield modest improvements in other basins in the southwest. These results suggest that the changes to the model structure and parameters from this project may be useful for improving NWM performance in other semi-arid regions of the US; however, more analysis is needed to confirm this.

Benefits and Lessons Learned: Operational Partner Perspective

The Benefits of this project for the NWC are as follows:

- At a high level, this project successfully illustrates the type of community collaboration that the NWC envisions, towards achieving improved water resources forecasting for the Nation. The PIs were able to access, study, and then modify the NWM (WRF-Hydro) and then perform rigorous evaluations. Modifying the National Weather Service’s river forecast models has always been a formidable task for collaborators.
- At a technical level, the PIs succeeded in developing an initial version of a component needed for the semi-arid southwest. While further work is likely needed, the PIs nonetheless demonstrated the utility of their channel loss function in improving streamflow simulations.
- The project also examined a calibration strategy for the NWM in the difficult hydrology of the semi-arid southwest, and achieved some success. Their work highlighted the difficulties of calibrating components of a complex distributed model (e.g., channel routing and runoff volume), especially in cases with less-than-optimal precipitation data. The PIs partially overcame this problem in one basin by developing and using a precipitation data set from a local gage network.
- Their model development and calibration effort highlighted the benefits of leveraging local knowledge about the test basins. Moreover, their calibrated model parameters could be passed to the NWC for possible inclusion into the official parameter set for the National Water Model.

Benefits and Lessons Learned: University Partner Perspective

The University collaborators were able to develop a WRF-Hydro modeling framework that can account for channel infiltration, making WRF-Hydro a viable modeling tool for the southwest US and other semi-arid environments. **Thus this work has helped the University of**

Arizona department of Hydrology and Atmospheric Science to develop a new research tool. The University of Arizona will now be able to use the modified version of WRF-Hydro to understand hydrologic processes and surface atmosphere interactions in semi-arid environments.

Furthermore, this seed project through the UCAR-COMET program helped the University collaborators to obtain funding through the NOAA JTTI program to continue developing WRF-Hydro in an operational environment. This JTTI project will enable the University to develop the channel infiltration function and calibration methods across the entire southwest CONUS. It will also allow the University of Arizona to fund more graduate students to continue this line of research into the future. Through the project, the University of Arizona will collaborate with the NOAA Hydrometeorology Testbed (HMT) and NWC further develop the aforementioned modeling approach.

Publications and Presentations

Lahmers T., H. V. Gupta, P. Hazenberg, C. L. Castro, D. J. Gochis, D. Goodrich, D. Yates, and A. L. Dugger, 2017: Enhancements to the WRF-Hydro Hydrologic Model Structure for Semi-arid Environments, In Preparation to Submit to *Journal of Hydrometeorology*.

Lahmers T., C. L. Castro, H. V. Gupta, D. J. Gochis, A. L. Dugger, and M. Smith, 2016: Enhancing the NOAA National Water Center WRF-Hydro model architecture to improve representation of the Midwest and Southwest CONUS climate regions, *2016 American Geophysical Union Fall Meeting*, San Francisco, CA, American Geophysical Union H43H-1556.

Lahmers T., C. L. Castro, H. V. Gupta, D. J. Gochis, A. L. Dugger, and M. Smith, 2017: Enhancing the NOAA National Water Center WRF-Hydro model architecture to improve representation of the Midwest and Southwest CONUS climate regions, *31st Conference on Hydrology*, Seattle, WA, American Meteorological Society.

Summary of University/Operational Partner Interactions and Roles

The University of Arizona collaborators executed all model calibration simulations, and are now in the process of evaluating updated model parameters and passing them to the NOAA NWC and NCAR-RAL research teams.

The NWC and NCAR-RAL research teams supplied the University of Arizona Collaborators with the NWM code, model domains, calibration scripts, plotting scripts, and initial parameters. NCAR-RAL also assisted in hard coding the channel infiltration function into the model; however, the infiltration function was originally developed as a Fortran subroutine at the University of Arizona. The NWC was responsible for assisting the University in obtaining archived NWM forcing and helping the University collaborators to fill in gaps in the dataset. While this forcing product has not yet been tested with the updated model parameters, the University of Arizona will evaluate the NWM in the Verde and San Pedro basins with this operational data later this fall, after the end of WY2017. This will permit the calibrated model to be tested with a full water year, including a full North American Monsoon season.

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Table 1: NWM WRF-Hydro parameter calibration configurations. 250 iterations were used for each calibration, except Sycamore and Beaver Creek, where 500 iterations were used.

Basin/Gauge	**Forcing Precip.**	**BEXP (m)**	**SMCMAX (m)**	**DKSAT (a)**	**DKSAT (m)**	**REFKDT (const.)**	**SLOPE (m)**	**Expon (const.)**	**ChannK (m)**
Walnut Gulch	WGEW-gauge	N	Y	Y	Y	Y	N	N	Y
Walnut Gulch	WGEW-gauge	N	Y	Y	Y	Y	N	N	N (0)
Walnut Gulch	Stage-IV	N	Y	Y	Y	Y	N	N	Y
Babocomari River	Stage-IV	N	Y	Y	Y	Y	N	N	Y
Beaver Creek	Stage-IV	Y	Y	Y	Y	Y	Y	Y	Y
Sycamore Creek	Stage-IV	N	Y	Y	Y	Y	Y	Y	Y

Table 2: Final parameters for each WRF-Hydro NWM calibration. All parameters marked with an (m) were adjusted spatially by a scalar multiplier, and all parameters marked with an (a) were adjusted spatially by a scalar addition constant.

Basin/Gauge	Forcing Precip.	BEXP (m)	SMCMAX (m)	DKSAT (a)	DKSAT (m)	REFKDT (const.)	SLOPE (m)	Expon (const.)	ChannK (m)
Walnut Gulch	WGEW-gauge	-	1.1869	9.40E-07	1.1906	2.2702	-	-	1.6025
Walnut Gulch	WGEW-gauge	-	1.1779	3.20E-07	1.3518	3.2000	-	-	-
Walnut Gulch	Stage-IV	-	0.8924	-2.01E-07	1.5266	3.2730	-	-	0.5731
Babocomari River	Stage-IV	-	1.1757	2.29E-07	0.8400	1.1826	-	-	5.6091
Beaver Creek	Stage-IV	0.4454	0.8228	-8.80E-07	5.8449	0.8788	4.9565	6.4340	7.8116
Sycamore Creek	Stage-IV	-	1.1967	-1.27E-07	7.7988	0.1495	3.4664	5.8314	1.2030

Table 3: NWM WRF-Hydro model performance after calibration, including from left to right: KGE, Correlation Coefficient, Percent Bias, and Coefficient of Variation Percent Bias. Skill scores highlighted in red indicate where calibration reduced the model skill.

Basin/Gauge	Forcing Precip	Calibration Years	KGE	COR	% Bias	CV % Bias
Calibration Period						
Walnut Gulch	WGEW-gauge	2010-2013	0.0994	0.9499	-6.5640	12.9440
Walnut Gulch NL	WGEW-gauge	2010-2013	0.2031	0.9491	-10.3071	-7.1761
Walnut Gulch*	Stage-IV	2010-2013	0.2358	0.9390	-22.5159	33.4817
Babocomari River	Stage-IV	2011-2013	0.3625	0.7118	-21.8216	31.3847
Beaver Creek	Stage-IV	2012-2014	0.2324	0.8061	-4.8065	17.5298
Sycamore Creek	Stage-IV	2011-2013	0.2855	0.7154	-2.2370	2.5801
Evaluation Period						
Walnut Gulch	WGEW-gauge	2010-2013	0.3048	0.8756	-13.9841	-11.7189
Walnut Gulch NL	WGEW-gauge	2010-2013	0.3738	0.8402	-8.4848	-26.4731
Walnut Gulch*	Stage-IV	2010-2013	0.8783	0.2459	-41.1734	39.0503
Babocomari River	Stage-IV	2011-2013	2.9947	0.2082	43.4016	168.8484
Beaver Creek	Stage-IV	2012-2014	0.8951	0.6391	-56.6158	-5.9366
Sycamore Creek	Stage-IV	2011-2013	1.6369	0.6767	48.6337	70.1466

Table 4: NWM WRF-Hydro Noah-MP level 1 (0-10 cm) soil moisture skill scores, compared to areal averages of 5-cm Walnut Gulch soil moisture measurements.

Evaluation Metric	Control (w/loss)	Calibration (no loss)	Calibration (w/loss)
Percent Bias	94.1493	108.4803	108.4104
Correlation Coef.	0.8530	0.8900	0.8920

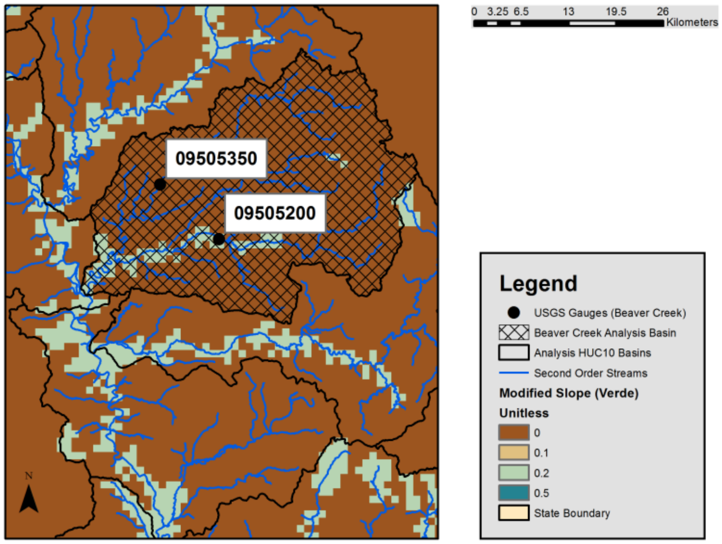


Figure 1: The modified a priori Noah-MP SLOPE parameter surface is shown in Beaver Creek.

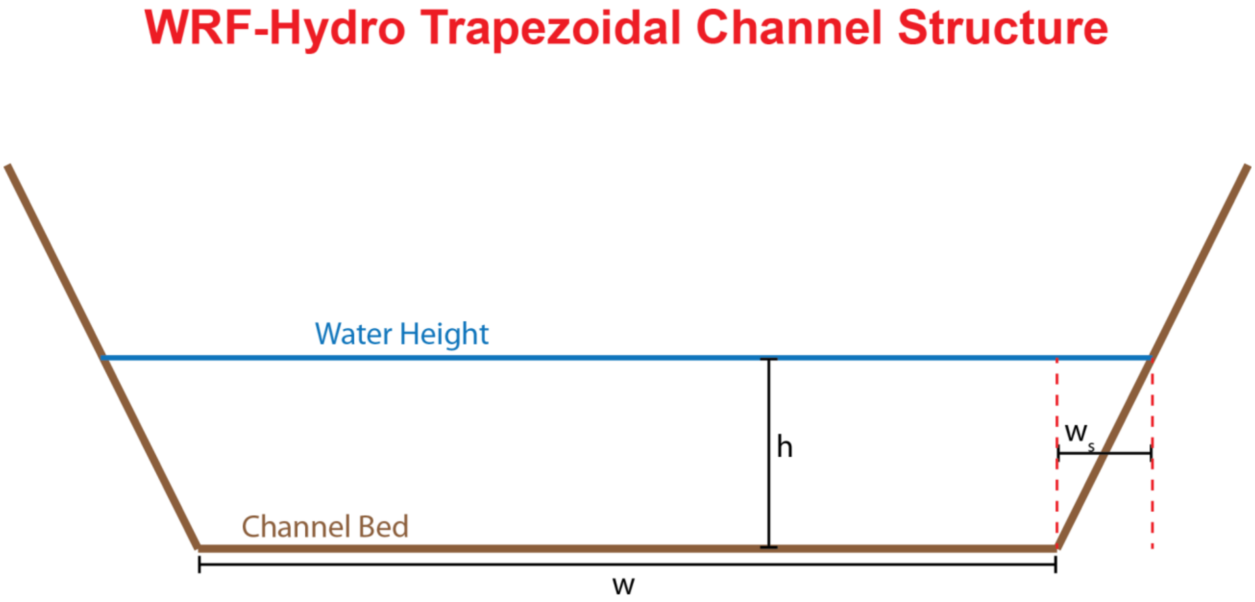


Figure 2: Vertical cross section of a trapezoidal channel used by the WRF-Hydro Muskingum-Cunge routing scheme. The sides of the channel are assumed infinite. The channel width (w) and the slope of the sides (s) are specified model parameters (usually a function of stream order).

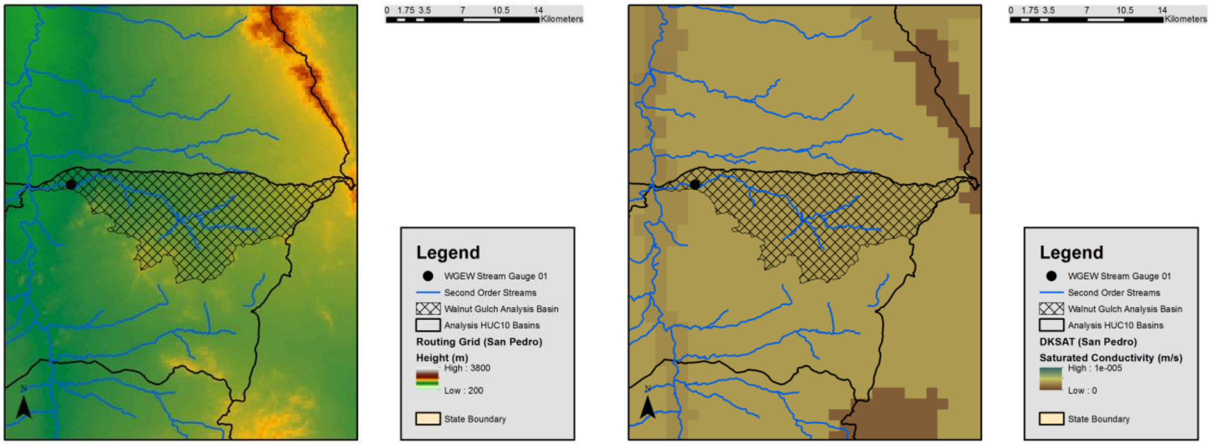


Figure 3: Walnut Gulch (shown in hatched area) terrain (left) and saturated soil conductivity (DKSAT) (right) are plotted.

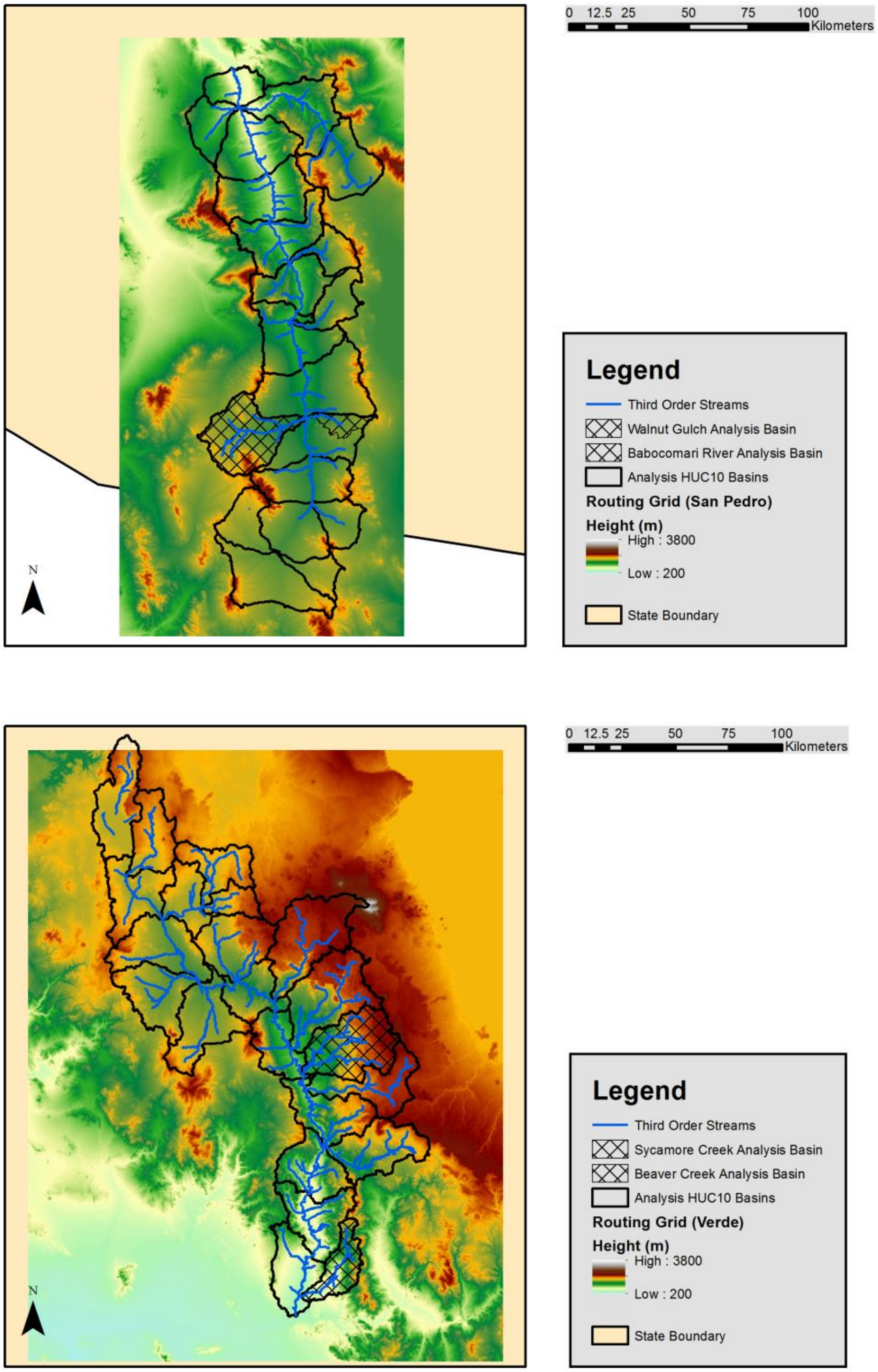


Figure 4: WRF-Hydro 250-meter routing grids and basin study areas are shown. These include the San Pedro River (top) and the Verde River (bottom) basins. Calibration basins, including Beaver Creek, Sycamore Creek, Walnut Gulch, and the Babocomari River are in the hatched area.

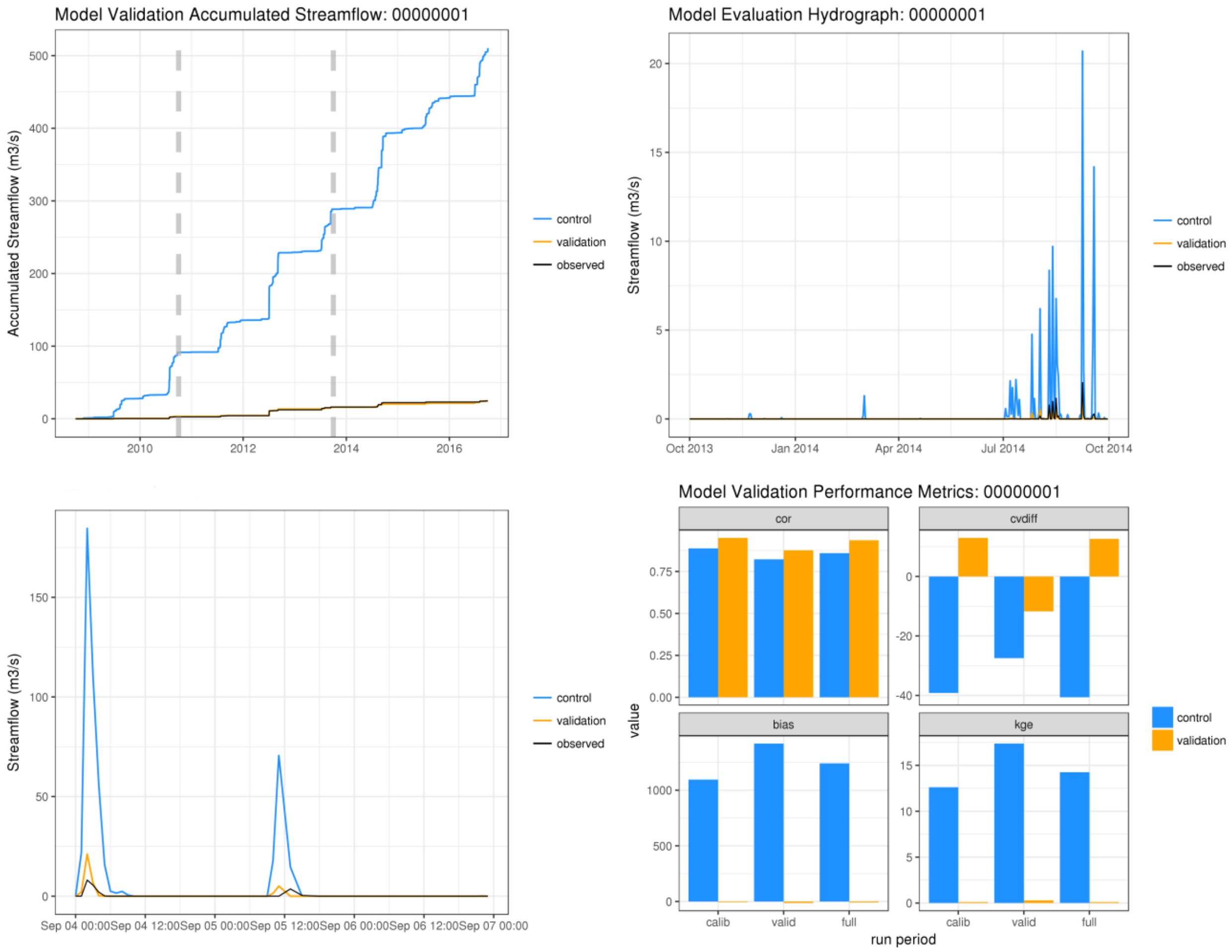


Figure 5: Samples of calibrated and control NWM streamflow at Walnut Gulch are shown. The model is forced with regridded gauge precipitation. Accumulated streamflow is shown in the top left, and the annual hydrograph from WY2014 is shown in the top right. A 48-hour streamflow sample is shown in the bottom left, and control and calibrated skill scores are shown in the bottom right, in blue and orange respectively.

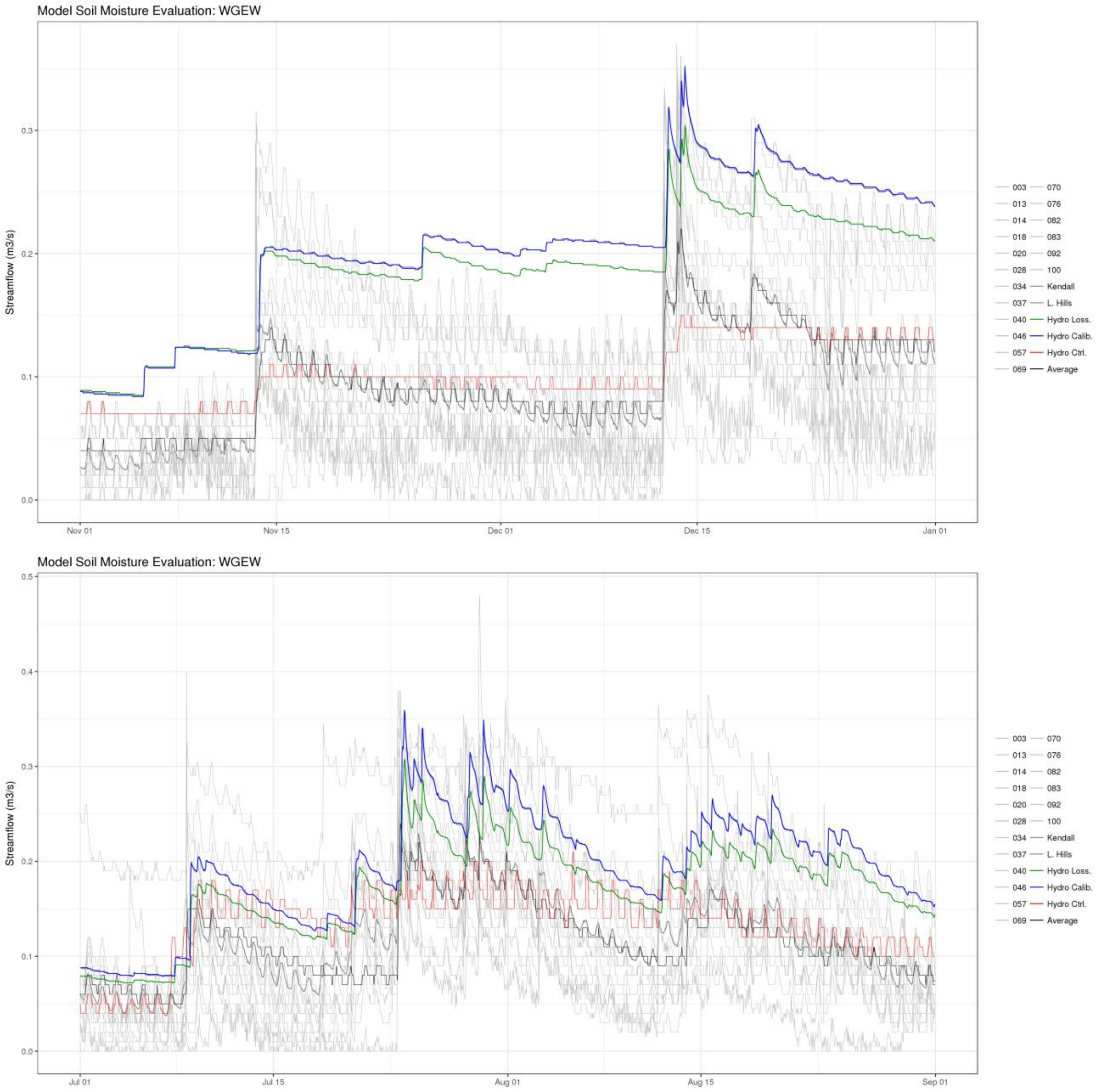
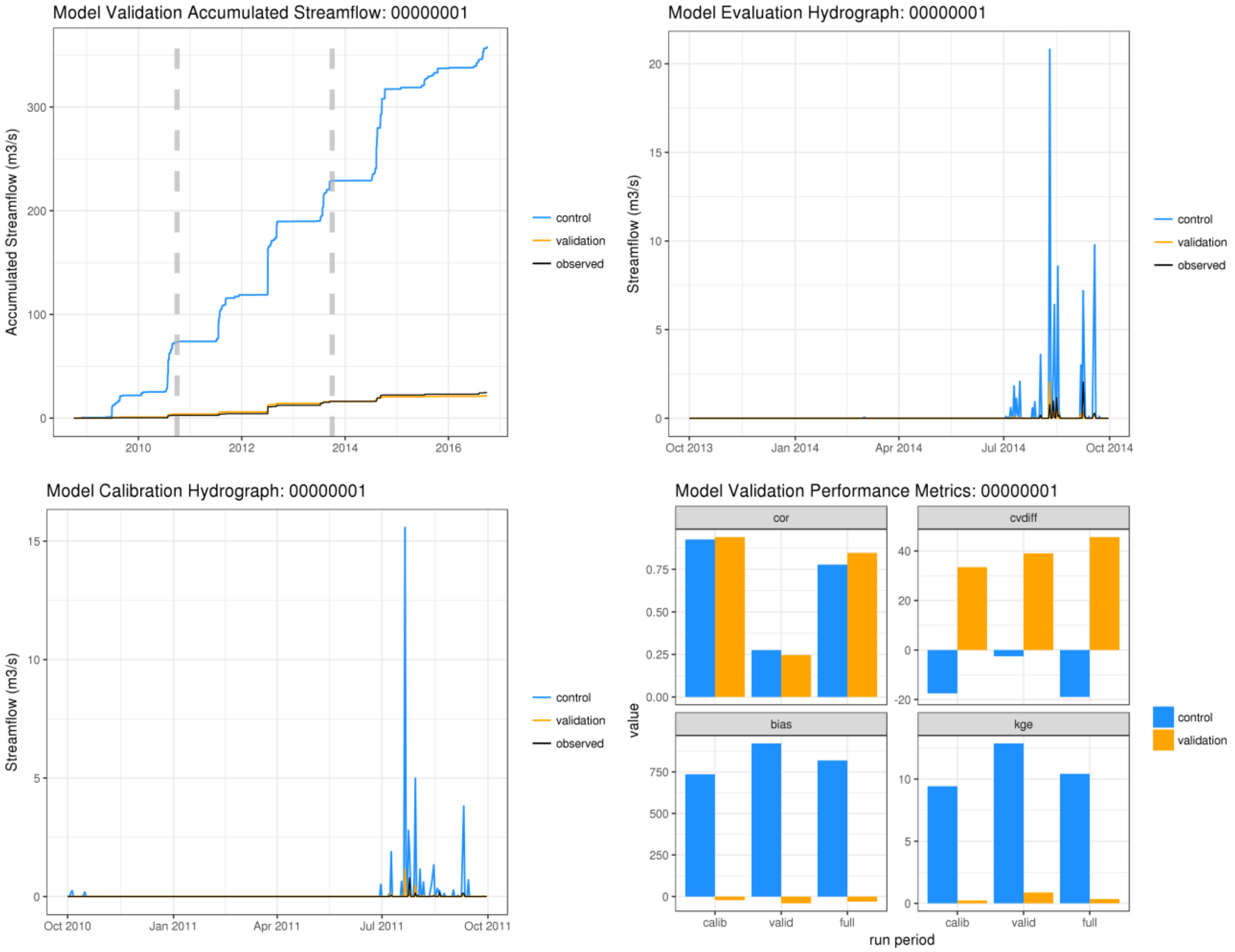


Figure 6: Area averaged near surface soil moisture in Walnut Gulch is plotted for July and August 2011 (top) and November and December 2011 (bottom). Area averaged observations are plotted with a dark black line. The control model simulation is plotted in red, and the calibrated simulations with channel loss (without channel loss) are plotted in green (blue). All individual station observations are plotted in lighter gray.



Model Validation Accumulated Streamflow: 00000001

Model Evaluation Hydrograph: 00000001

Model Calibration Hydrograph: 00000001

Model Validation Performance Metrics: 00000001

Figure 7: Samples of calibrated and control NWM streamflow at Walnut Gulch (WGEW Gauge 01, the basin outlet) are shown. The model is forced with Stage-IV precipitation. Accumulated streamflow is shown in the top left, and the annual hydrograph from WY2014 is shown in the top right. Annual streamflow from WY2011 is shown in the bottom left, and control and calibrated skill scores are shown in the bottom right, in blue and orange respectively.

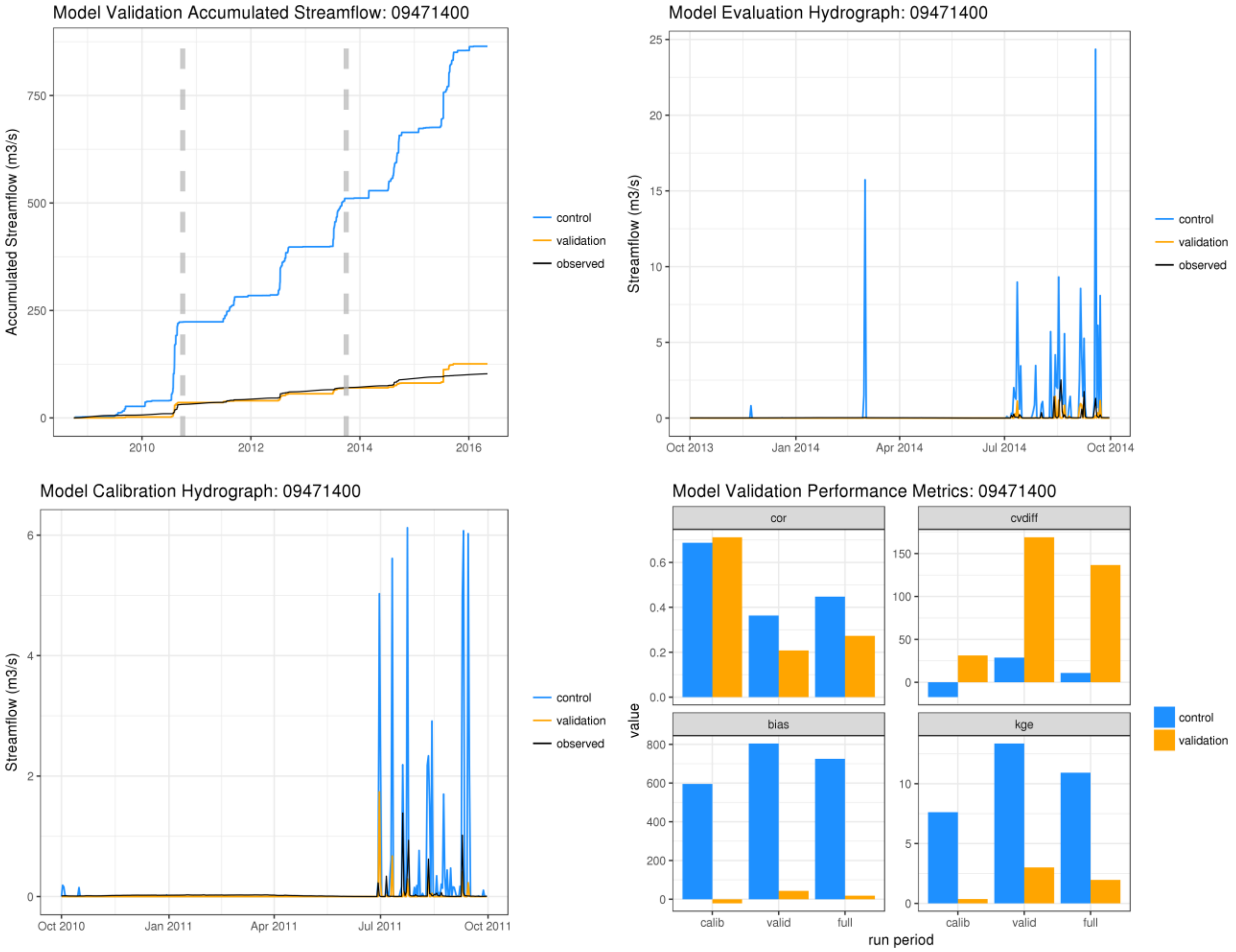


Figure 8: Samples of calibrated and control NWM streamflow at the Babocomari River (USGS Gauge 09471400) are shown. The model is forced with Stage-IV precipitation. Accumulated streamflow is shown in the top left, and the annual hydrograph from WY2014 is shown in the top right. Annual streamflow from WY2011 is shown in the bottom left, and control and calibrated skill scores are shown in the bottom right, in blue and orange respectively.

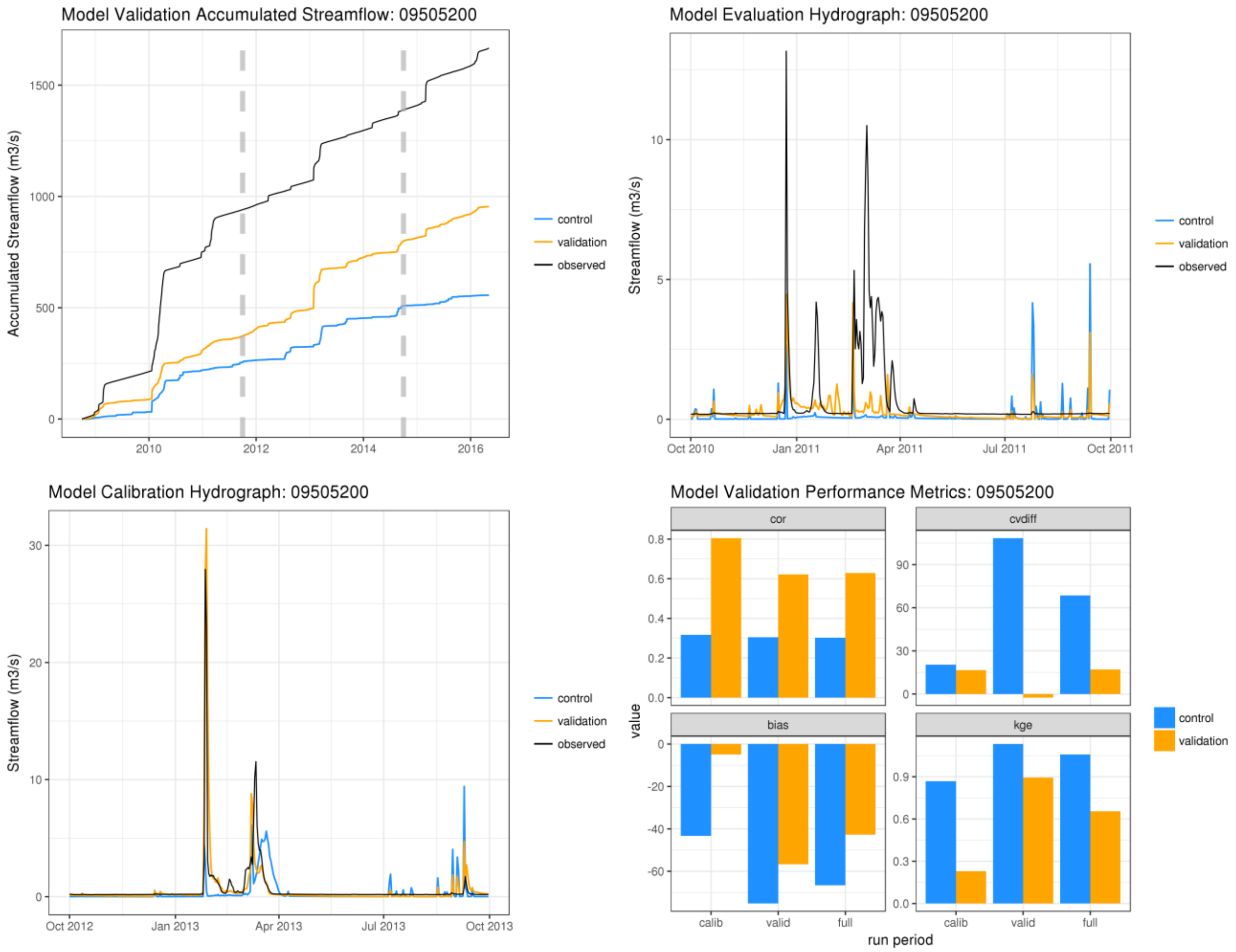


Figure 9: Samples of calibrated and control NWM streamflow at Beaver Creek (USGS Gauge 09505200) are shown. The model is forced with Stage-IV precipitation. Accumulated streamflow is shown in the top left, and the annual hydrograph from WY2011 is shown in the top right. Annual streamflow from WY2013 is shown in the bottom left, and control and calibrated skill scores are shown in the bottom right, in blue and orange respectively.

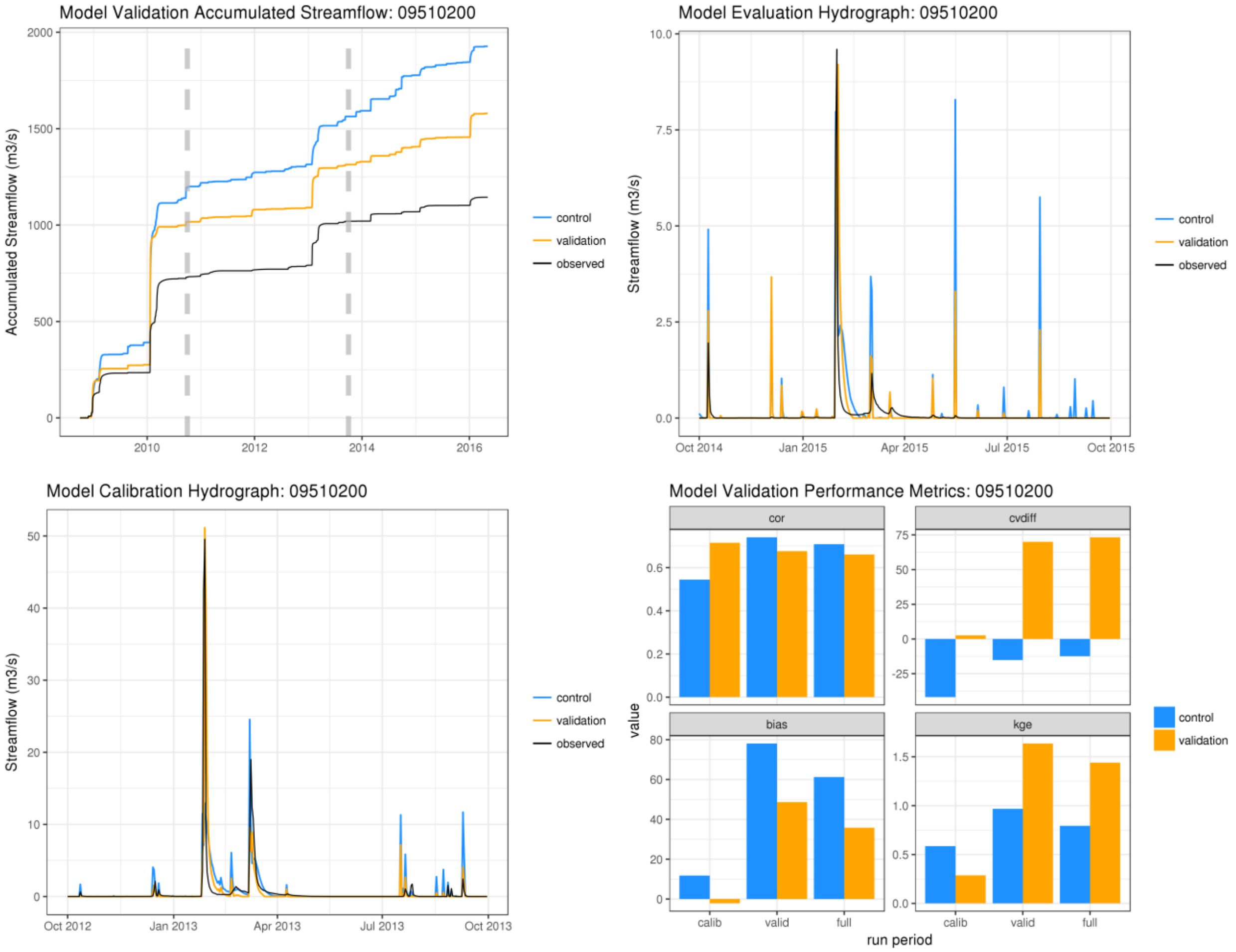


Figure 10: Samples of calibrated and control NWM streamflow at Sycamore Creek (USGS Gauge 09510200) are shown. The model is forced with Stage-IV precipitation. Accumulated streamflow is shown in the top left, and the annual hydrograph from WY2015 is shown in the top right. Annual streamflow from WY2013 is shown in the bottom left, and control and calibrated skill scores are shown in the bottom right, in blue and orange respectively.

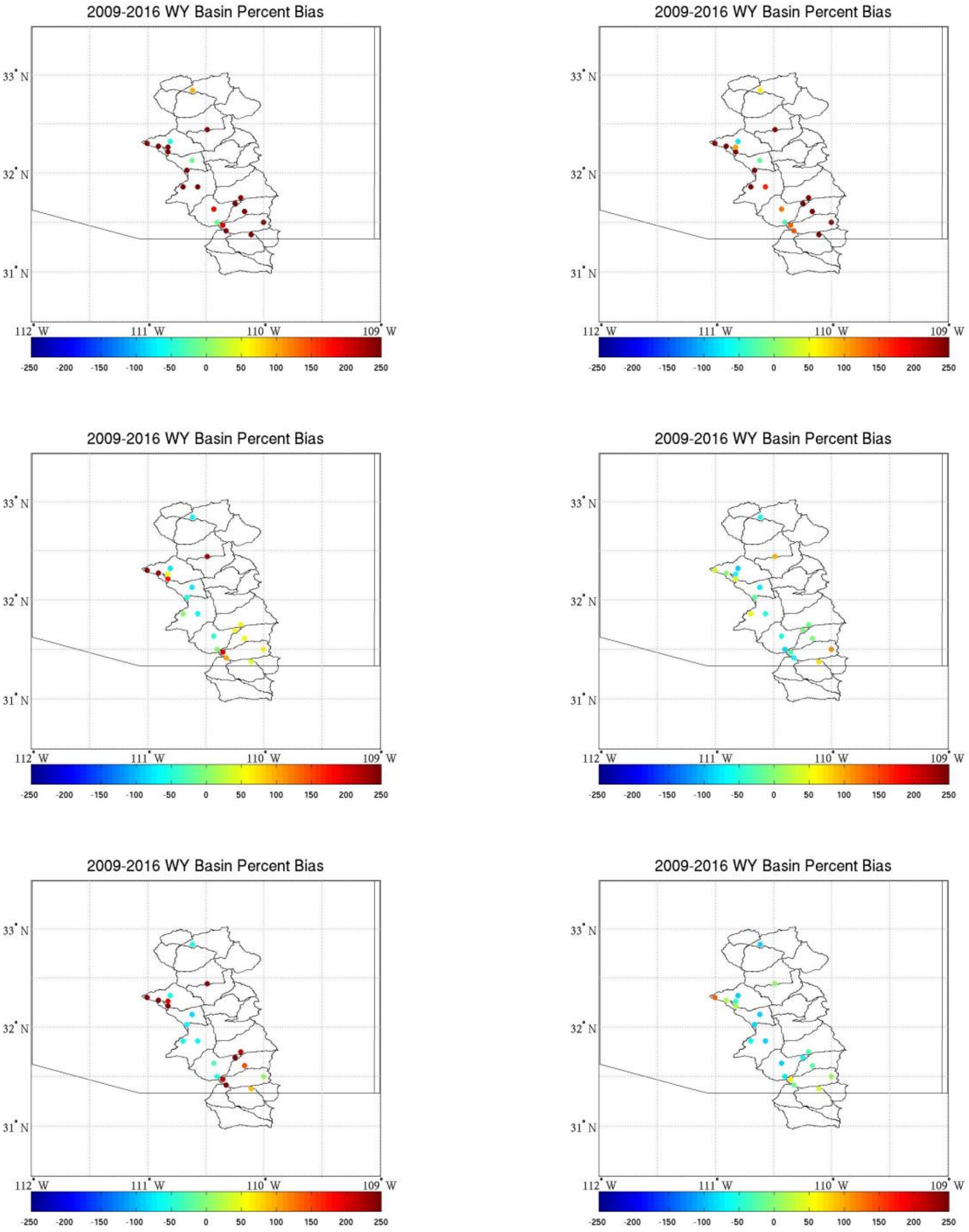


Figure 11: WRF-Hydro percent bias in the San Pedro and Rillito basins at all available USGS gauges. The control model without channel loss is shown in the top left panel, and the control model with channel loss is shown in the top right panel. The Walnut Gulch and Babocomari calibrated models with stage-IV forcing are shown in the middle left and middle right, respectively. The Walnut Gulch models forced with precipitation gauge data without loss and with loss are plotted in the bottom left and bottom right, respectively.

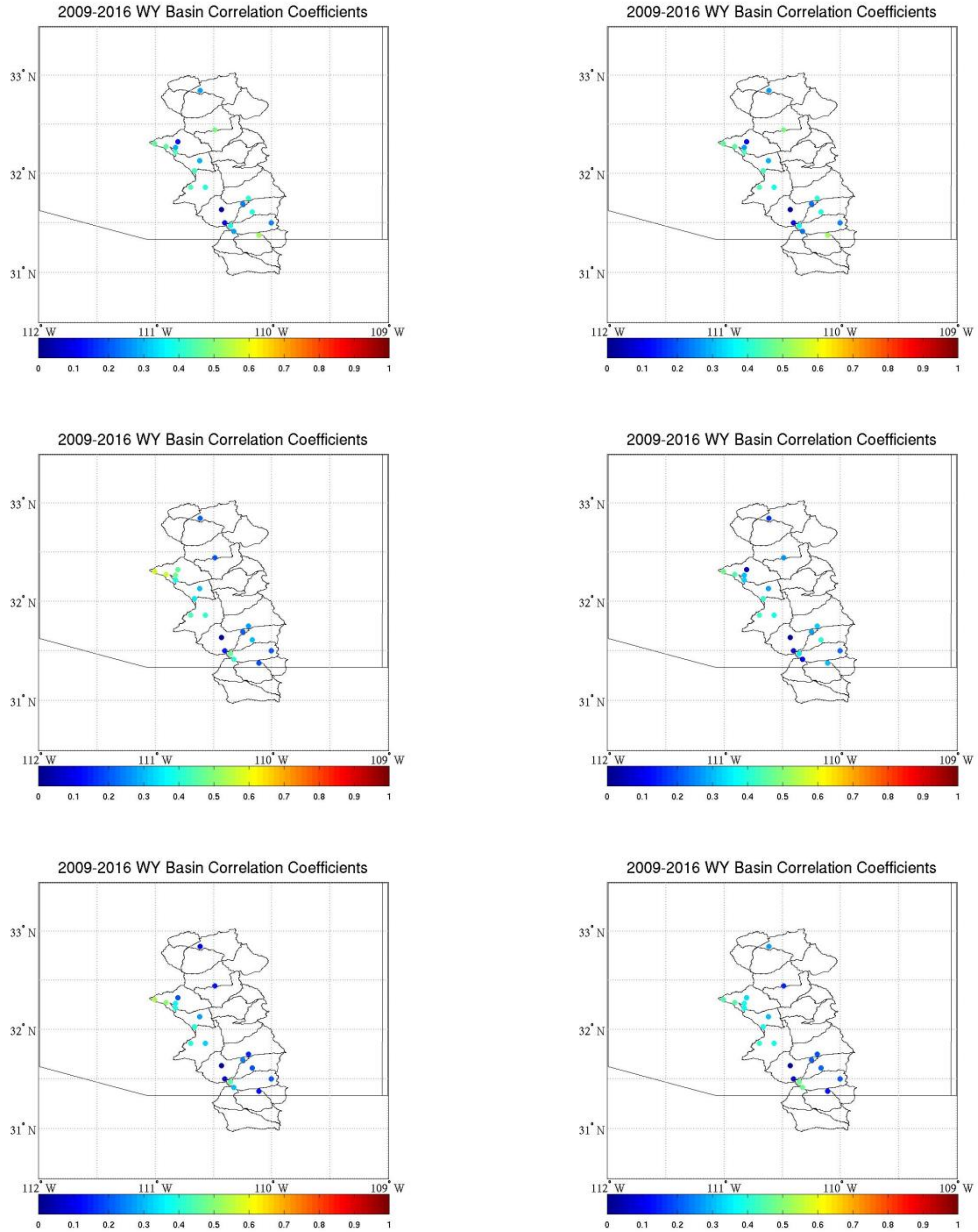
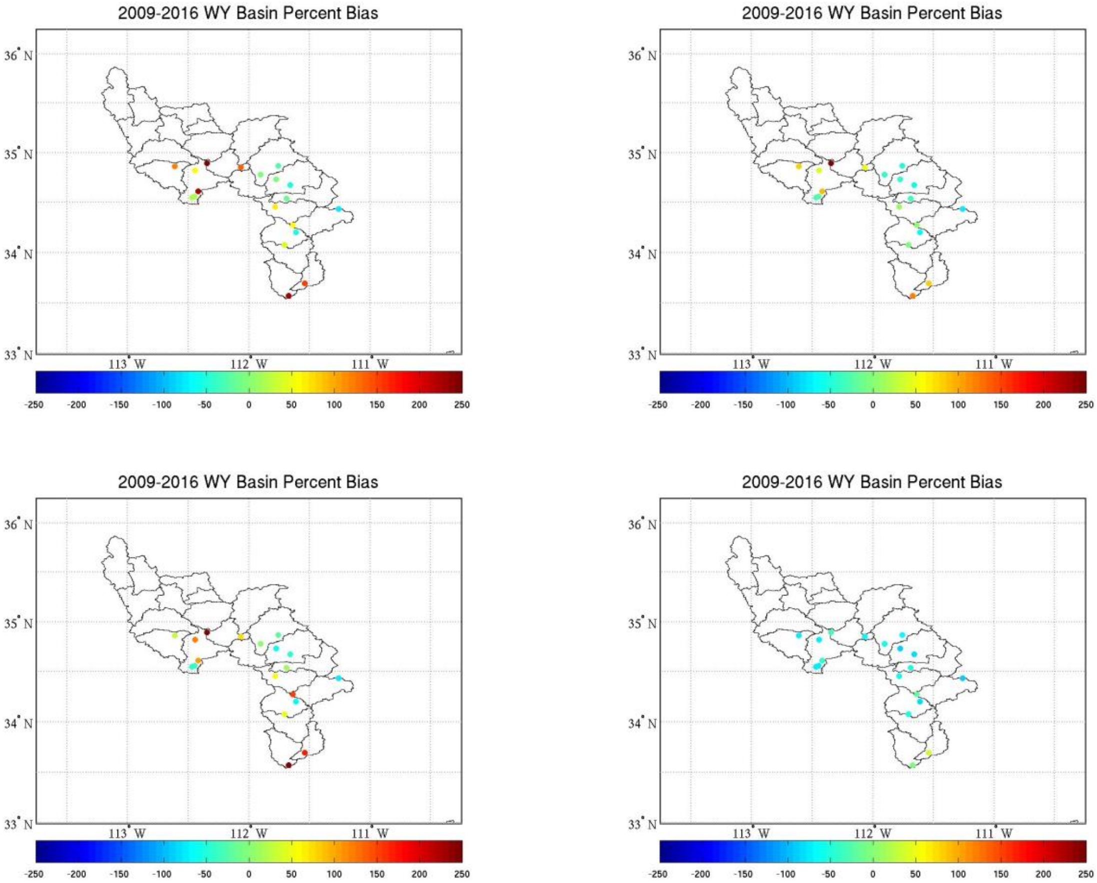


Figure 12: As in Figure 11, but for correlation coefficient.



2009-2016 WY Basin Percent Bias

2009-2016 WY Basin Percent Bias

2009-2016 WY Basin Percent Bias

2009-2016 WY Basin Percent Bias

Figure 13: WRF-Hydro percent bias in the Verde at all available USGS gauges. The control model without channel loss is shown in the top left panel, and the control model with channel loss is shown in the top right panel. The Beaver Creek and Sycamore Creek calibrated models with stage-IV forcing are shown in the bottom left and bottom right, respectively.

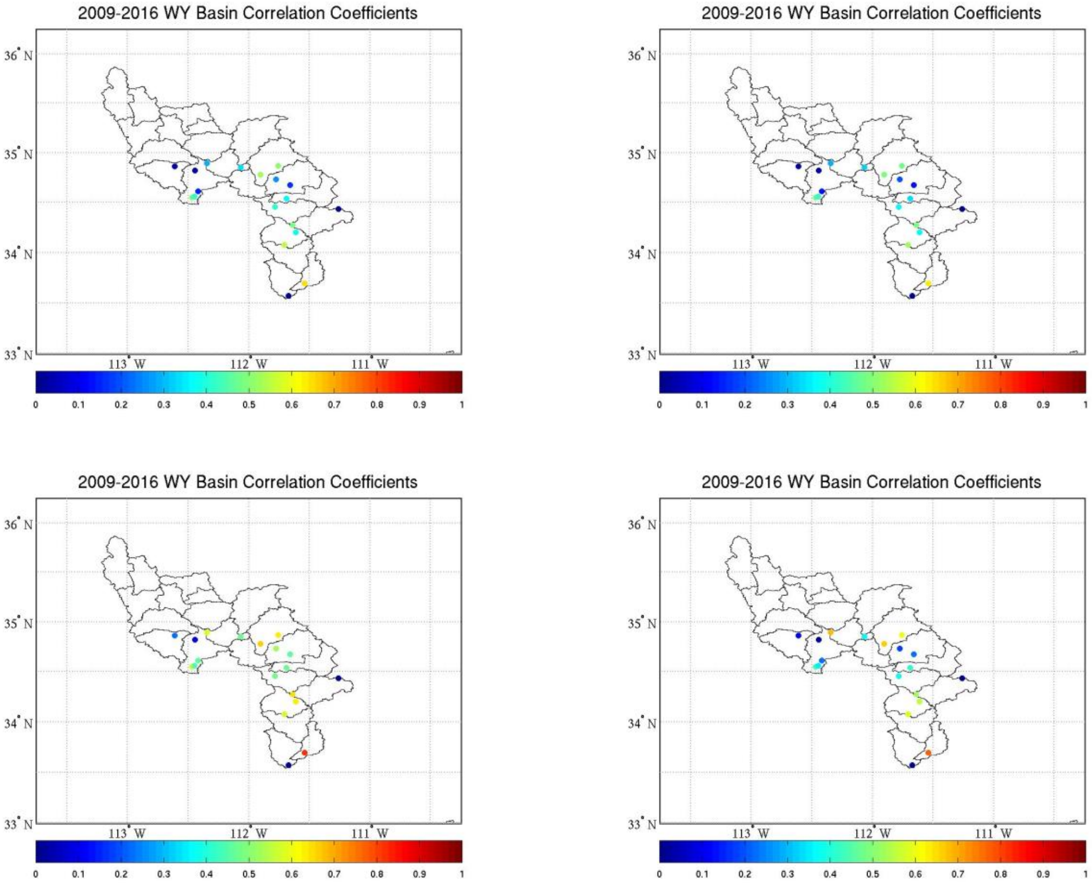


Figure 14: As in Figure 13, but for correlation coefficient.