# Enhancements to the WRF-Hydro Hydrologic Model Structure for Semi-arid Environments

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## National Water Model Configuration

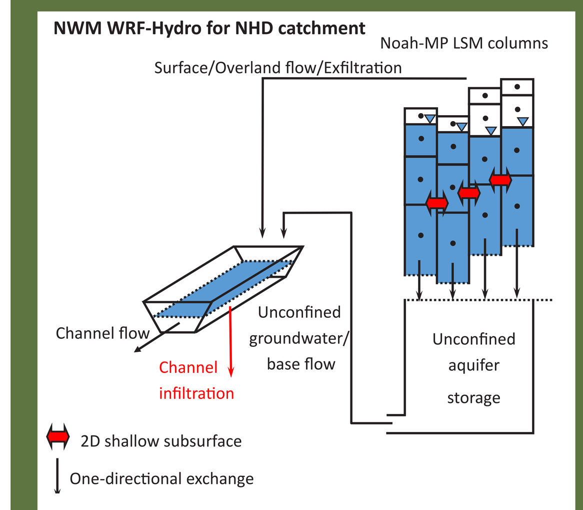


Figure 1: Illustration of the WRF-Hydro Hydrologic Model structure

The WRF-Hydro model (Gochis et al. 2015), configured as the NOAA National Water Model (NWM), is challenged to reproduce the hydrologic response of semi-arid catchments because it to does not account for infiltration of water out of flowing ephemeral channels into the underlying unsaturated soil below (e.g. Goodrich et al. 2004). In this study, we implement a conceptual channel infiltration function in WRF-Hydro that is based on that of the KINEROS2 semi-distributed hydrologic model (Goodrich et al. 2012). An illustration of the WRF-Hydro NWM structure is shown in Figure 1, and details of the NWM configuration are shown in Table 1. The model is calibrated in the Walnut Gulch Experimental Watershed (WGEW), where 1-km resolution gauge precipitation data are available and in three other basins in the Verde and San Pedro watersheds (Figure 2) with NCEP Stage-IV precipitation. Atmospheric forcing for the model is from the NLDAS-2 dataset.

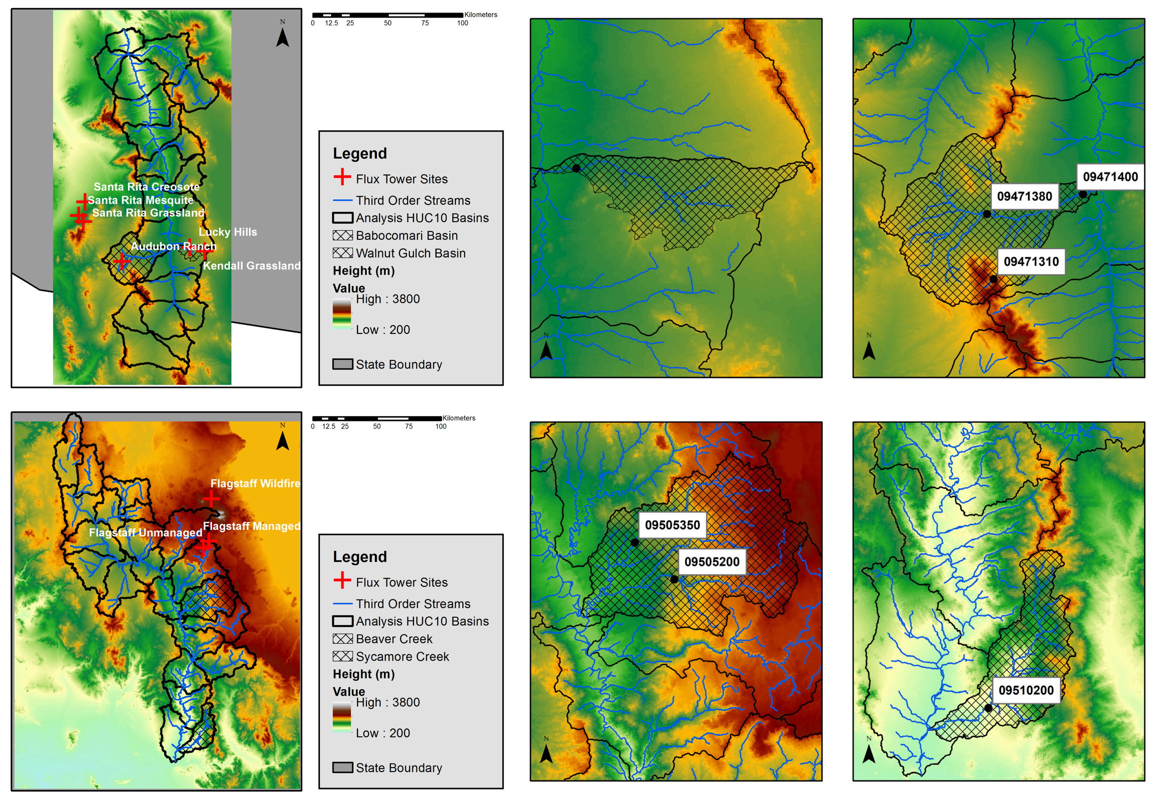

Figure 2: WRF-Hydro routing grids for large basins and study areas are shown. Walnut Gulch (top center) and the Babocomari River (top right) are in the San Pedro basin (top left). Beaver Creek (bottom center) and Sycamore Creek (bottom right) are in the Verde basin (bottom left).

| WRF-Hydro Module | Scheme |
|---|---|
| Land surface model | 1-km grid resolution Noah-MP (Niu et al. 2011) LSM |
| Subsurface flow routing | Boussinesq flow model |
| Overland flow routing | 1-Dimensional diffusive wave routing |
| Channel routing | Muskingum-Cunge routing (NHDplus version 2 channels) |
| Baseflow model | Exponential bucket, partitioned by NHDplus catchments |

Table 1: NWM WRF-Hydro modules and selected parameterizations.

## Calibration Description

The model is optimized using 500 iterations of the Dynamically Dimensioned Search (DDS) algorithm (Tolson and Shoemaker 2007) for a 3-year period with spin-up. The Kling-Gupta-Efficiency (KGE; Gupta et al. 2009), which equally weights correlation, water balance, and variance, is optimized. KGE shown herein is re-scaled to be optimal at zero. Optimized parameters, including the added channel bed conductivity parameter are shown in Table 2. Parameters are adjusted by multiplication or addition constants to a priori parameters based on land data, a form of spatial regularization (e.g. Pokhrel et al. 2008). The WRF-Hydro bucket model is a poor representation of baseflow in semi-arid environments, where groundwater recharge is unlikely to reach the local channel network. To prevent baseflow from the bucket model from entering the channel network, the bucket model is disabled except near perennial channels.

| Parameter | Description and Units | Use for Calibration |
|---|---|---|
| *BEXP* | Pore Size Distribution Index (dimensionless) | Beaver Creek only; multiplication constant |
| *DKSAT* | Saturated Conductivity (m/s) | Multiplication and addition constants |
| *SMCMAX* | Saturation soil moisture content (porosity; volumetric fraction) | Multiplication constant |
| *REFKDT* | Surface runoff parameter (unitless) | Constant for basin |
| *SLOPE* | Linear scaling of "openness" of bottom drainage boundary (unitless; 0-1) | Verde basins only; multiplication constant |
| *Expon* | Exponent controlling rate of bucket drainage as a function of depth (unitless) | Verde basins only; constant for basin |
| *ChSlp* | Channel Side Slope (unitless) | Multiplication constant |
| *ChannK* | Channel bed conductivity (for channel infiltration; m/s) | Multiplication constant |

Table 2: WRF-Hydro parameters and descriptions. The use of each parameter for calibration is also shown.

## Channel Infiltration in Walnut Gulch

To demonstrate the added value of channel infiltration, WRF-Hydro was calibrated in the WGEW basin in configurations with channel infiltration active and disabled. Figure 3 shows calibration is able to eliminate water balance errors, through the cumulative precipitation plot and the percent bias skill metric. KGE and correlation coefficients improve, and coefficient of variation percent bias has less negative bias. Including channel loss reduces the number of spurious peaks of streamflow, with calibration. KGE improves when loss is included in the model (0.07 with loss v. 0.13 without loss). These results demonstrate that WRF-Hydro, in the NWM configuration, with channel infiltration can be calibrated and produce a realistic hydrologic response in a small semi-arid catchment with gauge precipitation.

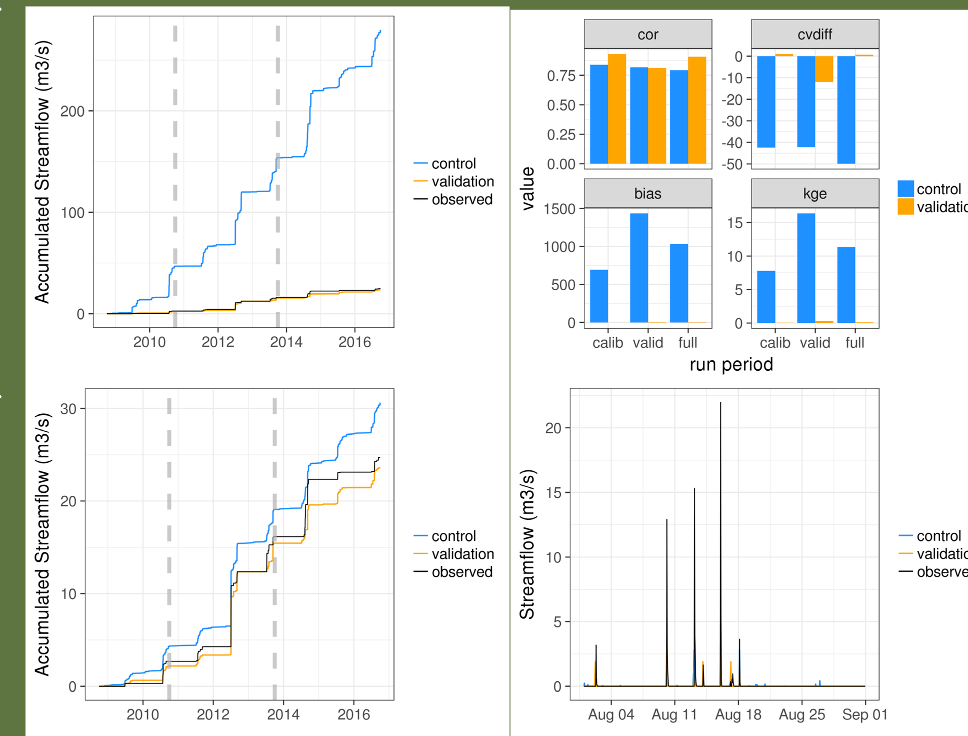

Figure 3: Calibrated and control NWM streamflow for Walnut Gulch, with gauge precipitation forcing. Upper panels show accumulated streamflow (calibration period in dashed lines; left) and skill scores (right), including KGE, % Bias (bias), CV % Bias (cvdiff), and Correlation Coefficient (cor). Below, accumulated streamflow with (without) channel loss in orange (blue) (left) and a sample hydrograph from July 2014 are shown (right).

## Calibration with NCEP Stage-IV Precipitation

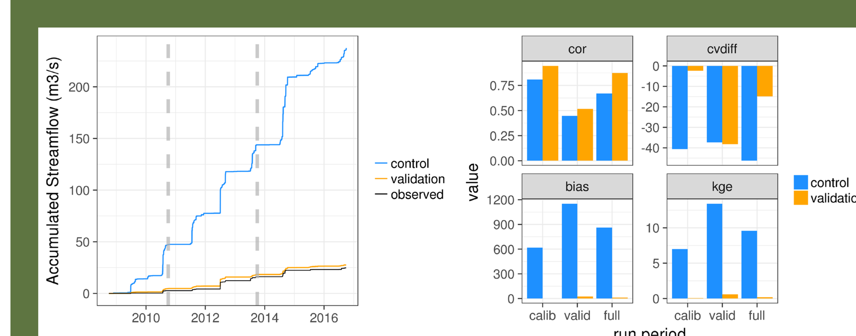

Figure 4: Calibrated (orange) and control (blue) NWM accumulated streamflow (left) and skill scores (right) for Walnut Gulch, as in Figure 3. Model is forced with Stage-IV precipitation.

### Walnut Gulch:

Calibration in WGEW with Stage-IV forcing still reduces water balance errors. Correlation coefficients exhibit little improvement outside the calibrated period (Figure 4). The fact that correlation coefficients for the same study area are degraded when Stage-IV precipitation is used instead of gauge data suggests that precipitation forcing may be a source of uncertainty for WRF-Hydro in this and similar basins.

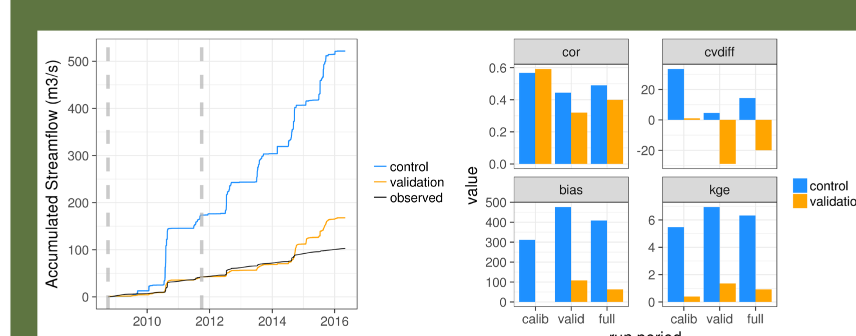

Figure 5: Calibrated (orange) and control (blue) NWM accumulated streamflow (left) and skill scores (right) for the Babocomari River, as in Figure 3. Model is forced with Stage-IV precipitation.

### Babocomari River:

The Babocomari basin is more spatially heterogeneous than WGEW, and calibration yielded less improvement. Calibration improved the water balance. The correlation coefficient for the calibrated model was low in both the calibration (WY 2008-2011) and validation periods (Figure 5). These results suggest that the Babocomari River and WGEW may be subject to similar precipitation timing errors.

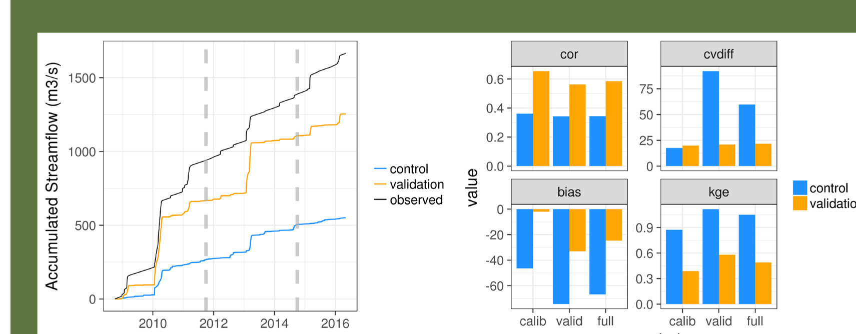

Figure 6: Calibrated (orange) and control (blue) NWM accumulated streamflow (left) and skill scores (right) for Beaver Creek, as in Figure 3. Model is forced with Stage-IV precipitation.

### Beaver Creek:

Beaver Creek, is the only catchment analyzed with significant snow melt. Figure 6 shows that for the calibration period (WY 2012-2014), WRF-Hydro can capture some snow melt. Stage-IV precipitation missed a snow event in Spring 2011, limiting the streamflow from the calibrated simulation. Calibration somewhat reduced the negative bias of the model; however, WRF-Hydro still has a difficult time capturing low flow.

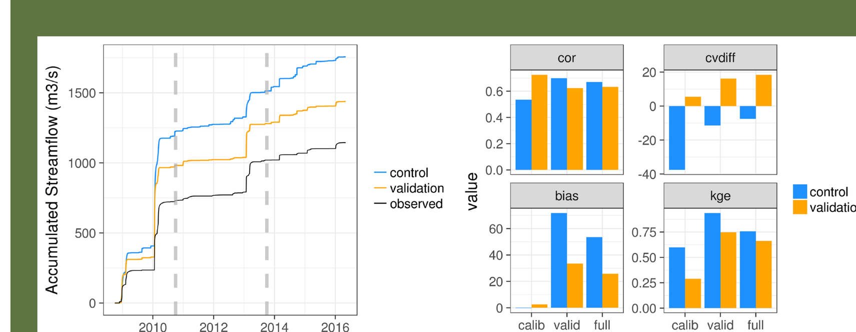

Figure 7: Calibrated (orange) and control (blue) NWM accumulated streamflow (left) and skill scores (right) for Sycamore Creek, as in Figure 3. Model is forced with Stage-IV precipitation.

### Sycamore Creek:

Calibration improved simulated streamflow output in Sycamore Creek (Figure 7). Calibration yielded a high channel infiltration parameter, which reduced spurious flashy peaks that were also present in Walnut Gulch and the Babocomari River. The cumulative streamflow plot shows that WRF-Hydro over-estimated a major runoff event early in evaluation period, leading to high bias and reduced model skill.

## Water Balance in Walnut Gulch

Observations from 20 5-cm soil moisture sites in the WGEW basin were compared to the area average of Noah-MP 0-10 cm soil moisture from WRF-Hydro. Calibration with gauge precipitation forcing in Walnut Gulch increased the positive bias of WRF-Hydro near-surface soil moisture, averaged throughout the basin, but to a lesser extent when channel loss was included (Table 3). Figure 8 shows the effect of calibration and channel loss on soil moisture for sample warm and cold seasons. Calibration reduces the negative bias of model ET at the Kendall Grassland and Lucky Hills flux tower sites in WGEW. This negative ET bias is consistent with the uncalibrated model's tendency to over-estimate streamflow. These results demonstrate that calibration is able to improve WRF-Hydro's representation of the water balance, by reducing positive streamflow bias and negative ET bias.

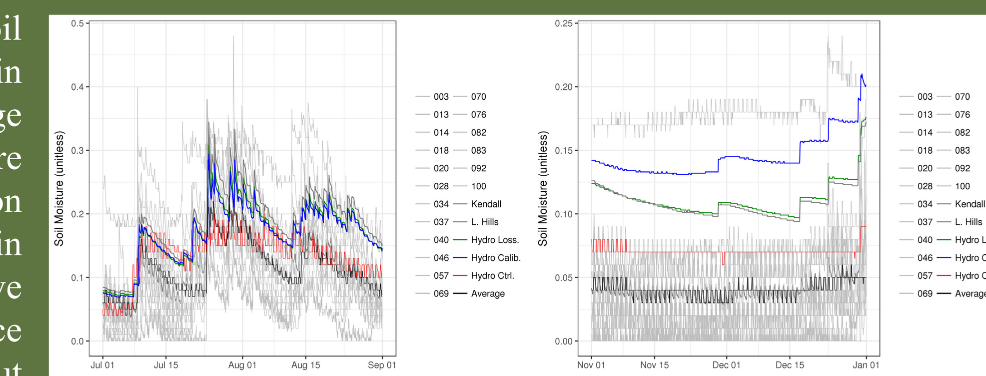

Figure 8: Area averaged near surface soil moisture in Walnut Gulch catchment for July-August 2011 (left) and November-December 2011 (right) from soil probe observations (black), the control model simulation (red), and the calibrated simulations with channel loss (green) and without channel loss (blue). Also shown are the individual observation locations, plotted in light gray.

| Evaluation Metric | Control (w/loss) | Calibration (no loss) | Calibration (w/loss) |
|---|---|---|---|
| Soil Moisture | | | |
| Percent Bias | 93.1831 | 105.2521 | 98.3288 |
| Correlation | 0.8587 | 0.8799 | 0.8096 |
| Lucky Hills ET | | | |
| Percent Bias | -9.2943 | -0.3393 | 0.7173 |
| Correlation | 0.8892 | 0.8887 | 0.8906 |
| Kendall Grassland ET | | | |
| Percent Bias | -14.0679 | -5.7794 | -5.3439 |
| Correlation | 0.8696 | 0.8692 | 0.8742 |

Table 3: WRF-Hydro Noah-MP level 1 (0-10 cm) soil moisture skill scores, compared to area averages of 5-cm Walnut Gulch soil moisture measurements are shown in the top rows. Flux tower ET at the WGEW Lucky Hills and Kendall Grassland sites are shown in the middle and bottom rows, respectively.

## Summary and Analysis

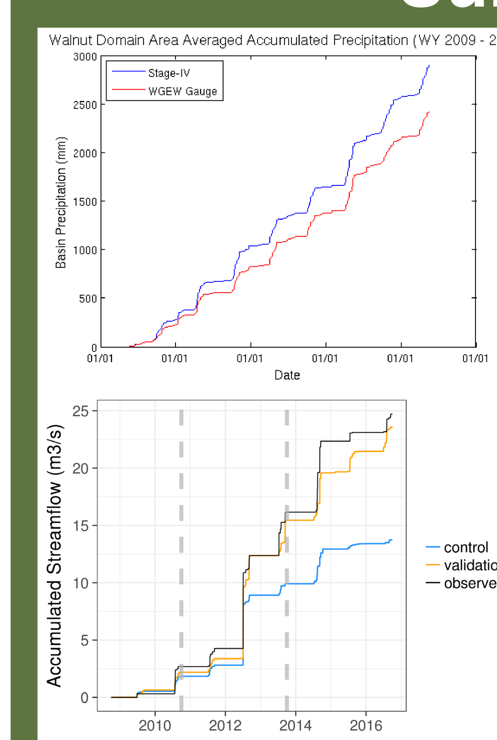

Figure 9: Area averaged accumulated WGEW gauge (red) and NCEP Stage-IV (blue) precipitation in WGEW (top) and accumulated NWM WRF-Hydro streamflow at the basin outlet with WGEW forcing (orange) and Stage-IV forcing (blue) with parameters optimized for gauge precipitation.

- **Uncertainty of forcing precipitation limits the skill of the calibrated model. Model performance is degraded in WGEW and in the Babocomari basin using the Stage-IV product.**
- **The addition of channel infiltration and subsequent calibration of WRF-Hydro has permitted the model to produce a more realistic hydrologic response and reduce water balance errors, when forced with high-resolution gauge precipitation.**
- **Future work includes coupling WRF-Hydro to WRF for a small domain and executing it as a regional climate model and testing regionalization methods to calibrate the model over larger areas.**

One reason for the model uncertainty is that precipitation in the radar-based Stage-IV product is subject to beam blockage (e.g. Zamora et al. 2014), which can cause it to both miss low altitude precipitation events and produce precipitation from high altitude radar echoes that evaporates before reaching the surface. The Stage-IV product can spatially buffer precipitation over the landscape. As surface runoff only occurs when there is sufficient precipitation to exceed the infiltration capacity of the soil, spreading of precipitation could reduce runoff that might otherwise occur over a small area associated with locally heavier precipitation. This might explain why the Stage-IV dataset produces more precipitation and less streamflow over WGEW (Figure 9).

## References and Acknowledgements

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