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Evaluation of a Hydrologic Model Applied to a Headwater Basin in the Rio Grande (USA) Using Observed and Modelled Land Surface Fluxes and States

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Abstract: Researchers at the Desert Research Institute are conducting research aimed at developing and calibrating both operational and physically based numerical models that can be used to predict the quantity and timing of runoff in semi-arid regions where the majority of runoff originates in the seasonal snow pack. Unfortunately, observations of hydrologic variables (precipitation, streamflow, evapotranspiration, snow water equivalent, etc.) are sparse in the semi-arid regions of the western United States and, therefore, the evaluation of model accuracy (usually in terms of streamflow) is often very limited. However, comparisons of model output with newly developed high-resolution estimates of hydrologically based land surface fluxes and states may provide insight to model accuracy in areas with little or no observed information. In this study, we apply a hydrologic model to a watershed in the headwaters of the Rio Grande to simulate the streamflow generated at the watershed outlet and several internal subwatersheds. The model simulations of streamflow are compared to values from long term land surface model studies and observations at streamflow surface water stations. Additional comparisons of model snow water equivalent (SWE) estimates are made with the SWE values from the long term land surface model studies and SWE observations at three point locations within the watershed.

Keywords: Surface water modelling; Model evaluation

1. INTRODUCTION

In arid/semi-arid areas of western United States (U.S.), water managers rely on seasonal forecasts of water supply to make important decisions about the management of water resources for urban, industrial, agricultural, and environmental uses. In many cases, the primary source of water is from spring runoff of snowpack in mountainous areas.

Streamflow forecasts are generally made using empirical relationships between historical observations of precipitation, snow water equivalent, and streamflow or with more physically based hydrologic models to simulate (at some conceptual level) the water and/or energy balance in a watershed. The empirical approach is limited to watersheds with sufficient historical hydrologic observations and to conditions observed in the historic record (floods, droughts, land use change, climate change, etc.).

The hydrologic modelling approach requires spatial and temporal estimates of model inputs

(e.g., precipitation, temperature, solar radiation, etc.) and parameter values to simulate current and future hydrologic conditions. In most areas of the western U.S., observations of model input variables are sparse and only available at point locations. Regional relationships are often used to transfer the point observations to and throughout the area of study. Model parameter estimation and evaluation also can be difficult due to limited availability of observations of spatial variability of important hydrologic information (e.g., soils, vegetation, streamflow, precipitation, temperature, etc.).

In this study, a hydrologic model is applied to a watershed in the headwaters of the Rio Grande to simulate the streamflow generated at the watershed outlet and several internal locations (nodes) within the watershed. The hydrologic model is calibrated to simulate the observed streamflow at the watershed outlet. The model simulations of streamflow at the watershed outlet and internal nodes are compared to values from long term land

surface model studies and observations at U.S. Geological Survey (USGS) streamflow surface water stations. Additional comparisons of model snow water equivalent (SWE) estimates are made with the SWE values from the long term land surface model studies and SWE observations at three United States National Resources Conservation Service (NRCS) SNOpack TELemetry (SNOTEL) sites within the watershed.

The primary goals of this study are: (1) to gain a better understanding of the model's ability to accurately simulate streamflow at locations internal to the calibration location – are we getting the right answer for the wrong reason?; and (2) investigate the use of the long term data set as a surrogate for observations in areas with little or no observed hydrologic information - both important issues presented within the Prediction in Ungauged Basins initiative.

2. METHODS

2.1 Study Area

The Upper Rio Grande watershed is approximately 83,400 km² and ranges in elevation from 1,200m near the New Mexico and Texas border to over 4,250m in the headwater areas in southern Colorado. Nearly one third of the water flowing in the Rio Grande is generated from snowmelt in the headwaters above the Del Norte surface water station in southern Colorado (see Figure 1). The Del Norte watershed is a mountainous (elevation range is 2,400m to 4,250m), snow-dominated, watershed in the Rocky Mountains of southern Colorado. The area contributing to the USGS surface water station at Del Norte is approximately 3,500 km². The contributing areas associated with each of the six internal subwatersheds are listed in Table 1. The vegetation is predominantly coniferous forests with a mix of alpine tundra and bare rock on areas above timberline.

2.2 Observed Data

The USGS and the State of Colorado maintain six surface water stations within the Del Norte watershed. The surface water station at the outlet (Rio Grande near Del Norte) serves as an index measurement of streamflow on the Rio Grande to determine water rights throughout the entire Upper Rio Grande Basin and, therefore, is the most important of the six stations. The remaining five stations provide continuous streamflow estimates at various locations throughout the study watershed. The NRCS has three automated remote sensing

SNOTEL sites within the Del Norte watershed that provide real-time (and historic – October 1988 to present) SWE, snow depth, precipitation, and temperature estimates at each site (see Figure 1).

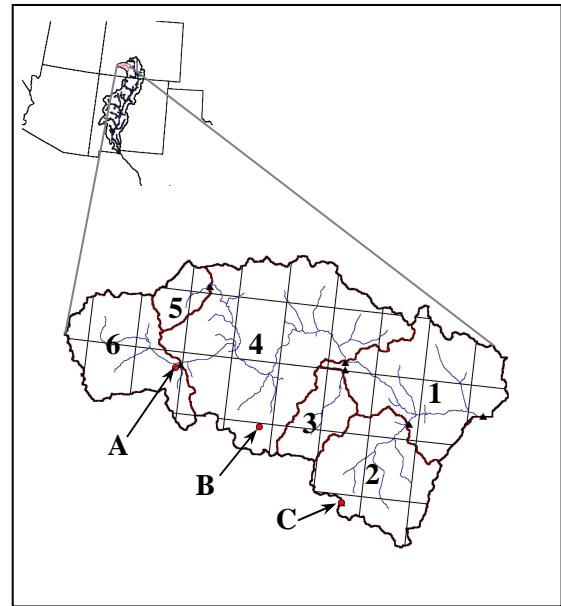


Figure 1. Location of study area (Rio Grande above Del Norte) within the Rio Grande Basin. USGS surface water stations (triangles), NRCS SNOTEL sites (circles A-C), and subwatershed boundaries (1-6) within the study area. The stream network and 1/8 degree grid are also shown.

Table 1. Contributing area and percent volume of total streamflow generated within each subwatershed.

| # | Area (km ²) | Volume (% of total) | | |
|---|----------------------------|---------------------|------|------|
| | | OBS | MMS | LTDS |
| 1 | 719 | 1.8 | 20.6 | 7.9 |
| 2 | 549 | 24.3 | 15.7 | 19.2 |
| 3 | 210 | 7.1 | 6.0 | 9.0 |
| 4 | 1376 | 39.3 | 39.5 | 34.0 |
| 5 | 125 | 3.3 | 3.6 | 3.6 |
| 6 | 510 | 24.2 | 14.6 | 26.2 |

2.3 Long Term Data Set

Maurer et al. [2002] developed a model-derived data set of land surface fluxes and states for the conterminous United States from 1950 to 2000. The data set includes surface forcings (e.g., precipitation and temperature) gridded (using a

linear relationship between elevation, latitude, and longitude) at a 1/8 degree resolution from observations. Simulated hydrologic variables (e.g., streamflow and snow water equivalent) from the variable infiltration capacity (VIC) [Liang et al., 1994] hydrologic model are also available at a 1/8 degree resolution. This long term data set (LTDS) was developed primarily to serve as diagnostic data set in studies where ground based observations are sparse.

2.4 Hydrologic Model

The USGS Precipitation-Runoff Modeling System (PRMS) [Leavesley et al., 1983] within the Modular Modelling System (MMS) [Leavesley et al., 1996] was applied to the Del Norte watershed. PRMS is a distributed-parameter, physical process hydrologic model that allows the user to partition the watershed into hydrologic response units (HRU) based on different characteristics of a watershed (e.g., slope, aspect, stream network, elevation etc.).

In this study, the Del Norte watershed was partitioned into HRUs based on the 1/8 degree grids (see Figure 1) used in the LTDS study to avoid possible issues related to scaling between the MMS and LTDS approaches. Daily values of precipitation and temperature were estimated for each HRU for the entire calibration period (1 October 1988 to 30 September 1997) using regional linear relationships between the elevation, latitude, and longitude of the SNOTEL sites and the centroids of the HRUs.

Many of the PRMS model parameters were derived directly from spatial information describing

important hydrologic characteristics of the watershed (e.g., soils, vegetation, slope, aspect, etc.) using existing empirical relationships. The remainder of the model parameters were estimated using a manual calibration approach to simulate the observed streamflow at the watershed outlet (Del Norte surface water station). The MMS-PRMS estimates of streamflow at each of the five internal nodes were not used in the calibration process.

3. RESULTS

The results of the MMS calibration at the outlet (Del Norte surface water station) are shown in Figure 2. Based on a visual comparison of the MMS simulated streamflow (solid black line) and the observed streamflow (black dots) over the entire nine year calibration period, the MMS simulation appears to be a “reasonable” estimate of the observed streamflow behaviour at the outlet of the watershed. This can also be seen in Figure 3a where the mean annual flow for each calibration year is plotted (solid black dots) versus the percent bias of the MMS simulated streamflow. The results suggest that performance of the MMS model, in terms of its ability to simulate streamflow during the calibration period, does not appear to be significantly influenced by the “wetness” or “dryness” of the year.

In contrast, the streamflow estimates from the LTDS overestimate the observed streamflow in all but the driest year (WY 1996). Like the MMS results, however, there does not seem to be a systematic relationship between the percent bias in the LTDS streamflow estimates and mean annual flow volumes (see Figure 3a).

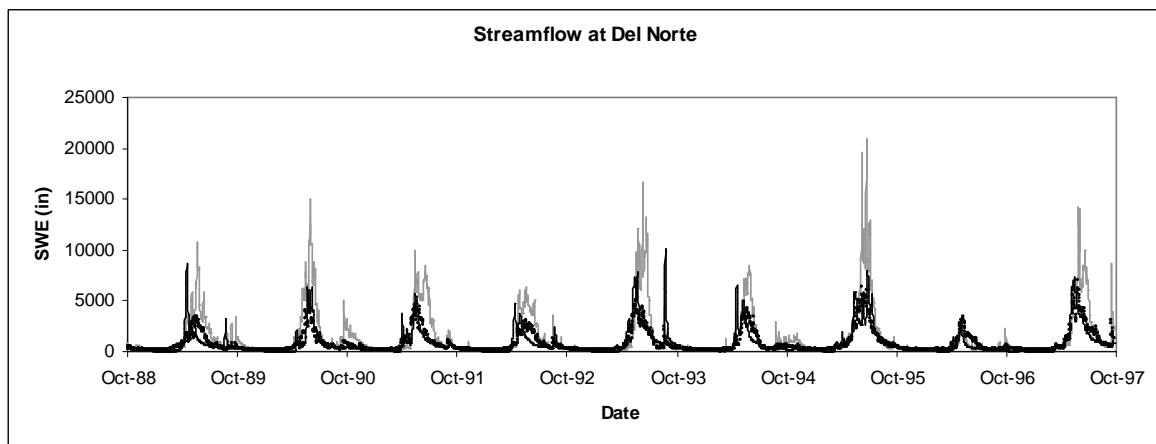


Figure 2. Streamflow hydrograph at the Del Norte surface water station. The black dots are the observed, the solid line is the MMS estimate, and the shaded line is the LTDS estimate.

The MMS streamflow simulations at two of the interior nodes (surface water stations at Southfork and 30 Mile Bridge) underestimate the observations in all but the driest year (WY 1997) at Southfork (Figures 3b and 3c). Again, there does not appear to be a significant relationship between the mean annual flow and percentage bias of MMS simulated streamflow. The LTDS estimates at South Fork tend to be overestimates with no significant pattern in wet or dry years. At the 30 mile bridge, however, the LTDS streamflow estimates appear to be more positively biased for drier years than for wet years.

Plots of the SWE for each of the three SNOTEL sites are shown in Figure 4a-c. Close inspection of these plots reveals two important behaviours. The first is that the LTDS SWE is greater than MMS SWE estimates in almost all years at all three sites. The second is that there appears to be a systematic spatial trend of underestimation from Wolf Creek, a close fit at Middle Creek and overestimation at Upper Rio Grande. Both of these behaviours are likely associated with errors in the spatial distribution of the precipitation (compared to errors due to model parameter estimation or algorithm complexity).

4. DISCUSSION and CONCLUSIONS

4.1 MMS Streamflow Simulation

In this study, the MMS model simulations of streamflow at the outlet node appear to be unbiased with respect to mean annual streamflow compared with the under-predictions at two of the interior nodes (Southfork and Middle Creek). This is an indication that, in this case, we may be getting the right answer for the wrong reason. That is, we have a “good” fit at the outlet (Del Norte surface water station) due to the under predictions and over-predictions throughout the internal areas of the watershed. The apparent spatial bias of SWE estimates with the MMS approach points to the spatial distribution of precipitation as a potential source of the problem.

4.2 LTDS in Ungauged Basins

In general, the streamflow estimates from the LTDS overestimated the observed streamflow at the outlet and internal nodes. It is important to note that the model used to generate the LTDS fluxes was not calibrated at the Del Norte surface water station. Further, the LTDS was not

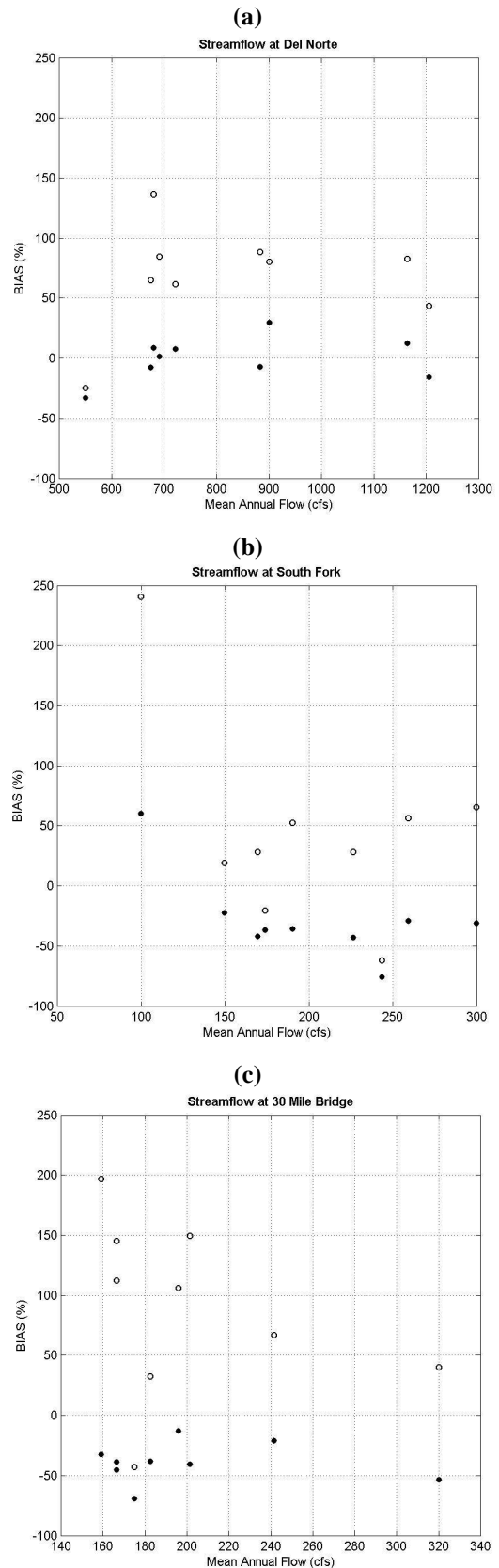
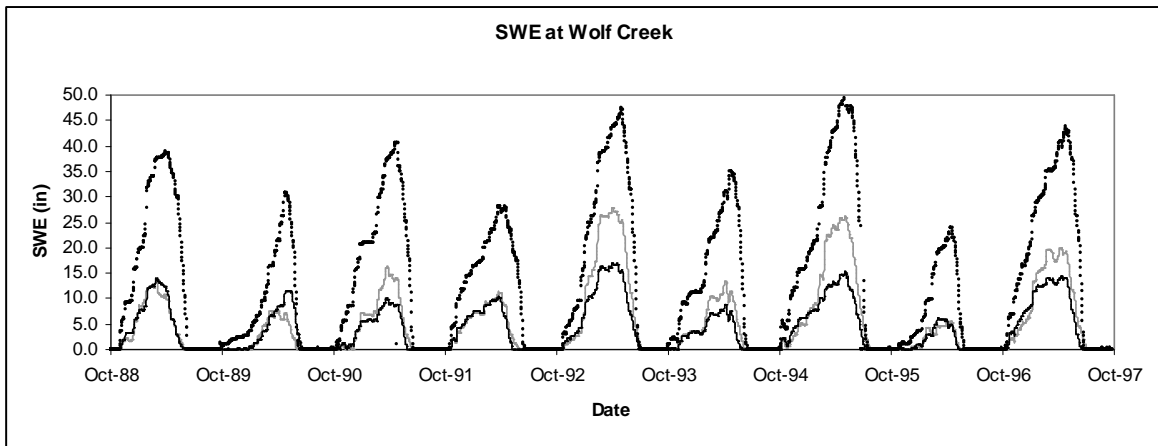
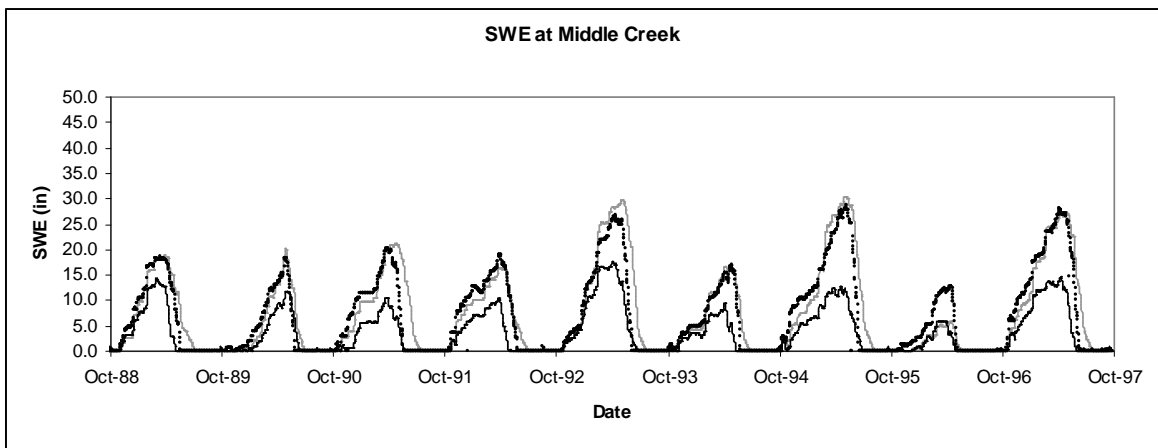


Figure 3. Plots of mean annual flow versus percent annual percent bias. The black dots are the MMS estimate and the open circles the LTDS estimate.

(a)



(b)



(c)

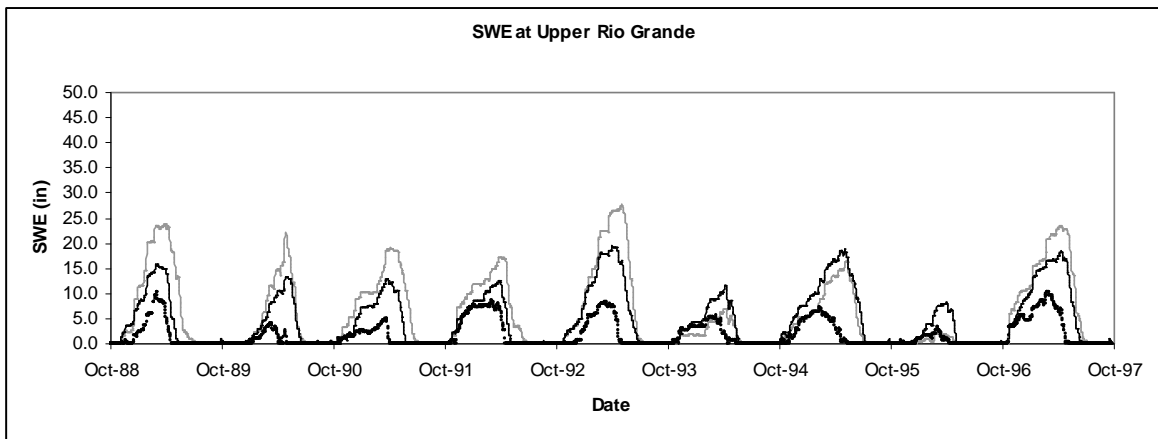


Figure 4. SWE time series at (a) Wolf Creek, (b) Middle Creek, and (c) Upper Rio Grande SNOTEL sites. The black dots are the observed, the solid line is the MMS estimate, and the shaded line is the LTDS estimate.

developed to provide accurate estimates of state variables (e.g., SWE) at point locations. The LTDS was, however, developed to serve as diagnostic data set in studies where ground based observations are sparse.

Based on the initial results from this study, however, it is not clear how to use the LTDS streamflow estimates as diagnostics since they appear to be heavily biased by mean annual flow volume in at least one of the sub-watersheds. As a result, using the LTDS as a surrogate for observed streamflow at nodes within this watershed may not have much value. The same could generally be said about the LTDS estimates of SWE in the watershed. However, there do appear to be some interesting relationships between the LTDS, MMS, and point observations of SWE that support the potential problem related to spatial distribution of precipitation.

The percent of total streamflow volume (at the outlet of the Del Norte watershed) generated from each subwatershed is shown in Table 1 for the observed, MMS, and LTDS estimates. Notice that the MMS estimate for subwatershed one is significantly greater than both the observed and the LTDS. Also notice that the MMS estimates for subwatersheds two and six are significantly less than both the observed and LTDS estimates. Subwatershed one is a low elevation area that generally receives less precipitation than the rest of the subwatersheds while subwatersheds two and six are high elevation areas that generally receive much more precipitation than the rest of the watershed. This result may be a further indication of a problem with the precipitation distribution used in the MMS approach. These results also indicate that despite the apparent bias in the LTDS streamflow, the spatial distribution of the generation of streamflow may provide some valuable information to the modeller in an ungauged watershed application. Researchers at DRI are currently exploring these and other ideas and will report interesting findings in the future.

5. ACKNOWLEDGEMENTS

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