Terrestrial Hydrology over the United States Driven by MM5-based Regional Climate Model (CMM5) Simulations

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Abstract

United States Department of Agriculture (USDA) Soil and Water Assessment Tool (SWAT) model was built for applications to study the terrestrial hydrology over the whole United States. Individual SWAT simulations were conducted on the 18 two-digit (major water resource region, MWRR) USGS Hydrologic Unit Areas (HUA) and then combined to cover the whole United States. Driven by daily precipitation and temperature weather station measurements, the SWAT was first calibrated for streamflow in each delineated watershed using the Fortran Feasible Sequential Quadratic Programming (FFSQP) optimization solver during 1980-1989. This study further compared the SWAT simulated streamflow over the whole United States during the validation period of 1990-2002 as driven by both observations and CMM5 outputs. Results show simulated monthly streamflow in good agreements with the USGS gage observations in the eastern US and great Mississippi region. SWAT driven by CMM5 outputs tracked the similar streamflow variation as driven by weather station measurements, with larger deviation to the observed flow in peak-flow and low-flow months.

Introduction

Terrestrial hydrology has great impact to water resource management and agriculture production. Hydrology simulations provide an important assessment tool to hydrologic systems. Hydrology investigation also helps better describe the interactive processes between atmosphere and land surface, which is important in the atmospheric modeling. Numerous hydrologic simulations have been conducted for spatial scales varying from a small watershed to the continental-scale (Arnold and Allen 1996, Arnold et al. 1999a,b, Rosenberg 2003). One of the difficulties in the large-scale watershed studies arises from the lack of sufficient high-quality observational data. In the previous US continental scale simulation using the structure of HUMUS (Hydrologic Unit Model for the United States), a total of 1130 weather stations were applied for the daily weather attributes (Arnold et al. 1990b). This study employs 7235 cooperative weather stations to provide a much enhanced data of daily precipitation and temperature for driving the SWAT simulations. To investigate the potential use of regional climate modeling in the study of the terrestrial hydrology, the CMM5 downscaling precipitation and temperature outputs driven by the NCEP-DOE AMIP II reanalysis (Liang et al. 2004) were employed as the weather forcing data for parallel simulations.

Methodology

The SWAT (Arnold et al. 1998) is a physically based water balance model operating continuously for watersheds in various spatial scales. The SWAT divides a primary watershed into multiple sub-basins and hydrologic response units (HRU). The model represents the water balance for each HRU in four vertical water storage components as: snow cover, soil profile (0-2m), shallow aquifer (2-20m) and deep aquifer (>20m). Flow, sediment *etc.* generated for each HRU are aggregated for the watersheds and routed to the watershed outlet through channel, pond and/or reservoirs. The SWAT simulates the hydrology through the processes of snowmelt, precipitation, surface runoff, evapotranspiration, ground water percolation, lateral flow and groundwater flow. A detailed description of the computation for each process, together with other capability of SWAT including plant growth, erosion and management practices is referred to Neitsch et al. (2002a,b).

Simulations were first conducted for the two-digit HUA (MWRR) and aggregated for the coverage over the whole continental US. Totally 16 watersheds were formed for the 18 two-digit HUA, where the Ohio (05) and Tennessee (06) basins, Arkansas-Red-White (11) and Texas Gulf (08) basins were combined as two single watersheds due to the stream connectivity along their boundaries. Within each watershed, AVWAST (Arcview interface for SWAT, Di Luzio et al. 2002) was used to delineate the region into functioning sub-basins and HRUs. Figure 1 shows the MWRR boundary and the delineated sub-basins. The topography Digital Elevation Model (DEM) and land coverage were derived from USGS gtop30 hydrologic data(http://lpdaac.usgs.gov/gtopo30/hydro). For the soil components, the USDA State Soil Geographic (STATSGO) database was employed. All datasets have a spatial resolution at a map scale of 1:250,000. The management operations adopted the default in AVSWAT. Totally 1775 sub-basins were delineated over the entire US, which is comparable to a scale of 2100 eight-digit HUA. Dominant land use and soil types were set uniformly for the discretized sub-basin where single HRU was created. An interface for input of precipitation, temperature and other surface variables were developed to incorporate weather station observations and CMM5 gridded outputs by applying the closest data point to the neighborhood HRU.

The FFSQP optimization solver (Zhou et al. 1997) was applied to automatically calibrate the SWAT for higher correlation (R) and Nash-Sutcliffe simulation efficiency (NS) between simulated monthly streamflow and USGS gage observations. In this study, we calibrated six parameters: curve number, soil evaporation compensation factor, plant uptake compensation factor, soil available water capacity, groundwater "revap" coefficient and groundwater delay time. The optimization searches the favorable decreasing direction for the minimum of object functions, which are defined as the 1-R and 1-NS, respectively.

Results and Discussion

Driven by the weather station observations, the SWAT was first calibrated for each delineated watershed. Figure 2 shows the flow calibration results conducted for the Upper

Mississippi basin (07). Monthly streamflow were compared to USGS075587450 gage observation at Grafton, IL. Figure 2a shows the time-series during 1980-2002. The simulation was started from 1979 which was considered as a spin-up period not used in subsequent analyses. In the first 10 years calibration period (1980-1989), the six chosen parameters were allowed to vary in a reasonable range for retrieving the best comparable streamflow using the FFSQP solver. The calibrated parameters were then fixed for the simulation during the validation period (1990-2002). The plot shows that the SWAT reasonably tracked the monthly streamflow variation for the entire simulation period. Although there is underestimation for the low-flow months, the peak-flow months' streamflow were well captured. Figures 2b and 2c show the regression plot for the calibration and validation period, respectively. Strong correlations were found between the measured and simulated flows, in that R and NS values are respectively, 0.87 and 0.62 in the calibration period, and even higher, 0.93 and 0.76 in the validation period. The results indicate that the SWAT accurately simulated the streamflow characteristics for the Upper Mississippi basin.

A similar calibration process was repeated for all other watersheds. A high degree of agreement with observations for streamflow was found in the great Mississippi region, including the Missouri (10), Upper Mississippi (07), Ohio and Tennessee (05, 06), Arkansas-Red-White and Texas Gulf (11, 08) basins. In those basins, the achieved R range from 0.87 to 0.89 and NS from 0.48 to 0.78. More impressively, higher values of R (0.89-0.93) and NS (0.59-0.81) were obtained in the validation period. This confirms that the SWAT was well designed to represent the hydrology characteristics in the plain basins. For other watersheds, an overall better agreement occurs in the eastern US than the dryer western mountainous region. The lowest correlation is found for Lower Colorado (15) in both calibration and validation periods. This poor performance may partially result from the fact that the SWAT was originally developed for application in agriculture basins instead of heterogeneous mountainous basins typical in the western US. The future development of the SWAT may focus on improving its skill for application in mountainous region (Fontaine et al. 2002).

Figure 3 shows the observed and simulated monthly mean streamflow variation during the validation period (1990-2002) driven by weather station measurements and CMM5 outputs. As indicated with high R^2 and NS values, SWAT with weather station measurements well simulated all major flow patterns in the eastern US and great Mississippi region. In particular, there is almost a perfect match between observed and simulated flows for the outlet gage in Ohio and Tennessee (05, 06) basins. Streamflow prediction driven by CMM5 outputs show a similar trend in these watersheds with a somewhat lower correlation, causing overprediction (underprediction) during peak(low)-flow months in some areas. A lower degree of agreement is also found in the dry western mountainous region, where the CMM5 driven SWAT significantly overestimated streamflow. This may be explained in part by the CMM5 overestimation of precipitation in northern Rockies during winter and spring, and also because the applied SWAT was calibrated by the weather station rain-gauge measurements which are usually underestimated in the mountains (Liang et al. 2004). It will be useful to calibrate the SWAT using CMM5 outputs and then evaluate the performance for validation period. This work is in progress.

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References

Arnold, J.G., and P.M. Allen, 1996: Estimating hydrologic budgets for three Illinois watersheds. *J. Hydro.*, **176**, 55-77

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998: Large area hydrologic modeling and assessment-Part I: model development. *J. Am. Water Resour. Assoc.*, **34(1),** 73-89

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and P.M. Allen, 1999: Continental scale simulation of the hydrologic balance. *J. Am. Water Resour. Assoc.* **35(5)**, 1037-1051

Arnold, J.G., R. Srinivasan, and T.S. Ramanarayanan, 1999: Water resources of the Texas gulf basin. *Wat. Sci. Tech.*, **39(3)**, 121-133

Di Luzio, M., R. Srinivasan, J.G. Arnold, and S. Neitsch, 2002: Arcview Interface for SWAT 2000 User's Guide. (http://www.brc.tamus.edu/swat/downloads/doc/swatav2000.pdf)

Fontaine, T.A., T.S. Cruickshank, J.G. Arnold, and R.H. Hotchkiss, 2002: Development of a snowfall-snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT), *J. Hydro.*, **262,** 209-223

Neitsch, S.L. J.G. Arnold, J.R. Kiniry, J.R. Williams, and K.W. King, 2002: Soil and water assessment tool theoretical documentation, version 2000. (http://www.brc.tamus.edu/swat/downloads/doc/swat2000theory.pdf)

Neitsch, S.L. J.G. Arnold, J.R. Kiniry, J.R. Williams, and R. Srinivasan, 2002: Soil and water assessment tool user's manual, version 2000. (http://www.brc.tamus.edu/swat/downloads/doc/swatuserman.pdf)

Zhou, J.L., A.L. Tits, and C.T. Lawrence, 1997: User's guide for FFSQP version 3.7: A Fortran code for solving constrained nonlinear (minimax) optimization problems, generating iterates satisfying all inequality a linear constraints. (http://www.isr.umd.edu/Labs/CACSE/FSQP/ffsqp-manual.pdf)

Rosenberg, N.J., R.A. Brown, R.C. Izaurralde and A.M. Thomson, 2003: Integrated assessment of Hadley Center (HadCM2) climate change projections on agricultural productivity and irrigation water supply in the conterminous United States, I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. *Agri. and For. Meteor.*, **117(1-2),** 73-96

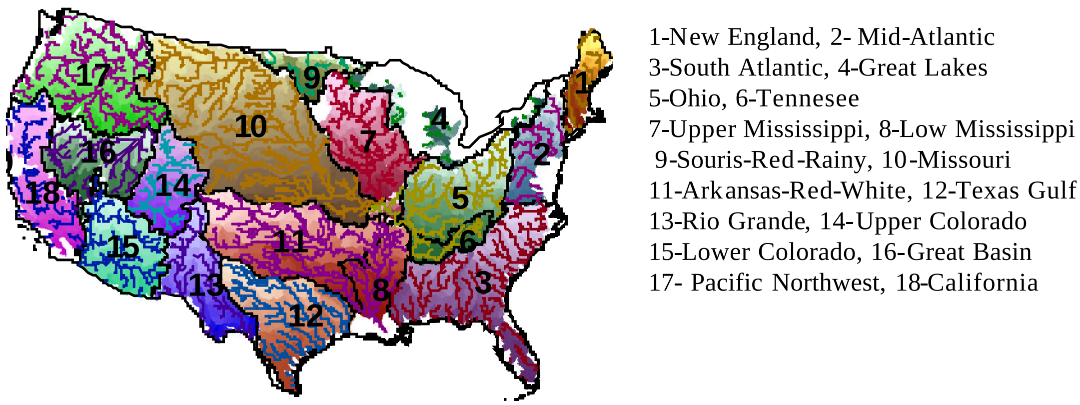

Figure 1. Conterminous US 2-digit HUA (MWRR) coverage and delineated watersheds.

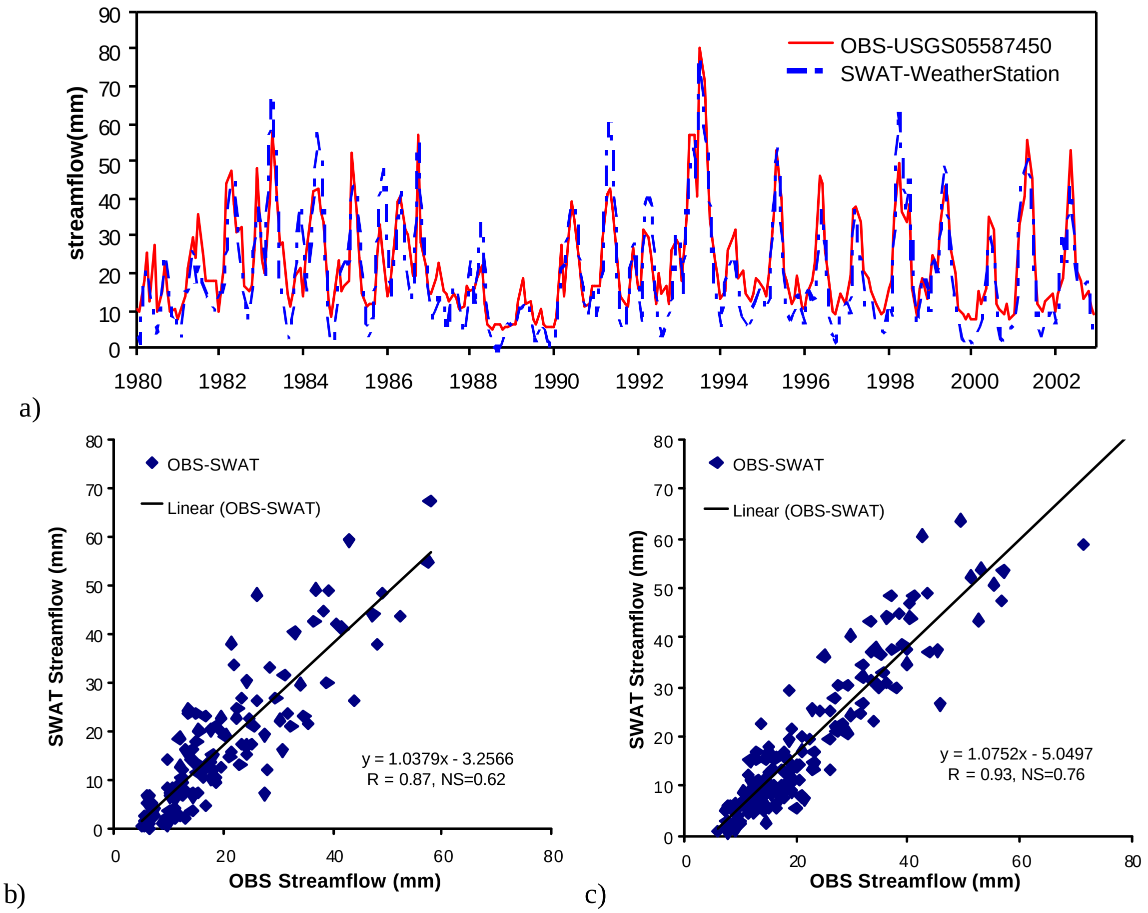

Figure 2. Monthly streamflow comparison between USGS 05587450 and SWAT simulation driven by weather station measurements, *(a)* time-series plot for both calibration (1980-1989) and validation period (1990-2002). *(b)* Regression scatter plot for calibration period. *(c)* Regression scatter plot in validation period.

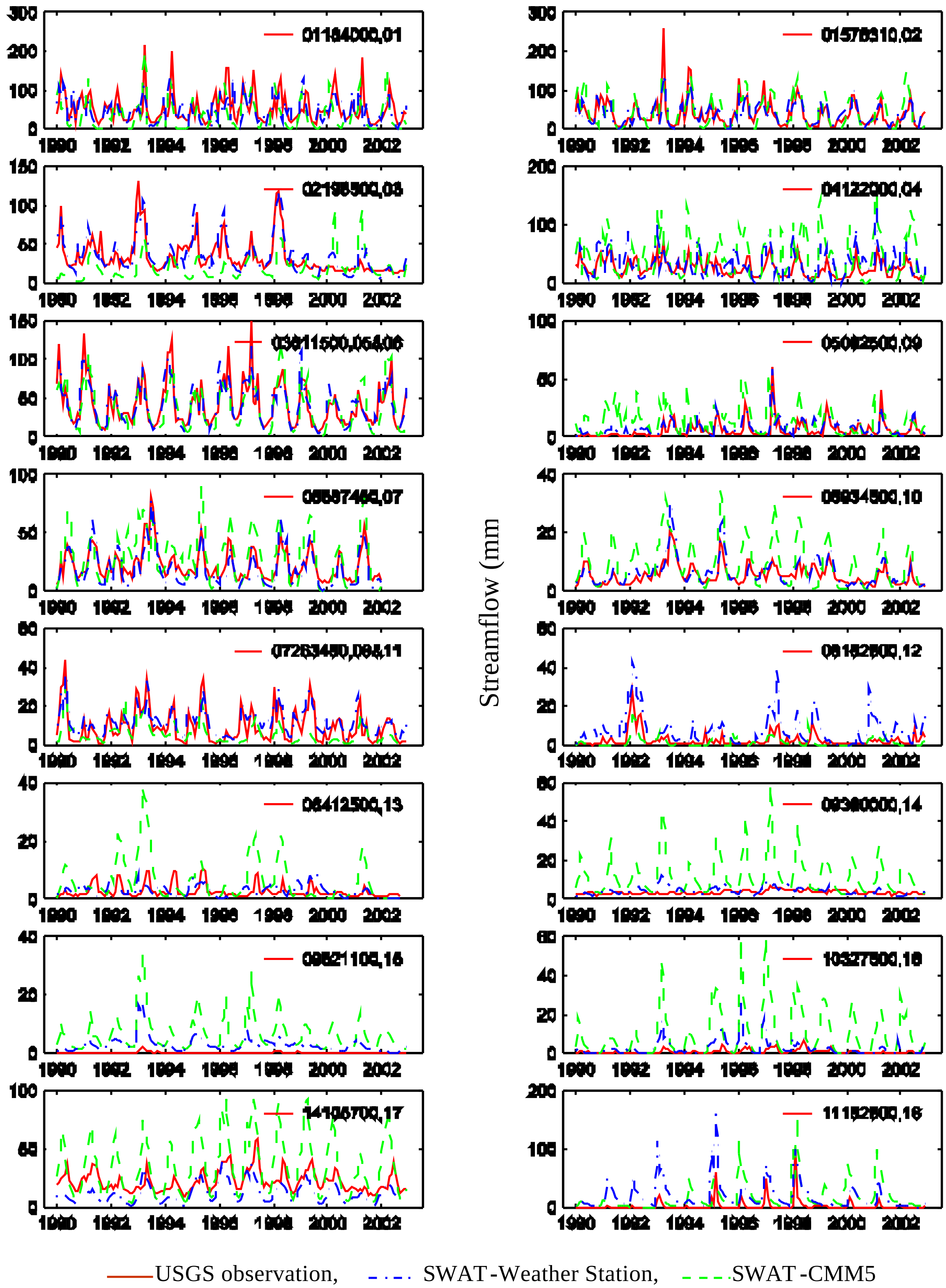

Figure 3. Monthly stream flow comparisons between USGS observation and SWAT driven by both weather observations and CMM5 outputs in the validation period (1990-2002) denoted with USGS stream gage and MWRR index.