Applying Drought Analysis in the Variable Infiltration Capacity (VIC) Model for South Carolina

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ABSTRACT. The objective of this research is to apply the Variable Infiltration Capacity (VIC) model for drought analysis in South Carolina. The VIC model is a macro-scale hydrologic model that solves both water and energy balance equations for the land surface portion of the hydrologic cycle. The model has been successfully applied to a wide range of river basins (Cherkauer et al., 1999, Maurer et al., 2001a, 2001b, 2002) to simulate complex interactions of water, energy and vegetation using soil properties and meteorological datasets for grid-based discretization of the land surface (Liang et al., 1994, 1996). The grid-based analysis also includes sub-grid variability of the land surface vegetation classes and soil moisture storage capacity. Using these features, VIC provides a means to estimate hydrologic variables that are difficult to quantify (i.e. soil moisture, evapotranspiration) at relatively high spatial and temporal resolution over larger regions.

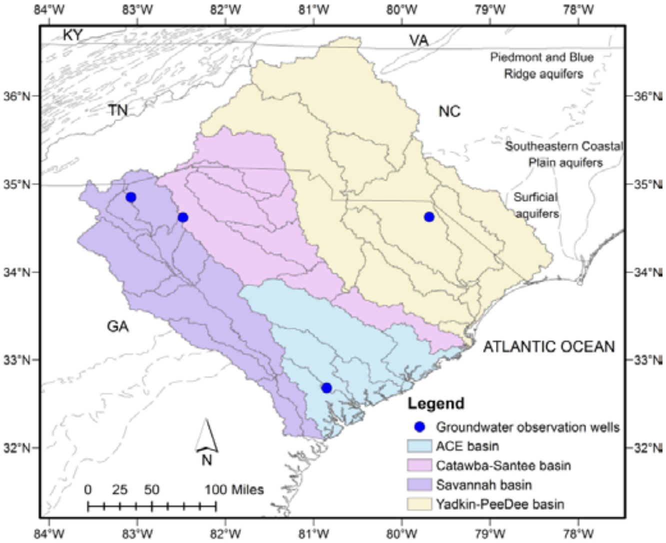

Figure 1: Map of the study area showing major river basins Yadkin-Pee Dee basin, Catawba-Santee basin, Ashepoo-Combahee-Edisto (ACE) basin in South Carolina including groundwater level observations.

The VIC model was applied to simulate the hydrologic conditions in South Carolina with spatial resolution of 1/8th of a degree (Figure 1). The time period was selected from 1998 to 2007 to simulate monthly hydrologic variables during and following the state-wide drought of 1998-2002. Three soil layers were selected for the model as part of the calibration process: 0 to 10 cm for the top layer, 10 to 40 cm for the middle layer, and 40 to 100 cm for the deep layer. The VIC model requires meteorological drivers (precipitation, maximum, minimum temperature and wind speed), as well as vegetation and soil properties to simulate hydrologic conditions. These meteorological datasets were collected from the National Climatic Data Center (NCDC) and the National Centers for Environmental Prediction in partnership with the National Center for Atmospheric Research (NCEP/NCAR) Reanalysis model. The station observed precipitation, maximum temperature, and minimum temperature datasets from NCDC were transformed into gridded input datasets for VIC using SYMAP interpolation algorithm (Shepard, 1984). The wind speed datasets were also converted into gridded input datasets for the modeling domain from NCEP/NCAR. The soil and vegetation datasets were both collected from the Land Data Assimilation Systems (LDAS) at a spatial resolution of 1/8th degree. The VIC model was calibrated using streamflow observations from the stream gaging station at Broad River in the Catawba-Santee basin (Figure 2). The calibration was carried out for the period of 1998-2002 considering seven parameters: variable infiltration curve (b), maximum base flow (D_{smax}), fraction of base flow where base flow occurs (D_s), fraction of maximum soil moisture content above which nonlinear base flow occurs (W_s), mid (d_2) and deep (d_3) soil layer depth, and minimum stomatal resistance (r_0). The Nash-Sutcliffe Efficiency (NSE) index was estimated to select the best combination of parameter values. Using these calibrated parameters, comparison of simulated and observed streamflow provided a NSE value of 0.70 for the period 1998-2002. Following calibration, the VIC model was validated using streamflow observations at same observation station for the period of 2003-2007. The results of the

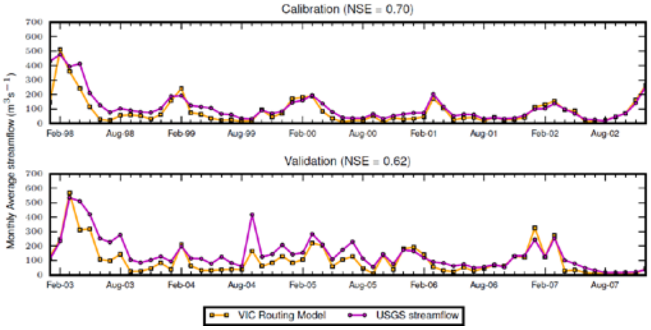

Figure 2: Calibration and validation of VIC model simulation comparing USGS streamflow and simulated streamflow.

validation showed that model was able to estimate streamflow with sufficient accuracy (NSE=0.62).

The model results show the spatial distribution of soil moisture in the soil layers (0-100 cm) from 1998-2002 due to the decreased precipitation in South Carolina (Figure 3). A 30% decrease in precipitation during this time resulted in a less than 20% soil moisture in most of the State. During the drought period, soil moisture in the coastal region of the State remained lower than in the upstate region. From the model results themselves, it is difficult to determine an exact reason for this result. Two possible explanations that could be explored through future work are (i) differences in regional precipitation during drought years and (ii) differences in soil properties between these two regions of the State. Higher soil moisture was estimated from 2003 to 2005 due to the high precipitation that marked the end of the drought. The precipitation decreased after 2005, resulting in low soil moisture at the end of the study period. Late years (2006 and 2007) marked a return to drought conditions in the State.

When viewed as a time series, soil moisture in the deep soil layer (40 cm-100 cm) showed the clearest indicator of drought conditions (Figure 4). On an annual basis, it is evident that during drought years (e.g., 2001 and 2002), this deep soil layer had a soil moisture equal to that in the top two layers, whereas during wet years (e.g., 2003), soil moisture in the deep layer was much higher than the top two layers. This basic signature is also present on a monthly basis, although the monthly time series provides additional insight into the seasonal aspects of drought impacts. For example, soil moisture showed high values in winter (Dec-Jan-Feb) and spring (Mar-Apr-May) months, in general, compared to summer (Jun-Jul-Aug) and fall (Sep-Oct-Nov) months. This was out of the phase with high precipitation in fall and low precipitation in spring months, and could be explained as soil moisture recharge lags in the system. Soil moisture in the deep soil layer was compared with groundwater level observations to justify the use of deep soil layer soil moisture as an indicator of drought severity and occurrence (Lakshmi et al., 2004). The comparison

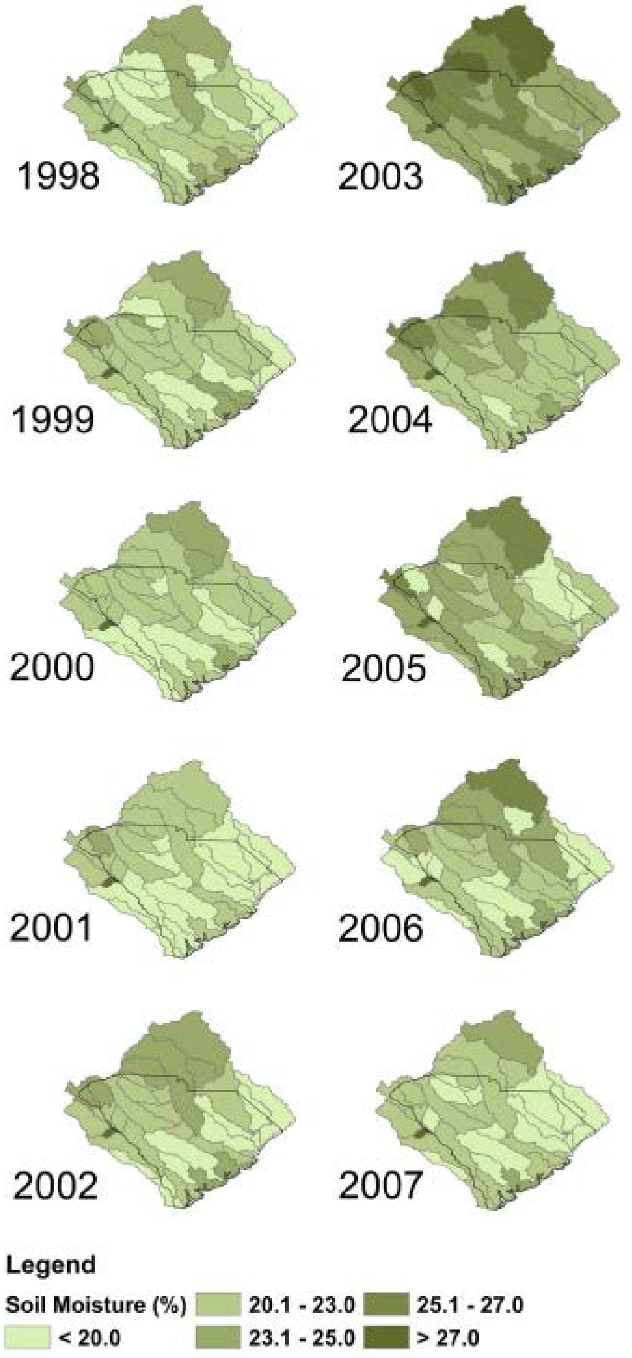

Figure 3: Spatial distribution of soil moisture in the combined soil layers.

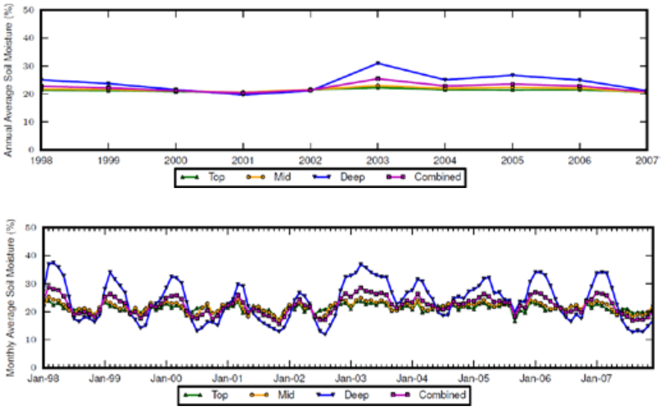

Figure 4: Interannual and seasonal variation of the soil moisture in top (0-10 cm), mid (10-40 cm), deep (40-100 cm), and combined (0-100 cm) soil layers.

showed that all basins followed a similar interannual and seasonal variation in deep soil moisture with evidence of drought impact during 1998-2002 and 2007 (Figure 5). Groundwater levels in the observation wells match reasonably well with all basins except for the Savannah. The groundwater well used for comparison in this plot shows evidence of local impacts that result in a nearly constant reduction in groundwater levels throughout the study period.

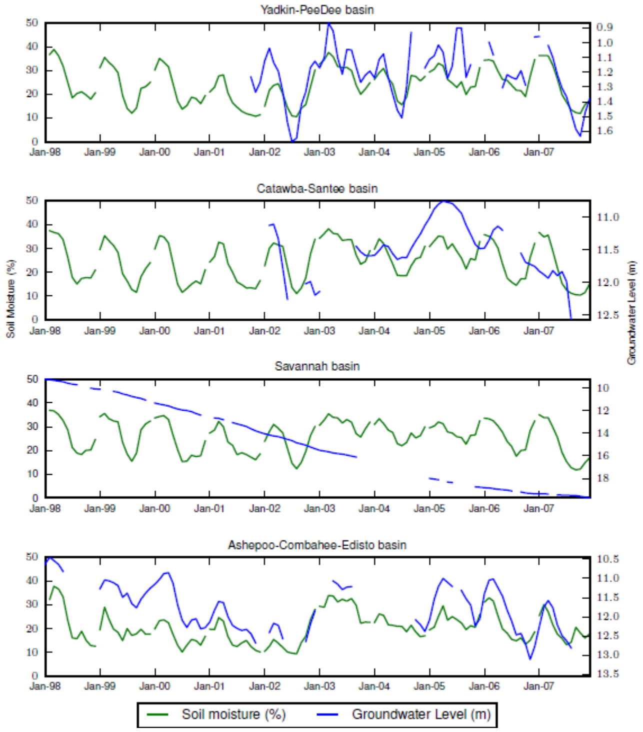

Figure 5: Comparison of groundwater level with soil moisture in the deep soil layer (40-100 cm).

In summary, we have calibrated and validated a VIC hydrologic model for South Carolina and demonstrated how the model can be used to gain insight into state-wide water resource conditions. While the model application described here is for analysis of a past drought event, the model could rather easily be applied for forecasting drought conditions by driving the model with forecasted weather conditions. Such an application of the model could provide a useful tool for managing state-level water resources.

LITERATURE CITED

Cherkauer, K. A., and D. P. Lettenmaier (1999), *Hydrological Effects of Frozen Soils in the Upper Mississippi River basin, J. Geophys. Res*., 104(D16), 19,599–19,610.

Lakshmi, V., T. Piechota, U. Narayan, and C. Tang (2004). *Soil moisture as an indicator of weather extremes. Geophysical research letters* 31 (11).

Liang, X., D. Lettenmaier, E. Wood, and S. Burges. (1994). *A simple hydrologically based model of land surface water and energy fluxes for general circulation models, J. Geophys. Res* 99 (14), 415–14.

Liang, X., E. Wood, and D. Lettenmaier (1996). *Surface soil moisture parameterization of the vic-2L model: Evaluation and modification. Global and Planetary Change* 13 (1-4), 195–206.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads (2001a), *Evaluation of NCEP/NCAR Reanalysis Water and Energy Budgets using Macroscale Hydrologic Model Simulations, Water Science and Application* Volume 3, pp. 137– 158, AGU series in Water Science and Applications, edited by V. Lakshmi, J. Albertson, and J. Schaake, pp. 137–158.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads (2001b), *Evaluation of the Land Surface Water Budget in NCEP/NCAR and NCEP/DOE Reanalyses using an Off-line Hydrologic Model, J. Geophys. Res.*, 106(D16), 17,841–17,862.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), *A long-term hydrologically-based data set of land surface fluxes and states for the continental United States, J. Clim.*, Vol. 15, 3237–3251.

Shepard, D., 1984. *Computer mapping: The SYMAP interpolation algorithm. Spatial Statistics and Models*, 133-145.