Influence of Scale on SWAT Model Calibration for Streamflow

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EXTENDED ABSTRACT

The Soil Water Assessment Tool (SWAT) was implemented in the 281,000 ha St. Joseph River Watershed (SJRW) to investigate the influence of multiple scales on stream flow model calibration parameters (Fig.1). The relationship between model calibration parameters and associated hydrological response units (HRU) between different scales is not well understood. In this investigation, two scales were used within the SJRW where such factors as land use, soil type, topography and management practices are considered similar, thus, conforming to the concept of downscaling rather than regionalization. The model was calibrated for streamflow in the SJRW. Critical parameters optimized for calibration were: 1) CN2, curve number, 2) ESCO, soil evaporation compensation factor, and 3) SOL_AWC, available water holding capacity. Using optimized parameters at the SJRW scale, stream flow estimates were evaluated in the 70,820 ha Cedar Creek Watershed (CCW), the largest subbasin and tributary in the SJRW. These same parameters were then optimized at the CCW scale and streamflow estimates for the CCW and the SJRW were evaluated by examination of the coefficient of determination (R^2) and the Nash and Sutcliffe (1970) model efficiency coefficient (E_{NS}). Modeled and measured streamflow data were statistically analysed at both scales based on their respective calibrations.

The results indicate that the SWAT model adequately simulated streamflow at both scales with little apparent difference between the scale at which the calibration was performed. However, at the larger SJRW scale having higher discharge rates, the model consistently underpredicted streamflow to a much greater extent (lower E_{ns} and R^2 values) than at the smaller CCW scale.

Model output for St. Joseph River streamflow calibrated at both the SJRW and CCW scales show that the trends for both model outputs are very similar (essentially the same line), and in general, match the trend for observed streamflow. However, modeled streamflows at both calibration scales were underpredicted. Modeled streamflow calibrated at the SJRW scale gave an acceptable E_{ns} model efficiency value of 0.50 and had an R^2 value of 0.61. The results are similar for St. Joseph River streamflow calibrated at the CCW scale with an E_{ns} of 0.48 and R^2 of 0.61.

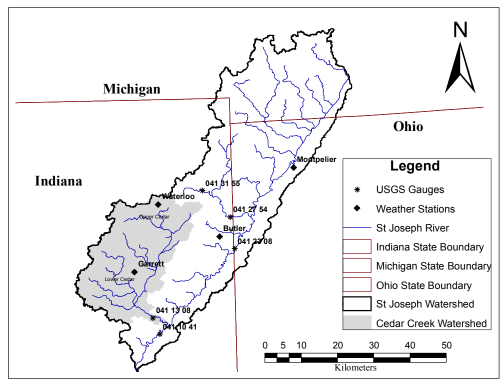

Figure 1. Cedar Creek Watershed within the St. Joseph River Watershed in Northeastern Indiana.

The greatest influence of watershed scale appears to be between daily and monthly estimates of streamflow. There was very little difference between daily and monthly E_{ns} values for streamflow at the SJRW scale, irregardless of the scale of calibration or with no calibration. On the other hand, the difference between daily and monthly E_{ns} values for streamflow at the smaller CCW scale was quite apparent. At the CCW scale the E_{ns} values for monthly streamflow are very good while the values for daily output are within the acceptable range. This would indicate that there may be greater uncertainty in SWAT streamflow estimates at higher discharge rates which are usually associated with larger watershed areas. A more quantitative analysis of the uncertainty in SWAT streamflow estimates at different scales is currently in progress, as well as additional work and analysis related to an expanded version of this study.

1. INTRODUCTION

Models serve as important tools for better understanding the hydrologic processes, developing new or improved management strategies, and in evaluating the risks and benefits of land use over various periods of time (Spruill et al., 2000). Spatially distributed hydrological models have important applications in the interpretation and prediction of the effects of land use change and climate variability on water quality, because they relate model parameters directly to physically observable land surface characteristics (Legesse et al., 2003). The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is a river basin-scale model that allows the user to divide a watershed into any number of sub-basins. The SWAT model can simulate and estimate pollution generation at the source and its movement from the source area to the receiving water body, providing flow and concentration histograms at various points in the watershed and entry points into the receiving water body.

The relationship between model calibration parameters and associated hydrological response units (HRU) between different scales is not well understood. In this investigation, two scales were used within the SJRW where such factors as land use, soil type, topography and management practices are considered similar, thus, conforming to the concept of downscaling rather than regionalization. The objective of this study was to investigate the influence of scale on SWAT model calibration for streamflow.

2. STUDY AREA

The St. Joseph River Watershed (281,000 ha) is located in northeastern Indiana and contains the Cedar Creek Watershed, its largest tributary covering approximately 70,820 ha (Fig. 1). Topography of the watershed varies from rolling hills in Noble County to nearly level plains in DeKalb and Allen Counties with a maximum altitude above sea level of 326 m, and average land surface slope of 3%.

Soil types on the watershed were formed from compacted glacial till and fluvial materials. The predominate soil textures in the immediate Cedar Creek are silt loam, silty clay loam, and clay loam. The average annual precipitation in the watershed is approximately 900 mm. The average temperature during crop growth seasons ranges from 10 to 23°C. The National Land Cover Dataset 2001 (NLCD2001) (Homer et al., 2004) reports that approximately 52% of the watershed area is agriculture, 17% pasture lands , 11% forested lands, and 9% urban. The majority of the agricultural lands are rotationally tilled predominantly with corn and soybeans, with lesser amounts of wheat and hay.

3. MODEL DESCRIPTION

The SWAT model was developed to simulate the hydrologic response of a large watershed with numerous sub-watersheds. It is a spatially distributed, physically based hydrological model, which can operate on a daily time step as well as in annual steps for long-term simulation up to 100 years. The SWAT model is a modification of the SWRRB (Simulator for Water Resources in Rural Basins) model that incorporates a new routing structure, flexibility in watershed configuration, irrigation water transfer, a lateral flow component, and a ground water component (Arnold et al., 1993). The SWAT model also incorporates shallow ground water flow, reach routing transmission losses, sediment transport, chemical transport, and transformations through streams, ponds, and reservoirs. The main purpose of the SWAT model is to predict the effect of different management practices on hydrology, sediment, and agricultural chemical yields in large ungaged watersheds.

Hydrologic processes simulated by the model include evapotranspiration (ET), infiltration, percolation losses, surface runoff, and lateral shallow aquifer and deep aquifer flow. The minimum weather inputs required by the model are maximum and minimum air temperature, and precipitation. Sediment yield is estimated using the Modified Universal Soil Loss Equation (MUSLE) developed by Williams (1975). Daily average soil temperature is simulated as a function of the maximum and minimum annual air temperatures, surface temperature, and damping depth (Saleh et al., 2000).

The Soil Conservation Service runoff curve number (SCS CN) (USDA-SCS, 1986) method or Green and Ampt (1911) infiltration model is used to estimate surface runoff from precipitation. While the Green and Ampt method needs sub-daily rainfall data, the SCS CN is adjusted according to moisture condition in the watershed. Evapotranspiration (ET) in the model (Arnold et al., 1993) is calculated by the Priestly-Taylor (Priestly and Taylor, 1972), Penman-Monteith (Monteith, 1965), or Hargreaves methods (Hargreaves et al., 1985).

3.1. Model Input

The ArcView SWAT2005 (AVSWATX) GIS interface was used for expediting SWAT model input and output. To obtain the proper stream path delineation, a 30-m Digital Elevation Model (DEM) from USGS with a minimum stream threshold value of 1000 ha was used to delineate 52 sub-basins.

In the SWAT model, Hydrologic Response Units (HRUs) are determined by the unique combination of land use and soils within each sub-basin, whereby, the model establishes management practices. The State Soils Geographic Database (STATSGO) spatial data, from the 1:250,000 scale underlying map and the US Geological Survey National Land Cover Dataset 2001 (Homer et al., 2004) in the St Joseph River watershed were used to determine the HRUs with multiple hydrologic response units of 5% land use and 5% soil, totalizing 676 HRUs.

Daily precipitation, and maximum and minimum air temperatures were obtained from the NOAA National Climate Data Center (NOAA-NCDC, 2007) for the Garrett, Waterloo, Butler, Angola, Montpelier Stations with records from 1980 to 2006 (Fig. 1). The information on solar radiation, wind speed, and relative humidity were generated by the SWAT model.

Conservation tillage has been widely adopted in the watershed. In Dekalb County 28% of all corn and 82% of all soybeans planted in 2004 were under a no-till system (Indiana Conservation Tillage Reports, 2004); therefore, both no-till and conventional tillage are used as input in the management file. The tile drain area was considered to have an average depth of 0.9 m, which required 48 h of drainage after a rain to reach field capacity, with a drain tile lag time of 2 h.

The Penman-Monteith method was selected to compute ET in order to capture the effects of wind and relative humidity. The SCS CN was used to calculate surface runoff. A skewed normal distribution was assumed for rainfall distribution. The channel water routing needed to predict the changes in the magnitude of the peak and the corresponding stage of flow as a flood wave moves downstream was based on the Muskingum routing method (Cunge, 1969).

3.2. Model Performance Criteria

The accuracy of SWAT simulation results were determined by examination of the coefficient of determination (R^2) and the Nash and Sutcliffe (1970) model efficiency coefficient (E_{NS}). The R^2 value is an indicator of the strength of the linear relationship between the observed and simulated values. The E_{NS} simulation coefficient indicates how well the plot of observed versus simulated values fits the 1:1 line. The E_{NS} can range from $-\infty$ to +1, with 1 being a perfect agreement between the model and real data (Santhi et al., 2001). E_{NS} statistics are defined as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(X_{oi} - X_{si}\right)^2}{\sum_{i=1}^{n}\left(X_{oi} - \overline{X_{oi}}\right)^2} \qquad [1]$$

Where $\overline{X}_{oi}$ is the average measured value during the simulation period, X_{si} is the simulated output on day i, and X_{oi} is the observed data on day i.

The simulation results were considered to be good if $E_{NS} \geq 0.75$, and satisfactory if $0.36 \leq E_{NS} \leq 0.75$ (Van Liew and Garbrecht, 2003). A negative value of E_{NS} indicates that the sum of squares of the difference between X_{oi} and X_{si} exceeds the sum of squares of the difference between X_{oi} and $\overline{X}_{oi}$, which means that the observed data is a better predictor than the simulated data (Van Liew and Garbrecht, 2003).

3.3. Model Parameter Optimization

The optimization was done by calibrating the model so that the simulated baseflow would approximate the fraction of water yield contributed by the baseflow from the USGS measured flow, which was found to be 47.5% using the recursive digital filter from the baseflow filter from the Web-Base Hydrograph Analysis Tool (WHAT) (Lim et al., 2005).

The SWAT model was calibrated according to the procedure recommended by Neitsch et al. (2002). The model was calibrated for streamflow for a 10-yr period from 1989 t0 1998 with a 3-yr warm-up period using measured data from USGS gauges located at the main outlets of the CCW near Cedarville, and the SJRW near Fort Wayne, IN. The model was calibrated first for the SJRW and the results were analyzed for both SJRW and CCW. A second calibration was implemented at the CCW scale and the optimized parameters were used at the SJRW to estimate the stream flow.

The calibration was implemented by changing one of the more sensitive parameters in the model and then observing the corresponding changes in simulated streamflow. In SWAT, the most sensitive parameters affecting flow were chosen as suggested in previous studies (Santhi et al., 2001; Van Liew and Garbrecht, 2003). These parameters are primarily the SCS CN, soil-available water capacity (SOL_AWC), and soil evaporation compensation factor (ESCO). The soil evaporation compensation factor (ESCO) is used to adjust the depth distribution for evaporation from the soil to account for the effect of capillary action, crusting, and cracks. Calibration of these parameters is considered most critical since they may vary from one watershed to another even within the same geographical area. Additionally, the SURLAG and the MSK_CO2 for the Muskingum routing method are also found to be sensitive to the streamflow. In this study, confidence is placed in a particular calibrated parameter set that produces a response most closely matching the measured data and with acceptable statistical metrics.

4. RESULTS

In an effort to distinguish between different model outputs at different locations we have adopted the following nomenclature in the sections below. CalSJ implies that the model was calibrated at the SJRW scale using measured streamflow from the St. Joseph River gauging station. CalCCSJ indicates model calibration at the CCW scale and CCW gauging station with output for the St. Joseph River gauge location. CalCC implies that the model was calibrated at the CCW scale using measured streamflow from the CCW gauging station. CalSJCC is for model calibration at the SJRW scale and St. Joseph River gauging station with output for the CCW gauge location. Basically, four abbreviations to discern the scale at which the model was calibrated and the modeled/measured output location.

4.1. St. Joseph River monthly streamflow output.

In Figure 2 model output for St. Joseph River streamflow calibrated at both the SJRW (CalSJ) and CCW (CalCCSJ) scales are shown. The trends for both model outputs are very similar (essentially the same line), and in general, match the trend for observed streamflow. However, modeled streamflows at both calibration scales were underpredicted. The degree to which streamflow was underpredicted is illustrated in the 1:1 plots in Figures 3A-B. Figure 3A shows modeled streamflow calibrated at the SJRW scale giving an acceptable E_{ns} model efficiency value of 0.50 and having an R^2 of 0.61 (e.g. Table 1). The results are similar for St. Joseph River streamflow calibrated at the CCW scale shown in Figure 3B with an E_{ns} of 0.48 and R^2 of 0.61 (e.g. Table1).

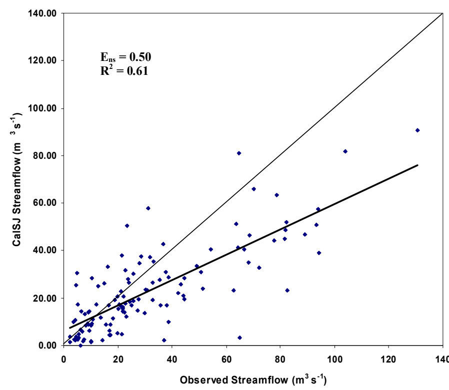

Figure 3A. Modeled vs measured monthly streamflow at the St. Joseph River gauging station, calibrated at the SJRW scale.

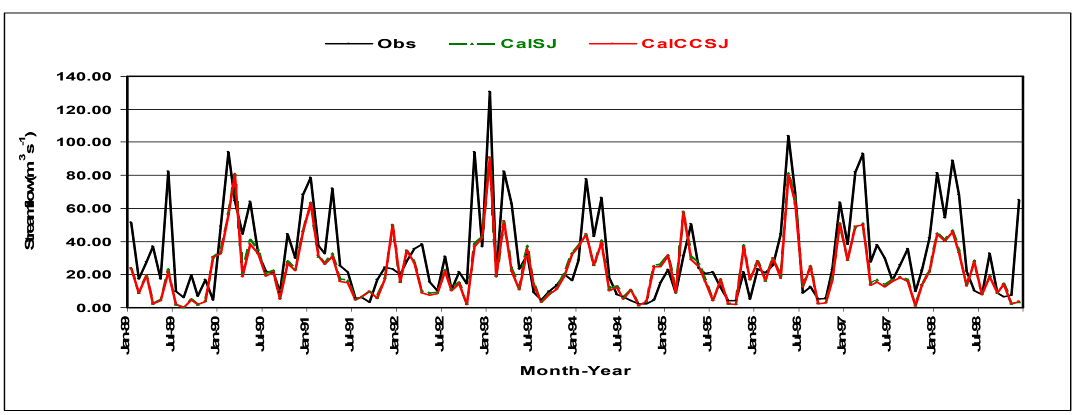

Figure 2. Modeled and measured monthly streamflow from 1989 to 1998 at the St. Joseph River gauging station.

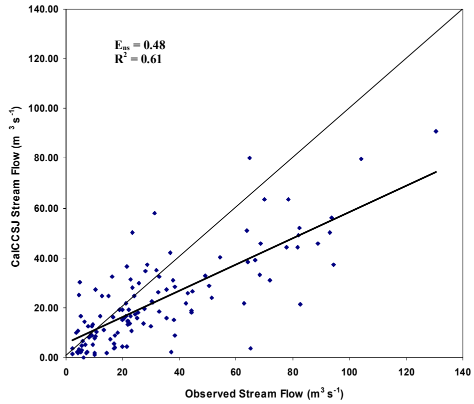

Figure 3B. Modeled vs measured monthly streamflow at the St. Joseph River gauging station, calibrated at the CCW scale.

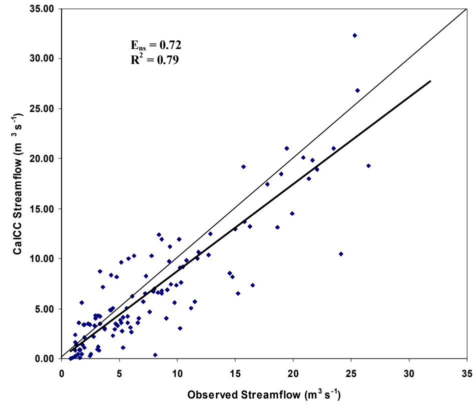

Figure 5A. Modeled vs measured monthly streamflow at the Cedar Creek gauging station, calibrated at the CCW scale.

4.2. Cedar Creek monthly streamflow output.

In Figure 4 model output for Cedar Creek streamflow calibrated at both the SJRW (CalSJCC) and CCW (CalCC) scales are shown. Again, the trends in data for both model outputs are very similar and match the trend for observed streamflow. The rate of measured discharge from Cedar Creek was considerable less (approximately 75% lower) than that measured at the St. Joseph River USGS gauging station. This is not surprising considering that the CCW is the main tributary for the St. Joseph River and accounts for approximately 25% of the area in the SJRW.

Although modeled streamflows at both calibration scales were again underpredicted, the differences between modeled and measured values are much less at the smaller CCW scale. The 1:1 plots in Figures 5A and B show CCW streamflow output calibrated at the CCW scale (CalCC) and at the SJRW scale (CalSJCC), respectively. Figure 5A shows modeled CCW streamflow calibrated at the CCW scale giving a high E_{ns} model efficiency value of 0.72 and having an R^2 of 0.79 (e.g. Table 1). The results are similar for CCW modeled streamflow calibrated at the SJRW scale shown in Figure 5B having an E_{ns} of 0.77 and R^2 of 0.80 (e.g. Table1).

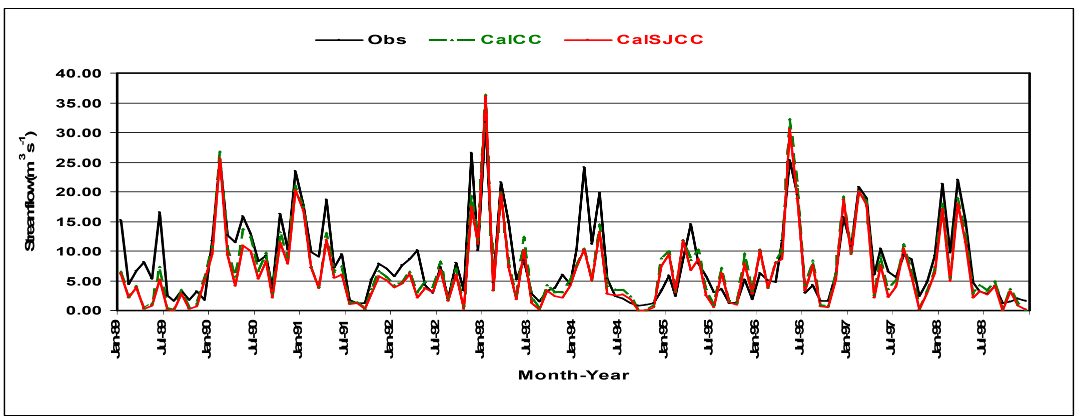

Figure 4. Modeled and measured monthly streamflow from 1989 to 1998 at the Cedar Creek gauging station.

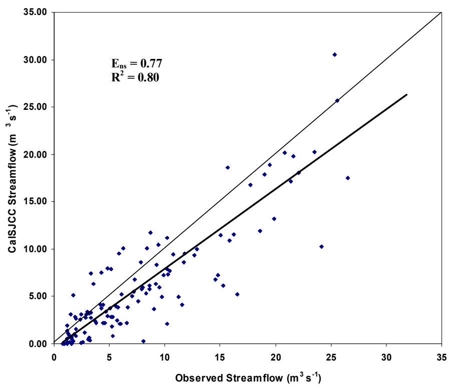

Figure 5B. Modeled vs measured monthly streamflow at the Cedar Creek gauging station, calibrated at the SJRW scale.

Table 1. Statistical metrics for SWAT model performance at two calibration scales and for uncalibrated mode.

Calibration Scales	Cedar Creek Gauging Station		St. Joseph River Gauging Station	
	Daily	Monthly	Daily	Monthly
Uncalibrated	E_{NS}=0.42	E_{NS}=0.71	E_{NS}=0.49	E_{NS}=0.47
	R^2=0.62	R^2=0.74	R^2=0.52	R^2=0.55
SJRW calibration scale	E_{NS}=0.57	E_{NS}=0.77	E_{NS}=0.51	E_{NS}=0.50
	R^2=0.65	R^2=0.80	R^2=0.55	R^2=0.61
CCW calibration scale	E_{NS}=0.56	E_{NS}=0.72	E_{NS}=0.49	E_{NS}=0.48
	R^2=0.65	R^2=0.79	R^2=0.54	R^2=0.61

5. DISCUSSION

Watershed models are very useful and efficient tools for simulating the effect of hydrologic processes and management on soil and water resources. However, there is limited information in the literature to facilitate model evaluation in terms of model application and the effect of variations in watershed scale.

In this preliminary study we investigate the influence of scale on SWAT model calibration for streamflow in the St. Joseph River Watershed (281,000 ha) located in northeastern Indiana and the Cedar Creek Watershed, its largest tributary consisting of approximately 25% of the area or 70,820 ha. The results indicate that the SWAT model adequately simulated streamflow at both scales (e.g. Figures 2 and 4) with little apparent difference between the scale at which the calibration was performed. However, at the larger SJRW scale having higher discharge rates, the model consistently underpredicted streamflow to a much greater extent (lower E_{ns} and R^2 values, e.g. Table 1) than at the smaller CCW scale.

The greatest influence of watershed scale appears to be between daily and monthly estimates of streamflow (e.g. Table 1). There was very little difference between daily and monthly E_{ns} values for streamflow at the SJRW scale, irregardless of the scale of calibration or with no calibration. On the other hand, the difference between daily and monthly E_{ns} values for streamflow at the smaller CCW scale is quite apparent (e.g. Table 1). At the CCW scale the E_{ns} values for monthly streamflow are very good while the values for daily output are within the acceptable range. This would indicate that there may be greater uncertainty in SWAT streamflow estimates at higher discharge rates which are usually associated with larger watershed areas. A more quantitative analysis of the uncertainty in SWAT streamflow estimates at different scales is currently in progress as well as additional work and analysis related to this study.

6. CONCLUSION

There are several issues to consider in the application of watershed scale hydrologic modeling, one of which is the influence of scale on model calibration parameters. This is especially true when using the model as an environmental assessment tool or as a decision-support system for soil and water resource management. The objective of this study was to determine to what extent the influence of scale affects streamflow estimates in a large scale agricultural watershed. Based on our results, the SWAT model shows greater sensitivity between daily and monthly streamflow estimates at the smaller watershed scale and more uncertainty associated with estimates at the larger scale. However, the actual scale at which the model was calibrated did not have a substantial impact on model results based on comparisons with observed streamflow at gauging locations representing each scale.

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