

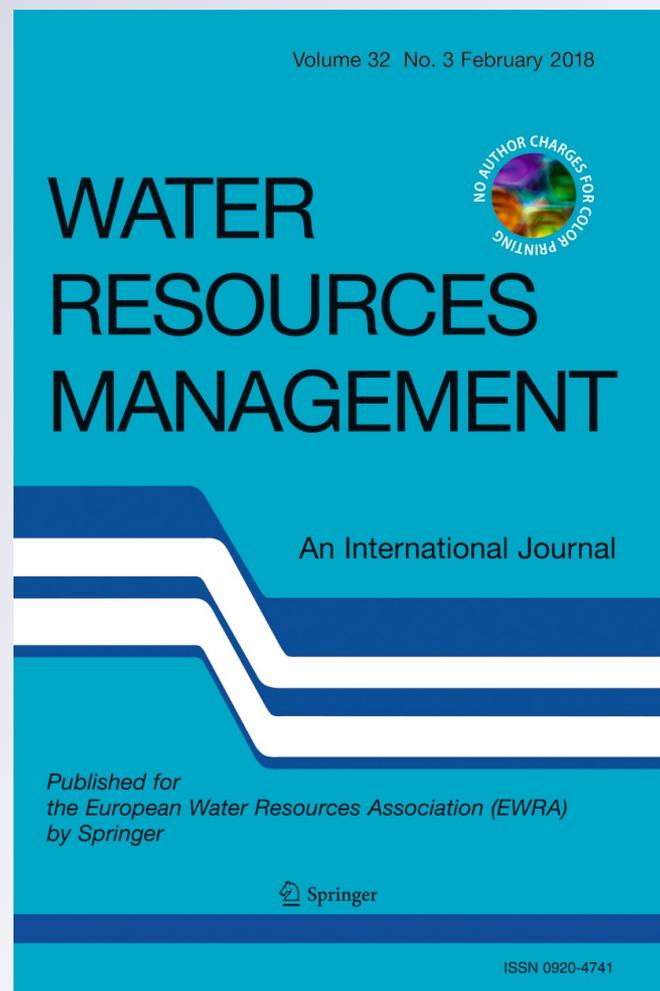
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Evaluation of Using Remote Sensing Evapotranspiration Data in SWAT

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Abstract This study applied a time series evapotranspiration (ET) data derived from the remote sensing to evaluate Soil and Water Assessment Tool (SWAT) model calibration, which is a unique method. The SWAT hydrologic model utilized monthly stream flow data from two US Geological Survey (USGS) stations within the Big Sunflower River Watershed (BSRW) in Northwestern, Mississippi. Surface energy balance algorithm for land (SEBAL), which utilized MODerate Resolution Imaging Spectro-radiometer (MODIS) to generate monthly ET time series data images were evaluated with the SWAT model. The SWAT hydrological model was calibrated and validated using monthly stream flow data with the default, flow only, ET only, and flow-ET modeling scenarios. The flow only and ET only modeling scenarios showed equally good model performances with the coefficient of determination (R^2) and Nash Sutcliffe Efficiency (NSE) from 0.71 to 0.86 followed by flow-ET only scenario with the R^2 and NSE from 0.66 to 0.83, and default scenario with R^2 and NSE from 0.39 to 0.78 during model calibration and validation at Merigold and Sunflower gage stations within the watershed. The SWAT model over-predicted ET when compared with the Modis-based ET. The ET-based ET had the closest ET prediction (~8% over-prediction) as followed by flow-ET-based ET (~16%), default-based ET (~27%) and flow-based ET (~47%). The ET-based modeling scenario demonstrated consistently good model performance on streamflow and ET simulation in this study. The results of this study demonstrated use of Modis-based remote sensing data to evaluate the SWAT model streamflow and ET calibration and validation, which can be applied in watersheds with the lack of meteorological data.

Keywords Evapotranspiration · Stream flow · MODIS · SWAT · Remote sensing

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1 Introduction

Hydrological models are developed with several model parameters, which are adjusted by the modeler during model calibration process. When the hydrological model predicts observed data satisfactorily as suggested by literatures, it may be considered as adequately calibrated (Moriassi et al. 2015). Precipitation, surface runoff, ET, and infiltration are major components in the hydrological cycle, in which precipitation and ET are the two crucial components. It is estimated that about 60% of the moisture input from the rain, yields back to the atmosphere due to the ET process within the hydrological cycle (Korzun et al. 1978; L'vovich and White 1990). In addition, the ET component uses about half of the solar energy captured by the earth surface (Hunt et al. 1986; Kiehl and Trenberth 1997). Hydrological model calibration process can be benefitted with the ET data derived from remote sensing (Immerzeel and Droogers 2008; Bastiaanssen et al. 1998; Doherty 2005). Land use and land cover conditions may impact on exchanges of water and energy between terrestrial and atmospheric layers. Therefore, Land use and land cover data, which generally provide vegetation information to the data layers are commonly utilized in hydrological modeling studies. Computer models utilize vegetation information variables or its richness based on maximum green vegetation fraction to estimate for ET, which are generally collected using remote sensing data (Broxton et al. 2014; Los et al. 2000). Vegetation absorbs fraction of photosynthetically active radiation such as leaf area index, fraction of green leaves measured by MODerate Resolution Imaging Spectroradiometer (MODIS). The MODIS data collection is carried by NASA's Terra and Aqua satellites, which provide biophysical and surface energy information or values for model input to estimate ET (Justice et al. 2002).

Terrestrial land use and land covers conditions, energy, carbon, and biogeochemical cycling are affected by hydrological processes (Potter et al. 2008). In addition, factors such as green vegetation fraction is important for agriculture and water related to agroecosystems (Asner and Lobell 2000; Lucht et al. 2002; Parmesan and Yohe 2003). In the terrestrial agroecosystems, the ET, which is a combined form of evaporation and the transpiration, is considered a major component of the hydrological cycle (Hussey and Odum 1992; Drexler et al. 2004; Parasuraman et al. 2007; Gao 2008; Zhou and Zhou 2009). Penman-Monteith, Priestley-Taylor, and the Hargreaves methods are generally used to estimate ET, which are based on climatological data such as heat flux, aerodynamic component, temperature etc. (Lopez-Urrea et al. 2006; Zhang et al. 2008). Depending upon the method used for estimating ET, different set of climatological daily input data are required in the hydrological model. These input data includes heat flux, daily maximum and the minimum air temperature, relative humidity, solar radiation and wind speed. The daily maximum and minimum air temperatures, solar radiation, and humidity data are needed to estimate ET using Priestley-Taylor method. The Hargreaves ET estimation equation needed daily maximum and minimum air temperatures data.

The actual ET estimation is a difficult process as it involves a complex instrumentation as well as physical and biological processes. The lack of measured meteorological data in the various watersheds to represent spatial conditions of the watershed can make ET estimation process even further complex. While field measured ET data are lacking, remote sensing data can be utilized to estimate net energy and the ET. Remote sensing data are widely available for the large scale watersheds or regional scale and easily accessible than the field measured data. The remote sensing data can provide essential information required to quantify the net energy and the aerodynamic effects of the evapotranspiration process (Tang et al. 2007; Gamage et al. 2011).

In the last few decades, development of hydrological models is growing to address the concerns from small to large scale watersheds modeling with distributed parameters. Especially for the large watershed scale modeling, the remote sensing (RS) data can provide a useful information for estimating ET (Overgaard et al. 2006). Accordingly, modeling methods are needed for validating the ET data retrieved from RS in the hydrological models. The objective of this study was to present an operational approach to validation of RS-derived ET data using a distributed hydrological model. The RS derived ET data, along with other field observed data including USGS stream flow data were used to calibrate and validate a hydrological model. In this study, the soil and water assessment tool (SWAT) model was applied and model predicted stream flow values were compared with observed stream flow data. The RS derived ET data were also validated accordingly. Among the advanced watershed scale, distributed parameter based hydrological models, the SWAT model has been widely applied for hydrological studies (Lirong and Jianyun 2012; Shrestha et al. 2012; Parajuli et al. 2013, 2016). In addition, the SWAT model was also applied to water quality (Pisinaras et al. 2010; Cho et al. 2012; Dakhllalla et al. 2016), and crop growth functions (Masih et al. 2011; Kim et al. 2013; Parajuli et al. 2013, 2016; Kim and Parajuli 2014) studies in various watersheds. The SWAT model has been used with appropriate calibration, validation, and sensitivity analysis (Kannan et al. 2007; Immerzeel and Droogers 2008; Thampi et al. 2010; Parajuli et al. 2013; Dakhllalla and Parajuli 2016; Daggupati et al. 2015; Yuan et al. 2015) as well as the climate change study (Ficklin et al. 2009). The method presented in this paper were tested and evaluated in the study area.

Calibration and validation of the SWAT model in the watershed studies are mostly focused on using stream flow data only (Stone et al. 2001; Rosenberg et al. 2003; Payne et al. 2003; Christensen et al. 2004; Parajuli 2010; Parajuli et al. 2013, 2016). In addition, lack of field measured weather data in the watersheds can make ET estimation process complex. While field measured ET data are lacking, RS data can be utilized in the model to estimate ET. This study offers an important addition to the existing literatures to evaluate the SWAT model streamflow and ET calibration based on remote sensing derived ET data. Four modeling scenarios were developed for the SWAT model simulation in this study. The specific objectives of this study was to compare SWAT model streamflow and ET calibration and validation using (i) default, (ii) stream flow only, (iii) MODIS ET only, and (iv) both stream flow and MODIS ET modeling scenarios, which are unique methods.

2 Material and Methods

2.1 Watershed and Model Use

The study area in this research is the Big Sunflower River Watershed (BSRW) which is located in the west central Mississippi, USA (Fig. 1). The watershed is located within the eleven Mississippi counties (Coahoma, Bolivar, Tallahatchie, Sunflower, Leflore, Washington, Humphreys, Sharkey, Issaquena, Yazoo and Warren). The watershed is dominated by agriculture with more than 72% croplands, primarily by corn and soybean crops. However other crops such as cotton, rice are also available in the watershed. Agricultural activities within the BSRW may have direct impact on the health or water quality of the Gulf of Mexico as it feeds the Mississippi River near Vicksburg, MS via the Sunflower and Yazoo Rivers.

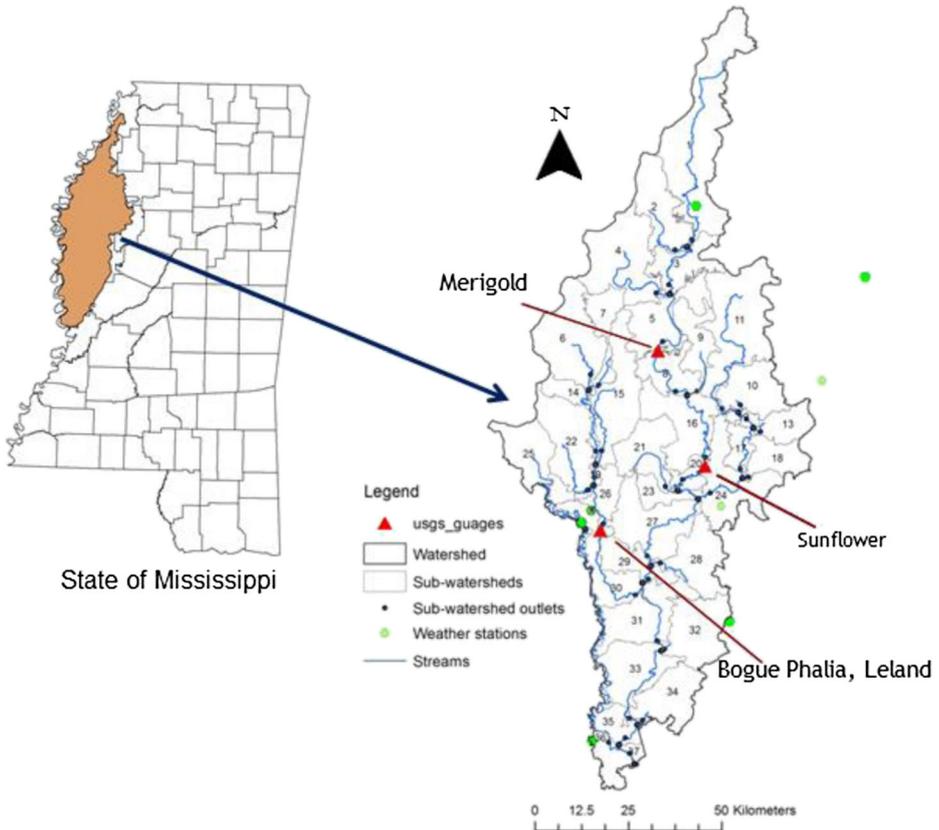


Fig. 1 Big Sunflower River watershed showing USGS gages and sub-watersheds within the State of Mississippi

The SWAT model is a continuous, semi-distributed hydrological and water quality model with daily or sub-daily time scales, simulates surface runoff, sediment and nutrient yields, and crop yields from the agricultural watersheds (Arnold et al. 1998; Neitsch et al. 2011). The SWAT considers watershed, sub-watersheds, and hydrological responsive units (HRUs) as various spatial units in the model. The HRUs are lumped land areas in the watershed sub-basins, which consist of unique soil, land cover, and management conditions in the model (Neitsch et al. 2011). The SWAT model can be simulated in a daily, monthly, annually depending on need. Model calculates water yield, sediment yield, nutrient yield, lateral flow and groundwater flow, evapotranspiration, crop yield, and in-stream process of water quality parameters for each HRU in every sub-watersheds and the watershed outlet.

The SWAT model considers crop planting and harvesting, crop rotations, tillage operations, irrigation management, and fertilizer application inputs as described by users in the model. The SWAT model in this modeling study used the curve number (CN) method to estimate surface runoff. The SWAT model utilized Environmental Policy Integrated Climate (EPIC) model within the SWAT to estimate crop growths, potential heat units, hydrological parameters including ET (Neitsch et al. 2011). The detailed SWAT model sub-routine descriptions are available in the theoretical documentation (Neitsch et al. 2011).

2.2 Model Input and Modeling Scenarios

In this study rainfall and temperature data were utilized from seven weather stations in which six weather stations data were available from the National Climatic Data Center (NCDC 2013; Fig. 1) and one from the Delta Research and Extension Center (DREC) within the watershed (DAWC 2012). This study utilized monthly stream flow data (2002 to 2009) from the Merigold, and Sunflower USGS gage stations available within the watershed. The soil data base in the SWAT model were created using Soil Survey Geographic Database (SSURGO) data (USDA 2005), which showed twelve major soils in the watershed. Primarily, fine-silty soil contributed about 62% of the watershed area (Parajuli et al. 2016). The USDA cropland data layer of 30 m by 30 m resolutions were utilized to generate land use data input in the model (USDA/NASS 2009). This study also utilized 30 m × 30 m pixel digital elevation model (DEM) data (USGS 2010) to delineate topographic characteristics of the watershed. Model inputs considered auto irrigation and auto fertilization only for corn crop. The common crop rotation in the watershed is corn after soybean crop rotation with conventional tillage (NASS 2013). The Penman Monteith equation was used to describe the potential evapotranspiration (PET) algorithms in the SWAT model (Neitsch et al. 2011). The MODIS data as carried by NASA's Terra and Aqua satellites was used for ET based model calibration (Mu et al. 2011).

Four modeling scenarios were considered for the hydrologic calibration of the SWAT model in this study. These modeling scenarios include: (i) SWAT model default scenario considered as a baseline condition after all inputs in the model representing the current watershed conditions, (ii) Flow-based modeling scenario considered calibration of flow related hydrological parameters in the model, (iii) ET-based modeling scenario considered use of Modis-based remote sensing ET data for hydrological calibration, and (iv) Flow-ET-based modeling scenario considered both flow-based and ET-based methods.

2.3 Streamflow Calibration and Validation

The SWAT-CUP SUFI-2 was used to automatically calibrate the SWAT model at the beginning (Abbaspour et al. 2007; Parajuli et al. 2013) then manually adjusted parameters to improve model performance. The SWAT model was calibrated and validated using monthly measured USGS stream flow data from the two USGS gage stations Merigold and Sunflower. In addition, to the twelve stream flow calibration parameters for the SWAT hydrologic model calibration as described in Parajuli et al. (2013); this study added two more parameters during refining model calibration. Therefore the total of fourteen hydrological parameters were selected for the model calibration. These parameters were curve number (cn2), base flow recession constant (alpha_bf), delay time for aquifer recharge (gw_delay), Manning's "n" value for the main channel (ch_n2), available water capacity (sol_awc), surface runoff lag coefficient (surlag), aquifer percolation coefficient (rchrg_dp), plant uptake compensation factor (epco), soil evaporation compensation factor (esco), revap coefficient (gw_revap), threshold water level in shallow aquifer in base flow (gwqmn), threshold water level in shallow aquifer for revap (revapmn), maximum canopy storage (canmx), and effective hydraulic conductivity in main channel alluvium (ch_k2). The canmx parameter was ranged from 0.00 to 100.00 with 2 as the final value considered during model calibration. Similarly, the ch_k2 parameter was ranged from 0.00 to 150.00 with 20 as the final value considered during model calibration. Model predicted outputs were statistically analyzed using Nash–Sutcliffe

model efficiency index (NSE), and coefficient of determination (R^2) based on previous literatures (Moriasi et al. 2007; Parajuli 2010; Parajuli et al. 2013; Kim and Parajuli 2014).

3 Results and Discussion

3.1 Monthly Stream Flow

The SWAT model predicted monthly stream flow values were calibrated and validated using eight years of monthly measured stream flow data from the Merigold and Sunflower USGS gage stations. The SWAT model simulation considered two years warm up period to improve hydrologic predictions. Monthly measured stream flow data from the Merigold, and Sunflower from January 2002 to December 2005 were used to calibrate the SWAT model, and data from January 2006 to December 2009 were used to validate the SWAT model (Table 1). The statistics of the model performance demonstrated the R^2 values up to 0.86 and NSE values up to 0.83 in both Merigold and Sunflower gage stations (Table 1).

Monthly measured USGS mean stream flow at Merigold, and Sunflower were $24.1 \text{ m}^3 \text{ s}^{-1}$, and $32.4 \text{ m}^3 \text{ s}^{-1}$ respectively during the model calibration and validation period. The SWAT default modeling scenario over-estimated monthly mean stream flows in both the Merigold and Sunflower gage stations. The SWAT model default modeling scenario simulated monthly mean stream flow of $35 \text{ m}^3 \text{ s}^{-1}$ at Merigold (~45% over-prediction, R^2 and NSE from 0.39 to 0.78), and $47.5 \text{ m}^3 \text{ s}^{-1}$ at Sunflower (~46% over-prediction, R^2 and NSE from 0.42 to 0.78) gage stations within the watershed (Table 1, Figs. 2 and 3).

The SWAT model flow only modeling scenario simulated monthly mean stream flow of $26.9 \text{ m}^3 \text{ s}^{-1}$ at Merigold (~11% over-prediction, R^2 and NSE from 0.78 to 0.86), and $36.5 \text{ m}^3 \text{ s}^{-1}$ at Sunflower (~13% over-prediction, R^2 and NSE from 0.72 to 0.86) gage stations within the watershed (Table 1, Figs. 2 and 3).

The SWAT model ET only modeling scenario simulated monthly mean stream flow of $28.0 \text{ m}^3 \text{ s}^{-1}$ at Merigold (~16% over-prediction, R^2 and NSE from 0.75 to 0.82), and $38.4 \text{ m}^3 \text{ s}^{-1}$ at Sunflower (~19% over-prediction, R^2 and NSE from 0.71 to 0.79) gage stations within the watershed (Table, Figs. 2 and 3). The SWAT model both flow and ET modeling scenario simulated monthly mean stream flow of $27.0 \text{ m}^3 \text{ s}^{-1}$ at Merigold (~12% over-prediction, R^2 and NSE from 0.69 to 0.81), and $36.9 \text{ m}^3 \text{ s}^{-1}$ at Sunflower (~14% over-prediction, R^2 and NSE from 0.66 to 0.83) gage stations within the watershed (Table 1, Figs. 2 and 3).

Table 1 Model calibration and validation efficiencies for Merigold and Sunflower stations with different modeling scenarios

Modeling scenarios	Merigold		Merigold		Sunflower		Sunflower	
	Calibration		Validation		Calibration		Validation	
	R^2	NSE	R^2	NSE	R^2	NSE	R^2	NSE
Default	0.78	0.39	0.78	0.44	0.74	0.52	0.78	0.42
Flow only	0.84	0.78	0.86	0.80	0.78	0.72	0.86	0.81
ET only	0.82	0.80	0.78	0.75	0.79	0.78	0.75	0.71
Flow & ET	0.77	0.69	0.81	0.79	0.73	0.66	0.83	0.81

ET, evapotranspiration; R^2 , coefficient of determination; NSE, Nash-Sutcliffe Efficiency Index

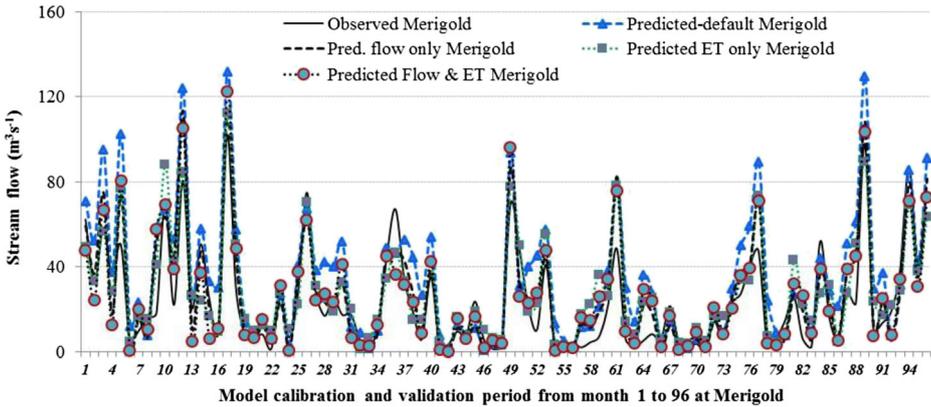


Fig. 2 Model calibration and validation with four stream flow modeling scenarios at Merigold gage station

Based on monthly mean stream flow prediction, the SWAT model flow only scenario had the closest match with the USGS measured monthly mean stream flow during model calibration and validation as followed by both flow and ET stream flow modeling scenario, ET only stream flow modeling scenario and default stream flow modeling scenario. However, based on model efficiency (R^2 and NSE) values ET only stream modeling scenario (R^2 and NSE from 0.74 to 0.78) was equally good as flow only stream flow modeling scenario (R^2 and NSE from 0.71 to 0.82) during model calibration and validation for monthly mean stream flow at Merigold and Sunflower USGS gage stations.

3.2 Evapotranspiration

In this study, spatial distribution of the MODIS-based ET on surface energy balance was utilized as an observed data as similar to previous studies (Venturini et al. 2007; Mu et al. 2011) to compare with SWAT model simulated ET outputs. The MODIS-based ET data was compared with the SWAT model simulated ET outputs for the prior model calibration and validation period from January 2002 to December 2009. The SWAT model simulation

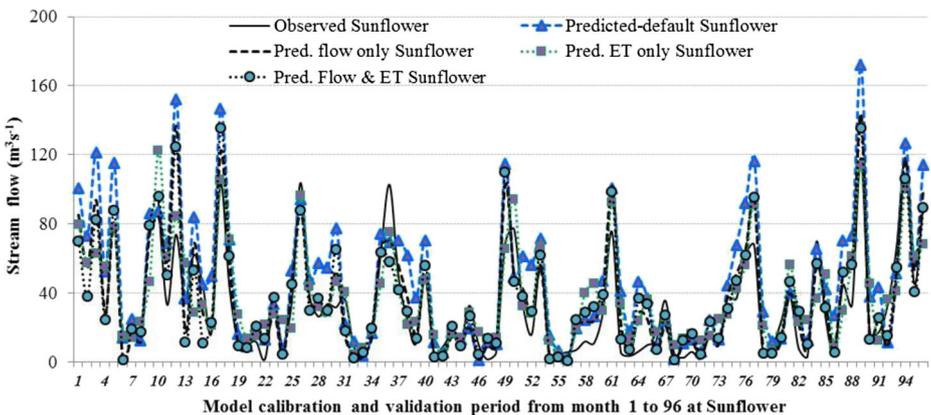


Fig. 3 Model calibration and validation with four stream flow modeling scenarios at Sunflower gage station

Table 2 Model calibration and validation efficiencies for the watershed with four ET modeling scenarios

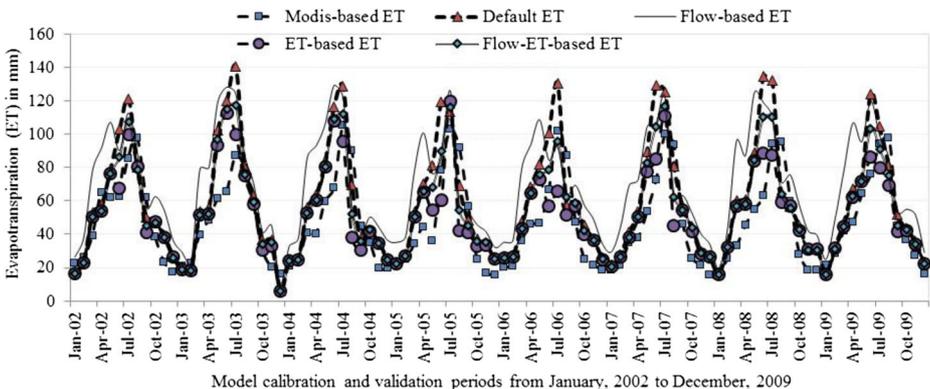
Modeling scenarios	Calibration		Validation	
	R ²	NSE	R ²	NSE
Default ET	0.71	0.28	0.70	0.27
Flow-based ET only	0.56	-0.34	0.50	-0.38
ET-based ET only	0.61	0.50	0.63	0.60
Flow-ET-based ET	0.68	0.50	0.72	0.60

ET, evapotranspiration; R², coefficient of determination; NSE, Nash-Sutcliffe Efficiency Index

considered default ET, flow-based ET only, ET-based ET only, and flow-ET-Based ET modeling scenarios in this study. The statistics of the model predicted four modeling scenarios in Table 2 below showed the R² values up to 0.72 and NSE values up to 0.60 during model calibration and validation. The model performance in this study showed reasonable results as supported by previous studies (Venturini et al. 2007; Gamage et al. 2011; Bowman et al. 2015).

The average monthly MODIS-based ET for the model calibration and validation period (January 2002 to December 2009) was 46.8 mm. In this study, the SWAT model generally over-predicted ET in all modeling scenarios as compare to MODIS-based ET (Fig. 4). The default ET predicted average monthly ET of 59.8 mm (27.5% over-predicted), flow-based ET predicted average monthly ET of 69.1 mm (47.3% over-prediction), the ET-based ET predicted average monthly ET of 50.8 mm (8.4% over-prediction), and flow-ET-based ET predicted average monthly ET of 54.6 mm (16.5% over-prediction).

The SWAT model simulated annual average ET, water yield (WYLD) and precipitation outputs from 2002 to 2009 (Fig. 5). Water yield is generally estimated annually is a mean water depth in mm that leave from the watershed to the stream. Water yield in fact is a sum of surface flow, lateral flow, and ground water flow subtracted from the transmission loss including pond abstractions as described in the SWAT model documentation (Neitsch et al. 2011). Annual average precipitation values were determined generally greater than ET and WYLD values. However, average annual precipitation values for 2003, 2005 and 2007 were slightly lower than combined ET and WYLD values (Fig. 6).

**Fig. 4** Simulated evapotranspiration (ET) with four ET modeling scenarios from the watershed

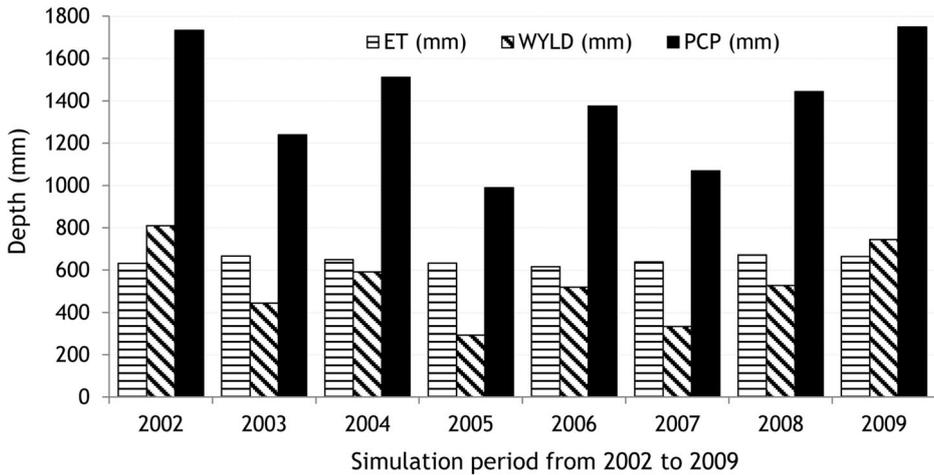


Fig. 5 Simulated evapotranspiration (ET), water yield (WYLD), and precipitation (PCP) outputs in mm

Annual mean water balance was calculated by subtracting annual mean rainfall with the sum of ET and WYLD. The calculated annual mean water balance for the watershed during the model calibration and validation period (2002 to 2009) determined mostly greater with a positive values with 1.04% for default, 3.39% for flow only, 15.75% for ET only, and 14.31% for flow-ET modeling scenarios. However, annual mean water balance values were calculated slightly lower with a negative values for the individual years of 2003 by 65 mm, 2005 by 98 mm, and 2007 by 15 mm only with the default modeling scenario (Fig. 6). However, model simulated average annual water balance with slightly low negative values for 2003 by 10 mm, 2005 by 57 mm, and 2007 by 2 mm only with flow only modeling scenario. It is possible to have a continuation of ET and WYLD processes, when there is no rainfall or more ET losses than rainfall due to other climatic factors including solar radiation (Hanson 1991). The SWAT model also permits movement of water from the bank storage into an unsaturated area to fulfill

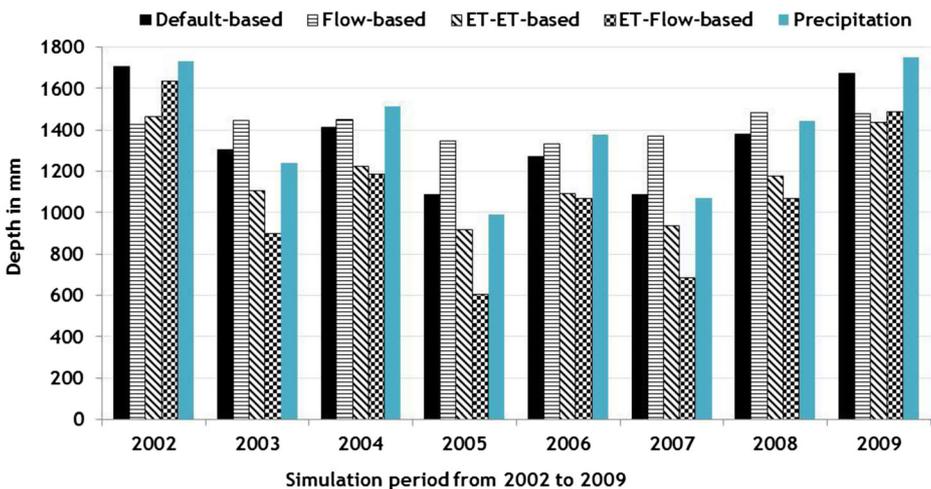


Fig. 6 Comparison of simulated sum of water yield and evapotranspiration with precipitation for four modeling scenarios from the watershed

the water demand for ET, which is considered as “revap” process in the model (Neitsch et al. 2011). The revap process can be significant in the watershed like the BSRW, where deep-rooted plants are growing due to corn and soybean cropping system and saturated zones are not very far below the surface.

4 Conclusions

The SWAT hydrological model was calibrated and validated within the BSRW using monthly stream flow data from the two USGS gage stations and four modeling scenarios with the default, flow only, ET only, and flow-ET scenarios. The flow only and flow-ET modeling scenarios showed equally consistent model performances for both coefficient of determination (R^2 from 0.66 to 0.87) and Nash Sutcliffe Efficiency (NSE from 0.59 to 0.84), followed by ET only (R^2 and NSE from 0.74 to 0.78) and default (R^2 and NSE from 0.33 to 0.78) scenarios during model calibration and validation at Merigold and Sunflower gage stations within the watershed.

This study used Modis-based ET data to compare the SWAT model simulated ET outputs with four modeling scenarios with the default, flow only, ET only, and flow-ET scenarios. The SWAT model generally over-predicted ET in all four modeling scenarios as compare to Modis-based ET. Out of four modeling scenarios, the ET-based ET predicted the closest average monthly ET (~8% over-predicted) followed by flow-ET (~16%), default (~27%), and flow based (~47%) ET scenarios. As discussed, the ET-based modeling scenario also had consistently good model performance on monthly streamflow simulation from both Merigold and Sunflower gage stations with R^2 and NSE values from 0.74 to 0.78. This study demonstrated use of Modis-based remote sensing data to evaluate calibration and validation of hydrological model SWAT and ET, which can be applied in the watershed with the lack of meteorological data.

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